CRANFIELD UNIVERSITY

PHILLIP EDWARD JUDKINS

MAKING VISION INTO POWER

DEFENCE COLLEGE OF MANAGEMENT AND TECHNOLOGY

Ph D THESIS

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Britain's acquisition of the world's first radar-based integrated air defence system
1935-1941

Supervisor: Professor T Taylor

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ABSTRACT

This thesis represents the first application of a current conceptual model of defence acquisition to analyse an historical process, the 1935-41 British acquisition of an integrated air defence system pivoted upon the innovative technology of radar.

For successful acquisition of a military capability, that model posits that balanced attention must be focussed across eight "lines of development" - not only equipment, but also doctrine and concepts, logistics, structures, personnel, organisation, training, and information, with an additional overarching requirement for interoperability.

The thesis contrasts what turned out to be a successful acquisition, of radar to achieve air interception capability by day in the Battle of Britain, with a less successful acquisition, of radar to achieve the same capability by night, where an effective system arrived too late to ward off the Blitz.

The results establish the validity of the model and its attendant lines of development concepts, and furnish new insights into acquisition processes and military history.

Acquisition lessons are derived for the capability-based involvement of industry, for the experience and personality necessary for key managers at different "life stages" of an acquisition, and for the avoidance of over-rapid "dysfunctional diffusion" of innovative technologies

Historical insights for the Battle of Britain include the suboptimal performance, for trivial reasons, of key South Coast radars, and the critical importance of the human elements of the radar-based air defence system. For the Blitz, airborne radar hardware has previously been identified as the key problem, whereas the research here exposes the greater need for accurate ground control radar, the sound selection and training of pilots and operators in new tactics, and provision of equipment maintainers and test gear. New evidence illustrates that pursuit of an alternative to radar significantly delayed the optimal solution, and throws fresh light both on personalities and on development process management.

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Phillip Judkins

DCMT Shrivenham, July 2007.

LIST OF CONTENTS

LIST OF TABLES.

LIST OF FIGURES

GLOSSARY

AA	Anti-aircraft guns; today, anti-aircraft artillery (AAA).
AC	Alternating Current.
ACAS(R)	Assistant Chief of Air Staff (Radio), in 1940 the Air Ministry post with responsibility for radar co-ordination.
ADEE	Air Defence Experimental Establishment.
ADGB	Air Defence of Great Britain.
ADRC	Air Defence Research Committee.
AMRD	Air Member for Research and Development.
AMSR	Air Member for Supply and Research.
AI	Air Interception radar; airborne aircraft-to-aircraft radar system.
AIH	Air Interception High, otherwise known as RDF 2, the airborne radar system with both transmitter and receiver inside the fighter aircraft.
AIL	Air Interception Low, otherwise known as RDF 1.5 or RDF 1A, the airborne radar system with the transmitter on the ground and only the receiver carried in the aircraft, used to intercept low-flying mine-laying aircraft.
AP	Air Publication; series of manuals issued by the UK Air Ministry.
ASV	Air to Surface Vessel radar; airborne radar system to detect ships and submarines.
AVM	Air Vice Marshal.
BBC	British Broadcasting Corporation.
BMHQ	Base Maintenance Headquarters, from 1940 the organisation responsible for the logistic and servicing support to UK radar stations.
C3I	Command, control, communication and information.
C4I	Command, control, communication, computing and information.
C-in-C	Commander in Chief.
CAS	Chief of the Air Staff.
CD	Coast Defence (radar).
CDU	Coast Defence U-boat (radar).
CH	Chain Home; UK early warning radar 1935-1955.
CHL	Chain Home Low; UK radar giving warning of low-flying aircraft.

CID	Committee of Imperial Defence
CRDF	Cathode Ray Direction Finding
CRT	Cathode Ray Tube
CSSAD	Committee for the Scientific Survey of Air Defence (the “Tizard Committee”), which met from January 1935 to August 1939. Chaired by Sir Henry Tizard, it researched all aspects of science related to UK air defence.
D/F	Direction Finding.
DC	Direct Current.
DCAS	Deputy Chief of the Air Staff.
DCD	Director of Communications Development.
DRC	Defence Requirements Committee.
DSIR	Department of Scientific and Industrial Research.
DSR	Director of Scientific Research.
DTD	Director of Technical Development.
ECC	Equipment Capability Customer.
ELINT	Electronic Intelligence.
EMI	Electrical and Musical Industries; a British company which designed and manufactured radio and audio equipment, and which subsequently became involved in radar.
FIU	Fighter Interception Unit.
FMCW	Frequency modulated continuous wave.
Freya	A German “beam” radar, 1936-1945.
FRS	Fellow of the Royal Society
GCI	Ground Control Interception radar; a 360-degree (all-round looking) radar which plotted the position of attacking and defending aircraft on a map-like display, allowing ground control of intercepting fighters fitted with AI (q.v.).
GL	Gun Laying, a series of Army radars to assist anti-aircraft artillery.
GM	A short-lived mobile radar used for AIL tests (q.v.) in June 1940.
GPO	General Post Office, at this period responsible for all telecommunications matters in addition to surface mail delivery.
H2S	A centimetric radar navigation and blind bombing system used by the RAF from 1942 onwards. There is no agreed derivation - the letters are variously

derived from "Home Sweet Home", or a comment ascribed to Lord Cherwell, "It stinks that no-one thought of this before – call it H2S".

ICH Intermediate Chain Home.

IEE The (British) Institution of Electrical Engineers, since 2006 the Institution of Engineering and Technology.

IEEE The (American) Institute of Electrical and Electronics Engineers.

IFF Identification Friend or Foe, today called secondary surveillance radar or SSR. An interrogating transmission from a friendly radar triggers a responding transmission from an equipment in the target, identifying it as friendly (or if no or inaccurate response, as potentially hostile) on the interrogating radar display.

IPCS Institution of Professional Civil Servants, an association for Government scientists with wage-bargaining rights.

IPTL Integrated Project Team Leader.

KHz. Kilohertz, a unit of frequency of 10^3 hertz, at this period known in the UK as kilocycles per second (Kc/s, colloquially pronounced "Kaycees").

LADA London Air Defence Area

MAP Ministry of Aircraft Production. From its formation in May 1940, the Ministry controlling UK radar research.

MB Mobile Base, an intermediate range mobile early warning radar.

MHz Megahertz, a unit of frequency of 10^6 hertz, at this time known in the UK as "megacycles per second" (Mc/s, colloquially "Megs").

MoD Ministry of Defence; the UK Department of State responsible for military matters.

MoS Ministry of Supply.

MRU Mobile Radio Unit, a mobile radar station.

NCO Non-Commissioned Officer.

NIV Not In Vocabulary, an expression meaning that a necessary item was not available from Ministry stores and therefore had to be procured, with considerable delay, outside normal channels.

NPL National Physical Laboratory

O.R. Operational Research.

PPI — Plan Position Indicator, a display in which the area searched by the radar is set out as a map, usually with the radar at its centre.

QF-site — A decoy site, otherwise known as “Starfish”, having ground fires and lights to lure bombers from their intended target.

“Radio” — Radio was used as a cover name for radar during this period; the term for radio as a communication medium was “wireless”.

RAE — Royal Aircraft Establishment, Farnborough.

RAF — Royal Air Force; since 1 April 1918, the military air force of the United Kingdom.

RCM — Radio Counter Measures.

RDF — Radio Direction Finding; a deliberately confusing “cover” name for radar in the UK from 1935 to 1943, when the term was superseded by the American palindrome “radar”.

RDF1 — Generically, a radar system with both transmitter and receiver on the ground; often used specifically to refer to the Chain Home system.

RDF1A — Otherwise known as RDF 1.5 or AIL (q.v.).

RDF 1.5 — Otherwise known as RDF 1A or AIL (q.v.).

RDF 2 — Otherwise known as AIH (q.v.).

RD/F — Radio direction-finding; the technique of locating an aircraft by taking bearings on a transmission from it, used to locate RAF fighters from 1937 onwards.

SAT — Scientific Adviser on Telecommunications.

SIGINT — Signals Intelligence.

SRO — Senior Responsible Owner.

STC — Standard Telephones and Cables.

WAAF — Women’s Auxiliary Air Force.

“Wireless” — The term for radio used as a communications medium during this period – the term “radio” was used as a cover name for radar.

Y Service — The UK military radio interception service, operated by all three armed forces.

MAKING VISION INTO POWER

“The Germans would not have been surprised to hear our radar pulses, for they had developed a technically efficient radar system which was in some respects ahead of our own. What would have surprised them, however, was the extent to which we had turned our discoveries to practical effect, and woven all into our general air defence system. In this we led the world, and it was operational efficiency rather than novelty of equipment that was the British achievement”

Winston S. Churchill, *The Gathering Storm*, London: Cassell, 1948, p. 122.

“The British had, from the first, an extraordinary advantage, never to be balanced out at any time in the whole war: their radar and fighter-control network. It was for us and our leadership a freely expressed surprise, and at that a very bitter one, that Britain had at its disposal a close-meshed radar system, obviously carried to the highest level of current technique, which supplied the British Fighter Command with the most complete basis for direction imaginable…We had nothing like it…”

General Adolf Galland, in E.G. Bowen, *Radar Days*, Bristol: Hilger, 1987, p.28.

I

PURPOSE, APPROACH AND SCOPE.

I.1. Introduction.

To win a war, it is first helpful not to lose it. Early in the Second World War, in June 1940, Great Britain faced exactly that challenge. It had evacuated its field army from France through Dunkirk, albeit minus most of its vehicles and weapons[1]. France, its sole major ally, would soon sue for an armistice with Germany[2]. Britain would shortly come under sustained German air attack from French airfields, initially by day, later by night[3]. For Britain to remain in the field, it would be critically important at least to hold off this air assault.

In the years before 1939, Britain's grand strategic posture had been defensive, relying primarily upon international disarmament and, should that fail, upon the deterrent power of offensive strategic bombing[4]. Lord Trenchard, the "founding father" of the Royal Air Force and its head for a decade after World War 1, completely identified with that strategy, partly perhaps because such a mission helped justify an independent air force[5]. The Air Ministry voted much of their resource to support it: the RAF high command enshrined it as the "Trenchard doctrine"[6]. Air defence, by contrast, was counter-strategic and less resourced. The 1934 Air Exercises displayed one result[7]. In the absence of any early warning beyond the few minutes given by sound locators and the Observer Corps, Britain's air defences were unable to prevent many of the "enemy bombers" from reaching their targets by day or by night, even under conditions exceptionally favourable to the defence.

It was the responsibility of Air Marshal Sir Hugh "Stuffy" Dowding first to resource, and then to implement, the counterstrategy of acquiring a comprehensive air defence system. Arguing for, and then making a reality of, this counterstrategy was a courageous move, since by so doing he would conceptually undermine, and potentially even divert resources from, the strategic bombing which was his service's stated doctrine and *raison d'être*. In 1935, as Air Member for Research and Development, he invested in the untried technique of locating aircraft by radio means which today is called "radar"[8]. Dowding went on to foster radar's development despite early disappointments[9]. When, in 1936, he was appointed the first Commander-in-Chief of the newly created Fighter Command, he increasingly organised the UK's air defences fully to utilise this technological innovation[10].

By the outbreak of war in September 1939, a chain of radar stations had been built on the east and south coasts ("Chain Home" or CH) to give early warning of intruders from 80-plus miles range[11] and, less reliably, to track their approach to the coast. This information was integrated into the UK's air defence system and could be used to deploy and control defending fighters[12]. Such a system was unique in the world[13]. Certainly, it had defects [14] – in 1939, the system had been rushed into operation with an intermediate level of hardware. Even had it then been completed to plan, British hardware was crude, certainly cruder than that of Germany at the time. Chain Home (CH) also was not used to track aircraft inland of the English coast, where the Observer Corps used their eyes and ears instead. Nevertheless, the total operational integration of the system, and its regular testing by Fighter Command, its user, mitigated those defects, as did a blessing of clear, fine weather, and the system would make a major contribution to Britain's defence when the first test came in 1940[15].

By the opening of the Battle of Britain in June 1940, Chain Home had largely been completed. Its information enabled the RAF not to have to fly standing patrols, but instead, using radar's early warning, to deploy its forces only when needed, and at that point to position its fighters advantageously[16]. This allowed Dowding to conserve pilots, aero-engine hours and aircraft, and to utilise these scarce resources sufficiently successfully to check the Luftwaffe, who eventually quit the field by day[17]. For this day battle, therefore, the acquisition of radar proved a success in achieving a day interception capability.

However, the German air assault continued, but after September 1940 increasingly by night. Here the crudity of the British radar hardware counted against the defence. On the clear, sunny days in which the Battle of Britain was mainly fought, fighter pilots could see their enemy several miles away – enough to compensate for radar's inaccuracies. But at night or in bad weather, when their visual range could be 1,000 feet or less, Chain Home was not sufficiently accurate to bring the defenders close enough to intercept the bombers. A different system was needed, with two radars additional to Chain Home – one on the ground, accurate enough to guide the fighter close enough to use its own radar, and one airborne in the fighter, to enable its crew to complete the "kill"[18]. These radars were called, respectively, GCI (Ground Control of Interception) and AI (Air Interception). This system was not ready in time, and, until it was set in place, Britain suffered significant casualties and damage in the 1940/41 Night "Blitz" [19] – casualties which might have been even worse but for poor weather in the first quarter of 1941 which often grounded the attackers. Judged by those criteria, the acquisition of radar for the night battle cannot be accounted a success. Night interception capability had been achieved, but too late.

I.2. Purpose.

The acquisition of any technologically-based military capability constitutes a significant programme with many requirements. Not least of these is the design of an acquisition process that will facilitate revolutionary innovation rather than merely ensure hardware replacement[20]. Many of today's military challenges arise from the need to manage acquisition programmes successfully. Success is presently defined as delivering a military capability to time, performance, and cost, within a broad framework initially titled "Smart Acquisition"[21]. A comprehensive conceptual model was developed after 1998 by the UK Ministry of Defence (MoD) and this sought not only to capture these elements of success in delivering military capabilities, but also to facilitate innovatory approaches to that delivery[22]. This model is described in detail in Appendix A, and in summary in Section I.3 below.

Using this MoD model as it stood in early 2005 to study the acquisition of Britain's 1940 radar-based defence system offers the opportunity to draw lessons for today from comparing two acquisitions of radar, that for the day battle ("day interception radar") on the one hand and that for the night battle ("night interception radar") on the other. It should of course be noted at once that since these battles were, as early as 1935, perceived to involve national survival, "success" in 1940's acquisition terms placed less emphasis on cost than upon timeliness and performance. The 21st century reader might consider this an enviable yardstick.

Of equal importance for the present thesis, the MoD conceptual model used has not previously been applied to historical analysis. Accordingly, a further potential opportunity exists, to identify historical lessons as yet unrevealed by traditional approaches.

In part because the subject matter of radar has historically not been approached from the perspectives of acquisition and of lines of development, a number of previously untapped sources are employed in this thesis. These are reviewed in greater detail below; the conceptual framework to the thesis is first considered.

I.3. Approach: Conceptual Framework.

Before 2005, the acquisition of military capability and the successful introduction of innovation to military forces was the subject of considerable research and analysis[23]. In particular, there is now a well-researched and persuasive literature demonstrating that the successful acquisition of a military capability depends upon far more than the simple availability of an innovation, no matter how radical this may be from a scientific or, potentially, a military standpoint[24].

It is important at this point to differentiate the terms "invention", "innovation" and "diffusion", and to define the term "dysfunctional diffusion" which will be used in this thesis:

?? "Invention" is the process whereby a new idea is discovered or created; thus, it is often said that "Edison is the inventor of the incandescent electric light bulb". Studies of invention would then typically seek to define the essential novelty of the incandescent electric light bulb, and whether Edison was preceded in his "invention" by Humphrey Davy's demonstration of light from electrically-heated platinum wire in 1802. Such studies will often refer to patents, scientific papers and demonstrations;

?? "Innovation" refers to the process by which a new idea is put into more widely-used practice, as in the example the incandescent electric light moved out of the laboratory to be applied to the lighting of homes, streets and workplaces. Studies of innovation will often refer to practicality, to larger scale production and to engineering; in the case of the example, to methods of achieving viable vacuums, bulb life, and avoiding blackening of the bulb envelope.

?? "Diffusion" is defined as the spreading of an innovation widely throughout society, so that, for example, significant demand is created in communities without that innovation, and individuals or organisations arise and act to fill that need. It has been observed that the subject of diffusion is more rarely studied than that of innovation[25], and although studies such as that of Everett Rogers[26] increasingly address this issue, these are often studies of diffusion in a civilian society. In the military context, where adoption of an innovation, whether an idea or equipment, there are fewer studies[27], as will be discussed in Chapter II below.

In the U.K., after 1998, the realisation that the successful acquisition of a military capability depends on more than the availability of the innovation led to the MoD's development of a conceptual structure that sought to maximise the military's grasp of possibilities offered by innovatory technologies[28]. Under that conceptual structure[29]:

?? An "**Equipment Capability Customer**" organisation would be responsible for
  - Identifying both current and emerging capability gaps;
  - Identifying the most pressing of these; and
  - Articulating the **User Requirements** which would enable the gaps so identified to be filled;

?? These **User Requirements** would be required to take account of dimensions above and beyond the development of the equipment and its technology, which needed to be fulfilled in order to deliver a military capability.

?? There were initially conceived to be five such dimensions in addition to the **Equipment** itself:

?? **Doctrine and concepts.** Concepts are defined as the capabilities likely to be used to accomplish an activity in the future, and doctrine as the codification of how the activity is conducted today;

?? **Logistics,** that is, keeping the equipment working (spares, maintenance) and moving it to where it is needed;

?? **Infrastructure,** e.g. housing and powering the equipment;

?? **Training -** ensuring users are prepared and experienced in operating the equipment;

?? **Personnel -** recruiting people to make use of it, and locating them in appropriate, perhaps novel, organisations.

The total of six dimensions (the five listed above plus Equipment) were referred to as "**lines of development**".

As further experience was gathered and analysed – often as a result of highly visible problems that arose in the procurement process previously used - these lines of development were expanded from six to eight[30]. In recognition of the fact that, in a fully integrated system, individual items of equipment both send and receive information, **Information** became a specific line of development. Likewise, 'People' came to be perceived as distinct from the 'Organisation' in which they perform their roles, and as a result **People** and **Organisation** became distinct lines of development. Finally, it was recognised that all these lines of development must work together seamlessly to deliver the desired capability, and an over-arching theme of "**Interoperability**" was introduced to give a ninth factor.

The acquisition of a radar-based defence system in the late 1930s represented a radical change for the UK, and required the rapid generation, sometimes from a near- zero base, of many of the associated lines of development[31]. Because the acquisition of such an innovatory acquisition has parallels today, research into the way in which acquisition, user requirements and lines of development were treated at that time - with both successful and unsuccessful outcomes - offers the prospect of valuable lessons for acquisitions now and in the future.

Equally, because the lines of development model is holistic, in that it requires a multi-axis approach to historical analysis which is both comprehensive and balanced, there is for the historian an enhanced possibility of a more coherent understanding of the drivers behind the events which took place during the acquisition process, and hence of their relevance today. The present thesis represents the first application of these concepts as a historical analytical tool to study the development of a technological innovation into a military capability, and several consequent issues will be addressed in the thesis:

1. Does the application to the present specific study show the conceptual model to be comprehensive and balanced – that is, are there historical facts unaccounted for, such that the conceptual structure itself requires modification (as indeed we have already seen it modified above)?
2. Does it yield insights of value historically, in addition to lessons for today?, and
3. Is it capable of wider application to subjects other than radar, and to periods other than 1935-41?

I.4. Approach: Historical Context.

Prior to the Second World War, Germany's growing military airpower capability helped deter and coerce European nations in ways favourable to Germany's expansionist objectives[32]. Some nations, such as Britain, considered that German strategic bombing would result in rapid, widespread destruction, civil disorder, and breakdown of Government control[33]. This they felt powerless to prevent - the British Prime Minister Baldwin's 1932 phrase "The bomber will always get through"[34] appeared to be validated by the German Condor Legion's bombing of Guernica in the Spanish Civil War[35].

The increasing speed of air attack created the technical challenge to prospective defenders. In the First World War, Zeppelin dirigibles and Gotha bombers flew at around 80mph[36]; radio interception, ground and ship-based observers, and sound locators were adequate sensors[37], and a centrally-controlled fighter and anti-aircraft gunnery defence system was created[38]. Developments of such sensors continued into the 1930s, when it became apparent that the anticipated speed of air assault (300mph) would soon render existing sensors useless[39], at least for early warning. In late 1934, the Air Ministry recognised the need for novel approaches to acquiring air defence capabilities, and formed the Committee for the Scientific Survey of Air Defence (CSSAD; often called the "Tizard Committee", after Sir Henry Tizard, its Chairman)[40]. The user requirement was therein rapidly refined to that of detecting and locating enemy aircraft[41], and a "proof of concept" experiment in doing so by radio means led to the funding of radar research by Dowding, then the Air Ministry's Air Member for Research and Development[42]. Britain's development of its air defence capability would henceforth depend in significant part on a major acquisition programme harnessing the novel technology of radar.

Britain was fortunate both in personalities and in pre-existing works. The RAF's "Equipment Capability Customer", Hugh Dowding, who within a year became Commander-in-Chief of the newly created Fighter Command, had a background in the use of wireless in World War 1. He had already applied that knowledge to air defence - for example, in air exercises, he had used observers and spotter planes with radios to advise the position of attackers, and so deployed his defenders to defeat them. He also inherited an air defence system which, while needing massive updating, contained several of the elements that would be used in 1940. Dowding, although a supporter of radar, maintained a healthy scepticism about what worked in practice, and prepared many contingency plans. From the "supplier" perspective, Sir Henry Tizard, the Chairman of the CSSAD, was both a scientist and a pilot who had flown in air defence in World War 1. He was additionally gifted in human relations, with the quality of allowing people to think that they had developed an idea themselves, rather than having been instructed by him. With this approach, and as a pilot himself, he was adept at handling the user interface with the RAF pilots.

The vast scale of the programme faced by this customer/ supplier duo can be appreciated by application of the conceptual model. Fulfilling the user requirement involved not only the technological development of the radar **equipment**[43], complex as this was. Equally essential were the building of a massive chain of early warning radar **structures**[44] around the UK coast ("Chain Home" or CH), and the creation of a force of **operator and maintenance personnel**[45] with the skills and supplies to keep these stations running on a 24-hour basis. It was likewise critical to develop **doctrine and concepts**[46] effectively to use the information produced by the radars. There was urgent need for the identification, and continual refinement by the new discipline of Operational Research (O.R.), of the **organisation**[47] to distil the radar data into a presentation suitable for executive control, and for the **communication**[48] of the resulting decisions in a timely fashion to fighter stations and aircraft. Underlying the whole was the necessity to **recruit**[49] and **train**[50] people (including, for the first time, women) to operate the entire system. To deliver the capability of interception, all elements of the system had to be completely integrated, or **interoperable**. Several countries lay claim to "the invention of radar", basing this claim on identification of concepts or elements of hardware[51], but it is generally acknowledged that Britain acquired the world's first radar-based integrated air defence system[52].

With this capability, Britain fought off the Luftwaffe's daytime assault in the 1940 "Battle of Britain". The system was just accurate enough, just in time, and worked just sufficiently well – it was far from flawless, as this thesis will show - to help achieve this[53]. Because of this success, British radar, and its place in the air defence system, has been the subject of historical research in terms of its technology[54], of political involvement in its development[55], and of its military application in this one significant campaign[56].

However, Chain Home's accuracy was not adequate to defend Britain by night[57]. By day, it was possible for defending fighters to see their enemy at five to ten miles range. By night, depending upon the clearness of the sky and on moonlight, a successful interception could need guidance to within 1,000 feet to identify the target[58]. To go on to destroy the target, ground radar needed to be supplemented by radar within the fighters themselves. As stated above, **two** further new radars had to be developed to achieve this. The first was ground-based, more accurate, and possessed of a more comprehensible display than Chain Home. Called GCI (Ground Control Interception), it took over after the early warning plots from Chain Home and provided the minute-by-minute accurate plots to guide the night fighter close to the attacker. The second radar, called AI (Air Interception), carried in the defending fighter, then took over to achieve the final approach and "kill"[59]. An interoperable system arrived all but too late to make any major difference to the Night Blitz[60]. In part this was because "Silhouette", an alternative, non-radar, solution of floodlighting the night sky (here detailed for the first time), had been pursued from 1935 to 1939, and in part because the attentions of customer and supplier had been elsewhere, on the day battle – rightly, because had the day battle been lost, there would have been no night battle. Doctrine, concepts, organisation, trained users, maintenance facilities, above all interoperability, were in every case deficient[61], and Britain suffered severe civilian casualties and economic damage as a result. Indeed, had it not been for bad weather in early 1941, these might have been even worse. Perhaps unsurprisingly, this area has been rather less studied, and published literature, claiming night radar success, usually refers to Spring 1941 or later[62], largely after the Blitz period. However, by then most of the Luftwaffe bombers were beginning to be redeployed to Operation Barbarossa, the invasion of Russia.

I.5. Scope.

The thesis sets out to give a balanced account of the acquisition of the radar based defence system. Balance is sought in three ways. First, the thesis focuses upon the delivery of a military capability, of air interception by day and by night, and not merely upon radar hardware. The limits in terms of scope are that the present thesis does not inquire into the acquisition of aircraft, for example, the Hurricane and Spitfire[63], nor of sufficient 100-octane fuel, nor of adequate guns and gun sights. This thesis is concerned with the "nervous system" of air defence, and within that, with the recruitment and training of people, improving the usability of equipment, keeping it running, and the communication of data, as much as with radar hardware per se.

Second, the American acronym "radar" derives from "radio detection and ranging". The British used the term "R.D.F." ("Radio Direction Finding", a deliberately confusing title)[64]. "Radar" will be used throughout this thesis to avoid confusion with radio D/F, a technology which is distinct and which was itself also a component of the UK air defence system. Locating a target by radio means is the essence of radar and by that definition many elements of the 1940 air defence system, while electronic and in some cases using radar techniques, were not strictly “radar”. However, because this thesis is concerned with the total “nervous system”, they are included in scope. Specifically, these elements include the high-frequency direction-finding (D/F) stations that directed British fighters; the British “Y” service, which intercepted German radio and radio-navigational transmissions; radio countermeasures (RCM)[65], which disrupted German radio-navigational beams, and Identification Friend or Foe equipment[66] (IFF, nowadays called secondary surveillance radar or SSR), which when operational in an aircraft identified it as friendly on British radar displays.

Third, the thrust of this research is development, innovation, diffusion and use, rather than invention, a subject already well-covered in the literature. One reason why invention received this coverage was the post-war establishment of the Royal Commission on Awards to Inventors[67], which made substantial tax-free awards to those proving such a claim, and which thereby provided journalists with rich material for publication. A group of radar scientists, headed by Sir Robert Watson-Watt, gained a tax-free £87,750, but stirred up ill-feeling (persisting to this day) among colleagues who argued that they had been working for the defence of the UK, not for pecuniary gain. For the present thesis, there are some instances where responsibility for invention is important, and these will be addressed, but these will usually be in the context of responsibility to solve a problem in the operation of the total system.

A further limitation of scope may seem relevant primarily to the technical reader, but has wider relevance. The devices here considered are metric-wave; this thesis is not concerned with the development of the resonant cavity magnetron[68] and the consequent move into microwave radar, which gave the Allies a major lead in this field after 1942. These developments were still in their infancy during the period here being researched. The relevance of this to the present thesis is that most general radar histories cover the entire Second World War, and so emphasise this post-1942, more advanced period, by which time radar and its acquisition processes had changed significantly and acquisition processes, including lines of development, were better understood. Simply assuming that the post-1942 picture applies to the 1935 – 1941 period either in technology or in acquisition terms is a significant error, a point addressed in Chapter II's Literature Review below.

Finally, to reiterate, an important thrust of this research is to give, for the first time, a balanced comparison of the acquisition of radar for the **night** battle, as much as of that used in the **day** battle. Possible reasons why previous emphasis has been on the day battle have been set out above. Nonetheless, from the earliest memoranda dealing with radar[69], defence against the night bomber was seen as significant. Why the night interception capability and the radars needed to provide it subsequently lagged - and incidentally whether that acquisition failure cost the Commander-in-Chief of Fighter Command his job[70] – is a significant theme of the present thesis.

I.6. Sources.

As explained, one element of the originality of this thesis rests upon the first application of a 21st century conceptual framework to a historical process of acquisition. A second element of originality lies in the use of previously untapped or lesser-tilled sources so to do. Without trespassing too far upon the literature review of the next chapter, published research appears to make use of less than the total range of relevant files available in the National Archives, Imperial War Museum, RAF Museum and Churchill College, Cambridge[71]. This may be because, lacking a holistic framework, research has approached radar-based air defence in 1940 from the perspective of traditional disciplines – histories of science and technological development, military histories, or histories of the involvement of historic personalities. The use of the present conceptual framework extends significantly the range of files to be reviewed – to maintenance, for example, and to training, to structures, and to operational research, for all of which the files appear relatively less tilled.

There is a further step still. As Edgerton[72] (among others) has pointed out, the richness and accessibility of Government records may have caused a bias in favour of the work of Government scientists. Also, even there, the radar scientists objected that the files trawled for the Official History – the scientists themselves were not interviewed – often bore scant relationship to the facts[73].

As a result, to balance written, mainly Government, records, the present research will adduce material from three other sources – material from private industry; oral/ video interviews; and field visits to sites and equipment, as follows:

- ?? **Material from Private Industry**

  Tracing of the records, memoirs and surviving personnel of the key builders of 1935-41 radar (chiefly Metropolitan Vickers, Cossor, Pye, and Ekco) and, where these exist, extracting information for comparison with Government sources.

- ?? **Oral/video interviews**

  Fortunately, there still survive a very limited number of individuals who held positions relevant to radar research and a programme of interviews with them was established. There are, of course, problems of recall, bias and ethics, and so comparison with the written record and with each other formed a component of this research, the methodology being referred to in the Literature Review of Chapter II. Particular use was also made of the Penley Archive[74], a collection of the largely unpublished memoirs of over 50 radar scientists, and of the oral histories of the Centre for the History of Defence Electronics[75], which will be deposited in the DCMT Shrivenham Library on the conclusion of this research.

- ?? **Physical evidence: Field Visits & Equipment Review**

  Official records can set out, as fact, events that may in reality never have come to pass – for example, proposals to build radar stations that were then superseded. The key sites have not been the subjects of consistent survey and a series of visits to compare documentary evidence with physical remains formed part of this research. Likewise visits have been made to surviving equipment at the Science Museum[76], RAF Neatishead[77], and the RAF Museum, Hendon[78], and the restored radars at – improbably – the Pitstone Green Farming Museum[79]. Use has also been made of the private Winbolt Collection of Air Publications[80] and of the Communications and Electronics Museum Trust[81] equipment collection now at the Imperial War Museum.

I.7. Summary and Structure of Thesis.

This chapter has established the combined purpose of this thesis as, first, the comparative analysis of two historic acquisitions of the innovative technology of radar to provide military capabilities, these being for air defence by day and by night, in order to derive lessons relevant in the 21st century; second, the assessment of the utility of the analytical tool employed, contemporary MoD acquisition concepts, to historical exegesis; and third, use of previously untapped sources. The conceptual framework has also been expounded, the scope defined and the originality of sources used identified.

In the following chapter, review of published literature establishes that neither the proposed treatment of the subject, nor the subject itself, have previously been addressed, other than partially or tangentially. The thesis therefore constitutes an original contribution to present knowledge.

The thesis thence proceeds to address its basic purpose in five chapters:

1. an examination of the early (1935-7) phases of acquisition of the radars employed in the day air defence system of the U.K., illustrating, for example, how rapidly user requirement and "proof of concept" testing was established, how quickly radar advanced in terms of technical readiness levels, and how certain lines of development were addressed early - but how disregard of others such as infrastructure delayed delivery of the capability;
2. analysis of the major phase of the introduction of radar as an element in the UK's air defence system, 1938-1940, showing that many lines of development issues were anticipated and resolved to yield a successful result in battle, but how ignoring others, such as maintenance and calibration, almost led to disaster.
3. a comparative examination of the initial phases (1936-1938) of the acquisition of the radars involved in the more embryonic night air defence system, illustrating the greater technical problems to be overcome, and detailing the alternative concept of "Silhouette", a scheme to illuminate the cloud-base and so silhouette attacking bombers. The development of airborne radar also

initially concentrated less on air interception and more on its anti-shipping application. As a result there was in respect of radar-assisted air interception an almost complete disregard for lines of development by both service user and scientist supplier, and this paved the way for an unacceptable result in terms of timeliness, performance, and cost in waste of resources, physical damage and lives lost;

4. analysis of how, with the abandonment of the Silhouette alternative, the compressed timeframe remaining to develop radar's lines of development led to confusion and muddle; and how major efforts by both user and scientist to overcome these problems eventually succeeded, but too late to be of real value in holding off the night "Blitz" of 1940-1.
5. discussion of the conclusions of the thesis in two areas – first, of the lessons of acquisition and lines of development which were relevant in 1935-41, and those which are relevant today, including factors which may further inform and refine the MoD acquisition process; and second, of the value of the concepts used in the analysis within the thesis for future historical research, whether in the field of acquisition of innovative military technology or on a broader basis.

I.8.

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II

LITERATURE REVIEW

II.1. Introduction.

Radar was a technology bred for war. Its very few historiographic papers recognise that fact in their analyses; its even fewer bibliographies recognise it in their taxonomy.

To some historiographers[1], radar's martial origins set it apart from its kindred technologies of radio, television, telecommunications and computing. They note in passing that, in acquisition terms, 1930s radar was distinguished from these sibling technologies in having no civilian market, purchasers or acquisition process, but explore no further. To others[2], the effectiveness and efficiency of major nations' acquisitions of radar in the 1930s are simply a consequence of differing national strategies. Radar was seen as essentially defensive, and so, for example, its acquisition by the military was handled with indifference in Germany (nationally expansionist), aggressively in Britain (nationally defensive) and disinterestedly in the USA (isolationist). Analysis of the acquisition process itself drills down no deeper than this elevated level of causality. However, such historiographic debates have been few and peripheral[3]. The reality has been that published literature on radar and its acquisition has tended to focus along avenues of approach which reflect traditional disciplines and academic structures.

Four such disciplinary approaches are especially relevant to this thesis – those of the history of science and technology; of military history; more recently, of personality-based political/ military history; and of local, corporate and social histories concerned with locations of importance to the radar story. Beyond the academic literature, relevant publications essentially comprise the memoirs and biographies of scientists, engineers and servicemen and women; instructional manuals; and training films. This categorisation is recognised in the radar bibliography most relevant to our purpose[4].

Given such a series of approaches to the subject, it will be a matter of little surprise that there is almost no published literature devoted to the process of acquisition of a military capability or of lines of development related to radar, the topic of this thesis. Many of the lines of development - logistics, infrastructure, organisation, people, training, communication, concepts and doctrine, interoperability - have been perceived as near to, or beyond, the limits of the four primary disciplines listed above, even though details of the technological hardware, its development and use have not. Accordingly, as will be illustrated, where secondary sources refer to these lines of development at all, it is incidentally rather than as an essential component of the early history of radar.

In this review, it will be convenient initially to include references to acquisition and lines of development within a discussion of the approach of each of the four disciplines. These references will then be drawn together at the conclusion of the review of these secondary sources, to identify clearly that acquisition and lines of development in the context of early radar are not specifically addressed in the published literature.

II.2. Secondary sources: Histories of Science and Technology.

Historians of science and technology have tended to approach the acquisition of radar-based defence systems from three perspectives – primarily, that of the "invention" of radar; less frequently, from the history of the development of specific systems and/or components; and more recently, in considering radar as an example of innovation. The fact that such approaches, which address acquisition only incidentally, are neither complete nor even comprehensive is a known issue within that discipline. David Edgerton[5], as Professor of the History of Science and Technology at Imperial College, has written critically on the tendency of his discipline to focus first on invention, and then on innovation, rather than to study development, diffusion and use. He comments also that there are few studies of relative failure.

II.2.1. Histories of Science and Technology: Radar in studies of Invention.

Petzold[6] observes that histories of electronics, including radar, which focus on "invention", are often written from a perspective of national "heroes", and that the aim even of excellent technical histories is to propound or examine claims of "who invented radar".

Helpfully, this approach is most comprehensively addressed by Dublin's Sean Swords[7], for his native Ireland has no claim in this area. Accordingly, his is an even-handed account of not only British, US and German "inventions of radar", but also those of France, the Netherlands, Italy, Germany, Japan, Russia and Hungary. Essentially, as his title "*Technical history of the beginnings of radar*" makes clear, his partly-mathematical work is concerned with scientific ideas, circuits and hardware. There are only occasional references to other lines of development, with, for example, only a single page devoted to organisation, people and training.

Debates about invention being peripheral to the present thesis, the essential point to be noted here is that "invention debates" usually hinge on the exact definition of the hardware being invented. In the context of radar, German writers[8] helpfully distinguish "reflection technology" (i.e. merely detecting an object) from "radar" (i.e. radio detection *and location*, which involves fixing the position of the target. The original German word for radar, "Funkmess", translates as "radio measure"). Keeping this useful distinction in mind, it will be found that there is general acceptance in otherwise voluminous, contentious and confusing literature that Christian Hulsmeyer's 1904 Telemobiloscope[9] for ship-based detection of obstacles was the first "detector", but that Watson Watt's 1935 Orfordness equipment[10] was probably the first operational "locator". It is equally relevant that within months many countries, each working in secrecy and isolation, had developed detection and location apparatus, because the underlying technologies (such as understanding of radio reflection) were, as Swords[11] and Bryant[12] point out, a matter of widespread scientific knowledge at that time. A grandly revisionist approach on this basis is taken by Tom McArthur and Peter Waddell[13] who argue that John Logie Baird, inventor of a mechanical television system, should be credited with many radar advances rather than Watson Watt. Undoubtedly Baird played some role, but in the field of invention and not acquisition, and their interesting work is not directly relevant to this analysis.

What is more important for the present thesis is what each nation did with the resulting hardware in the context of providing a capability of air defence. Beyerchen, in the paper cited above[14], incisively points out how the pace of acquisition of radar for that purpose was determined by the grand strategies of nations. Germany, with a strategic offensive approach after the First World War, saw radar as a mere defensive technology, and so in the main left its scientists without a user requirement, to experiment as they wished. Britain, whose grand strategy was essentially defensive, saw the same radar technology as a "definite solution to a pressing problem"[15], and its airmen, having a firm user requirement, pushed the development ahead. The USA, by contrast, being geographically isolated from potential enemies, perceived radar as a "vague answer to uncertain threats"[16] and left it to filter slowly from the laboratories to the services. Bryant[17] and Brown[18] both point out that only in the UK was radar seen from the very start as a component of a comprehensive air defence system delivering the military capability of air interception.

Certain of the accounts of other nations' developments are of interest. Those of Germany are most accessible (in English) through the work of Pritchard [19], who acknowledges his debt to the excellent series of works by Trenkle[20] and Bekker[21]. German publications concentrate heavily on hardware, with a strong bias towards demonstrating German primacy of "invention"; thus Kummritz[22], Brandt[23] and Kern[24], the last largely based on Trenkle. It is left to the British historian Devereux[25] to illuminate a lesson more relevant to this thesis – that, given the German national strategic focus on the offensive, there was but one user requirement from the German armed forces for radar. This was from the Kriegsmarine, who saw radar as an aid to naval gunnery at night and in poor weather, and for coast-watching. Their resulting, excellent, "Freya" radar was offered to the Luftwaffe only when it was realised to be rather better at plotting aircraft than ships. Not integrated into an air defence system before 1941, it nonetheless scored the first radar-located "kills" of attacking (British) aircraft on December 18, 1939, and went on to form the backbone of the later German air defence early-warning system. This thesis will illustrate how, in the UK, the War Office's coastal defence radars would similarly be taken over and adapted by the RAF, first as Chain Home Low (CHL) to "fill gaps" in their Chain Home early warning system, and later – modified further still – to serve as the precision ground control radar, GCI, to deliver a night interception capability. The same War Office equipment was adopted by the Navy, for coastal defence against the U-boat, being then termed type CDU.

American literature on invention and developments is also extensive, and, because until 1941 US developments were outpaced by UK advances, most US works give at least superficial treatment to early British radar. Unfortunately for the present thesis, the USA did not enter the war until late 1941 and so the bulk of published US literature is concerned with the post-1941 period. As was observed in Chapter I, not only is this period beyond the scope of the present thesis, but it is also precisely that period which coincides with the American adoption of the technological advance of the magnetron and of microwave radar which had played no part, outside the laboratory, in the pre-1941 period. Acquisition processes were also by then better understood as a result of British experience in 1935 – 1941. From both a technical and an acquisition standpoint, therefore, the focus of the bulk of US literature has a limited bearing on the present study.

There are other, historiographic, problems also. The most major study, the two-volume history of work at the main US radar research establishment, the Radiation Laboratory, by Henry Guerlac[26], written in 1946 but published only 40 years later, is nowadays recognised as attempting the impossible. His declared aim, above and beyond writing the history of the 150+ microwave radar systems produced after 1941 at the Radiation Laboratory, was to "write the biography of a secret weapon". As Dennis points out[27], this required four further studies - an attempt at radar's genealogy; reviews of early British, US, Japanese and German work; of the total of systems developed in World War 2; and of their combat use world-wide. Such a vast brief was impossible to fulfil in 1946, not least because German and Japanese work could not be assessed. Guerlac also became dispirited at his monumental task, describing his output as "dull, dull, dull"[28]. To the reader, it does, in parts, resemble an exhaustive listing of system development after system development. More relevant to the present thesis, Guerlac relied on very limited discussion for his 60 pages on pre-1941 work in the UK. The source physically available to him was Dr E.G.”Taffy” Bowen, who was in the USA because he was at odds with the UK radar management hierarchy. As may be seen from Bowen’s memoirs[29], he was not an impartial source, and especially not so in his appreciation of the acquisition of radar for the night battle. Guerlac therefore essentially tells the story of the British developments from a technical “invention” standpoint, with distilled, and somewhat partial, accounts of its use. There is little reference to the wider problem of acquisition in general or to individual lines of development in particular.

The histories of the two significant US defence laboratories, of the Army[30] and Navy[31], consider their own early work from a hardware perspective, with an aim, comparable to German writers, of “we invented radar”. From the perspective of this thesis, it is enough to note that little is said therein about acquisition or lines of development in the USA precisely because there is little to say. There was no real user concept of what radar could do. Perhaps because the USA was physically remote from any likely aerial aggressor, little attempt was made to create an air defence system using radar, even after visits and talks by Dowding about its use in the Battle of Britain. Almost every line of development was neglected, from concepts and doctrine to communications. The outcome was the 1941 Pearl Harbour debacle, where a US SCR-268 radar tracked the attacking Japanese planes from many miles away, but was unable to summon any defenders due to lack of a coherent and tested air defence system.

Guerlac’s objective of a “biography” of radar was recently attained by his fellow-countryman, Louis Brown[32]. Brown’s *A Radar History of World War II: Technical and Military Imperatives* is a well-researched and balanced description of the total sweep of radar’s impact in that conflict, suffering only from the extreme compression necessary to cover his subject in 460 pages. The result is a bias in favour of hardware, and of emphasis on post 1941 “microwave” war. That period is of course more interesting to the technical reader – the book is published by the US Institute of Physics - and importantly for a US readership, the post-1941 period more directly involved the USA. The 40 pages which address British radar pre-1941 do not permit more than tangential mention of acquisition or of lines of development, and no such theme is developed.

Nonetheless, Brown's work outclasses in its scrupulous judgements the earlier publications of Buderi[33] and of Fisher[34]. Buderi extended his coverage of the radar story until as late as 1960, in a volume of similar size to Brown's. The natural result was even more extreme compression, and an even greater emphasis on post-1941 events, coupled once again with over-reliance on Bowen as the UK source for the earlier period. By contrast, Fisher - the majority of whose published work is for the young adult audience[35] – does focus on the pre-1941 period, and gives his work a racy immediacy by focussing upon personalities and including unreferenced, perhaps imagined, conversations in a journalistic style. His quoted references appear to show a work apparently heavily reliant upon secondary sources[36].

It may be concluded at this point that studies of "invention" have, as might be expected, focussed only marginally upon the acquisition process and touched but lightly upon lines of development. The insights gained are modest.

II.2.2. Histories of Science and Technology: Histories of individual radar systems.

Turning to the second approach of the scientific and technical historians, the development of individual systems, it is helpful for the student of British radar that a wide sweep of pre-war and wartime hardware developments were described in the papers of two major Conventions of the Institution of Electrical Engineers (IEE) – those of 1946, on Radiolocation (Radar) [37], and of 1947, on Radio[38]. These form a significant near-contemporary source upon which Swords[39] and others rely heavily. Additionally, as is to be expected of a learned society, many of these papers are heavily mathematical and concentrate upon the scientifically more interesting later-war developments in microwave technology. Finally, it should be noted that those papers which appear to describe equipment relevant to this thesis in fact describe hardware in its late-war versions (often without specifically stating this), and must be used with great care for assessing early-war capabilities.

A regular pattern may swiftly be established for reviewing the sources available for each individual early-war radar system. Typically, there will be found a scientific hardware description in the IEE Convention papers. There will also be a User and

Servicing Manual for the equipment in the Air Ministry Air Publications series, which will give user instructions and electronic details, from which personnel and communications factors can be derived. Lastly, there are often one or two papers on its development history, usually published by a scientist or engineer who had worked on the system. The radar's role in the air defence system may usually also be described in the Air Historical Branch's *RAF Signals History*[40]. It will be helpful to illustrate, by examples, the gaps left in the reader's knowledge of acquisition and lines of development after consulting these sources, and to make explicit our resulting need to refer to the primary sources of documents and memoirs which are discussed at the end of this Chapter.

Taking a first example, Chain Home (CH), the UK's main early-warning radar, is described in terms of its technology by Ratsey[41], Jenkins[42] and Dodds[43] in the IEE 1946 Convention papers[44]. What its users and maintainers needed to know is detailed in Air Publication 2911 [45] by the Air Ministry, and its technical development is discussed by B.T.Neale in papers of 1985 [46] and 1988 [47], while Chain Home's position in the air defence system is described in Volume IV of the *RAF Signals History*[48]. From each source, there are hints inferring specific problems resulting from ignoring lines of development, but these are refracted through the prisms of memory or of official documents. For example, one does not gain the fact that the amount of wood consumed in Chain Home's receiver aerial towers was far greater than the UK's entire national stock, and that severe delays to the whole acquisition were caused by awaiting wood from Canada[49]. One has also to have recourse to private memoirs to be told that, even in the emergency conditions of approaching global conflict, the Chain Home transmitters were being slowly craft-built, with certain key materials coming from Germany[50]! Likewise, the reader is also not advised by any of these sources that lack of attention to spares and maintainability caused a near-collapse of Chain Home when 24-hour working was adopted after Munich.

A most helpful work of reference does exist to assist in validating statements made about Chain Home, and this draws attention in passing to a number of acquisition issues. Michael Bragg, himself a retired radar engineer, in producing his *RDF1*[51] exhaustively validated most of the events in Chain Home's development, albeit principally against National Archives files. The result is an extremely useful chronological work of reference for the development and construction of Chain Home. Bragg achieves his objective, which was to correct a number of myths about the period by reference to National Archives files. Given such an objective, and the fact that acquisition concepts were still being developed at the time of Bragg's research, there are few references to the wider literature, acquisition concepts or lines of development. The book provides an excellent source of referenced evidence, but reflects, as it is bound to do, the bias of such National Archive files as survive. *RDF1* stands as an essential work of reference on radar for the day battle, but explicitly is not a study of the acquisition of the capability of air interception by day and by night.

A second example of an individual system history is that of the Identification Friend or Foe (IFF) system, an airborne "black box" which, on receiving a pulse from UK radar, returned a pulse identifying itself as friendly – critical, if one wants to avoid shooting down friends ("blue on blue"). IFF's electronics were not especially novel and so merited just two pages at the IEE Convention[52]. By contrast, IFF's service use was extensive, with at least one "box" in every aircraft and vessel. As a result, various models of IFF occupied twenty four Air Publications[53]. IFF's history has been the subject of recent papers both by Trim[54] and White[55], in addition to extensive references in the *RAF Signals History* Vols. IV and V[56]. What is not emphasised in these documents is that the critical factor was one of production supply, and how far this became an issue in night air defence. For example, IFF was not installed in many RAF aircraft at the time of the Battle of Britain, which caused a number of problems. Worse, lack of IFF caused real difficulty when developing techniques for night air interception, because without it, the ground controller could not tell which aircraft of those on his radar screen was friend, and which foe. Even urgent night fighter trials on 21 September 1940 could not obtain a night fighter fitted with IFF[57]. This lack meant that tactics could not be developed, nor training begin, and the resulting shortage of trained night fighter aircrew would be a major problem during the night Blitz[58].

It is unnecessary and tedious to repeat a similar analysis for every item of equipment, but two – Air Interception (AI) radar and Ground Control Interception (GCI) radar – are particularly important because their development for the night battle forms a major element of this thesis, and these are now considered.

The metric-wavelength Air Interception (AI) radar used in 1940-41 had been rendered obsolete by microwave equipment before 1946, so that the Radiolocation Convention papers refer only to minor components of that earlier equipment such as cathode ray tubes[59]. Air Publications are also few in numbers [60]. Although the RAF Signals History devotes reasonable space to AI's use[61], the number of other papers written on AI's inception and innovation is indeed modest – one, that of White[62], albeit that this paper was subsequently extended to book length by its author. What is not found here, and what individual memoirs have to be accessed to discover, is just how extensive was the failure in producing timely AI equipment. This thesis will illustrate that the 1930s RAF doctrine of strategic offence conceptualised defence against night attack into two responses – bombing of the enemy's night bomber airfields; and searchlight or floodlight illumination lighting up the night sky so as to permit a "daylight" fighter battle. There was until 1940 no agreement on whether night fighting would be carried out by a pilot in a single seat fighter or by a pilot and crew, a significant issue where radar has also to be operated and viewed. Likewise, there was no agreement on the aircraft platform to be used. Tizard's CSSAD Committee and the RAF had made the judgement that the day battle would be pivotal. Priority of resources was therefore given to the Chain Home scientists, whereas the airborne radar team was always small. In 1935, the problems of compressing Chain Home radar into an aircraft seemed insuperable. Only as techniques and components were developed for the shorter wavelengths used did air interception (AI) radar appear possible. CSSAD was distracted by alternative proposals to deliver night air defence, such as the Silhouette illumination scheme described in Chapter V below, and by alternative concepts of "interception" such as Lindemann's aerial minefields. The AI team were also diverted for over a year by the fact that airborne radar could be used for Air to Surface Vessel (ASV) purposes, in which the Admiralty and Coastal Command both showed a genuine interest. Finally, mistakes in manufacturing instructions delayed the arrival of hardware. When, as late as

November 1939, serious thought began to be given to how the equipment would actually be used to achieve the capability of night interception, it was realised by the researcher who flew with the aircrew that a new, more accurate ground control radar was needed, to help direct the fighter close enough to the bomber to use its own AI radar effectively. Unfortunately, the Air Ministry ignored lines of development, and ordered early marks of AI in grotesque quantities. They then did not assign relative priorities to AI and ASV, leaving the small team of scientists totally unable either to cope in fitting equipment in aircraft, a role for which they were untrained and too few, or to carry out research. The impact of these decisions then combined with an unchallenged user requirement for a 300 feet AI minimum range, and created an excessive multiplication of Marks and variants (six within nine months, nine within 18 months) as the scientists desperately sought to create suitable equipment in an inadequate timeframe. It is easy to predict that, in lines of development terms, the failure would be almost total, from the lack of service doctrine[63] and consequently of user requirement, to a lack of early scientific analysis of how the equipment might be used in combat[64]. Application of the lines of development model also highlights with stark clarity the position known only too well to the aircrew users– frequent breakdowns, poor maintenance, bad selection of operators and inadequate training among them[65]. It is in the primary records – Squadron and personal diaries and memoirs – that we discover the depth of the failure[66].

So it is also with the Ground Control Interception (GCI) radar that was supposed to be guiding these interceptions. GCI enjoys more space than metric AI in the 1946 IEE Convention papers, albeit mainly about details[67], and there are good descriptions of its technicalities in the Air Publications[68]. A paper by Putley[69] gives further, very well illustrated, detail but has only a tantalisingly short text. What is nowhere explained is why only in *November 1939* was it realised that the long range Chain Home was not accurate enough for the night GCI guidance task[70], so that a user requirement for this dedicated, shorter-range, more user-friendly radar was apparent. Again reference must be made to the primary sources of memoirs and archive papers, where it may be identified that time was spent on re-examining alternatives to GCI, and that senior and eminent Chain Home developers had mounted so strong a campaign on behalf of the

Chain Home system that the specification of GCI was not agreed until July 1940, and the development of GCI was being impeded as late as September 1940[71].

As may now be seen, these histories of individual systems may yield specific insights into acquisition problems, although these are more usually present in personal memoirs. As a result, the facts relevant to the present thesis are scattered and individual, and no overall analysis has been attempted.

II.2.3. Histories of Science and Technology: Radar in studies of Innovation.

Moving on from the development of specific systems to the third approach of historians of science, radar as an example of innovation, perhaps the most useful starting point is the relatively populist post-war Government paperback *Science at War*[72]. Although its subject matter extends well beyond radar, it is the innovation of radar that forms the bulk of the content. It is also one of the few works on radar to allocate proper space to the contribution of Operational Research (O.R.) which the radar scientists themselves considered to be of equal value to their hardware[73]. The relevance of O.R. to the present thesis is that, within two years of radar's discovery, scientific investigation was being made into the problems of staffing, organisation, training and communication throughout the radar-based air defence system, and it was from these investigations that O.R. grew up. Its very name is in fact the idea of one of the radar scientists. Therefore, there is here a useful foundation stone for study, but no analysis is made or general conclusions drawn within the publication cited. Over the last decade, a series of papers culminating in a well-researched book has been produced by Kirby[74]. In the context of the present thesis, the 1936 - 41 period is there seen as the prehistory of Operational Research as carried out today, rather than as a significant component of enhancement of lines of development and acquisition of a capability.

Radar in the context of the innovation of alternative methods of achieving interception capability is a theme very rarely treated academically. This may be because there has not, before the present thesis, been recognition of the significance of the alternative Silhouette scheme in diverting attention from the lines of development work needed to make AI radar effective for night interception. Review of alternatives in general has received attention in two papers by Professor Burns[75] and peripherally by Zimmerman[76], but neither detail Silhouette's progress or significance.

The theme of innovation from a process standpoint was then the major thrust of the Official History on *The Design and Development of Weapons*[77], which took radar as one of its major subjects. Nahum, commenting on its treatment of a second subject, the jet engine[78], observes that this Official History is judicious in its material, omitting for example stories of contention even where lessons could be derived. So it is with its treatment of radar; for the pre-1941 period, the safe ground of the well-known story of radar's invention and research is detailed. Fortunately, in the National Archives there survive the broader-ranging theme papers drawn up preparatory to this Official History[79], and more fortunately still the comments and criticisms of senior radar scientists are also still extant[80]. Unfortunately the focus here is once again on the later-war period and upon descriptions of the Government research establishments, rather than upon a structured account of the totality of the lines of development and their impact on the radar story. Certainly also, failure was a subject not to be analysed – indeed, if possible, not to be addressed.

In 1965, Guy Hartcup carried forward the perspective of military innovation, of radar among other developments, in *The Challenge of War*[81]. Here, once again, radar is treated as a series of individual system developments, and as a result there is little to say about acquisition or lines of development, Hartcup's work broke new ground in several areas – for example, some failures were (briefly) considered.

More recently, technological innovation in the military field has become recognised as a multi-faceted problem worthy of significant academic study. There has been some attempt to cross-compare the context of 1930's radar development – uniquely military as has been stated - with those of civilian electronic technologies. Norberg and Seidel[82], for example, refer to Thomas Hughes' classic study of electrical power distribution *Networks of Power*[83], but, despite their paper's being subtitled *A Comparison of Efforts in the US and the UK in the 1930s*, concentrate mainly on the USA. It is left to David van Keuren[84] to highlight that 1930s US academic and industrial laboratories were far better funded and staffed, but were essentially not interested in early warning systems. From the US military perspective, there was simply no user requirement.

Recent military innovation literature considers military radar in the 1930s as creating a revolution in military affairs (RMA) rather than itself constituting a military revolution, a complete change in the way that warfare as a whole is waged[85]. That underlying military revolution is seen as the combined-arms operations of the First World War being carried into full flower by 1930s technologies[86]. In addition to Blitzkrieg, the associated and resultant RMA's included strategic bombing, carrier- and submarine-warfare, to all of which the RMA of radar offered the possibility of creating a countervailing capability[87].

In passing, we note that historians of science and technology support this view, for they consider the simultaneity of the development of military radar hardware in many countries (Britain, Germany, USA, Japan, Netherlands, Russia, and Italy[88]) as being the outcome of techniques and studies pioneered in or after the First World War, but brought to effective use by 1930s technologies[89].

Williamson Murray and Allan Millett[90] typify the most recent writers in the field, their conclusions regarding radar resting heavily on Alan Beyerchen[91]. It was noted above that Beyerchen argues, from comparison of UK, US and German experience in the 1930's, that national strategic perception, which in turn formed service user demand, was key to radar's successful innovation.

Terry Pierce[92] in *Warfighting and Disruptive Technologies: Disguising Innovation* is more inclined to see a role for presentation. If, he asserts, a technology is first put forward as solving a present problem, the swift acceptance resulting will then ensure full harvest of the gains from its more revolutionary nature. Later in this thesis, it will be shown how the champions of radar, the airman Dowding and the scientist Tizard, acted with success in just this way in the late 1930s to secure the support of pilots for radar-based ground control[93], albeit that this was after the user demand for radar had been formulated. Their proposition to the pilots was that this control placed them in an advantageous position to attack, and this was accepted even if with reluctance and on occasion rebellion. We may contrast the attitude of the Luftwaffe leaders. General Adolf Galland is often accepted as one of the most progressive of the Luftwaffe leaders, who built on his experiences in the Condor Legion in Spain to develop modern fighting tactics. By good fortune, his Group Communications Officer, Ulrich Steinhilper, also a fighter pilot but with added responsibility for ground control of interceptions, has also published his memoirs[94], and these tell rather another story. After a particularly successful exercise in ground control just after the outbreak of war, Galland said

> "Steinhilper .. you were talking too much. You were just bothering us all of the time. And as I've always told you, it would be best to throw out all of these damned radios! We don't need them. We didn't need them in Spain and without them we could fly higher and faster!".

There were, however, problems in the UK also – attempts to introduce radar to solve the night-fighting problem when the hardware was not ready, worked against its effective introduction[95].

Scientific and technical histories, as has been illustrated, do not have a study of acquisition as their central purpose. Unsurprisingly, therefore, their literature provides us with only individual insights, and no coherent study of acquisition. As explained, invention rather than diffusion has been a focus of such scientific and technical histories, and it is research into diffusion which is more likely to result in studies of acquisition. To date, diffusion is an area which scientific and technical historians are only beginning to address, and radar has not so far been a subject of research from this discipline. This thesis may therefore be considered a contribution to that field, additional to its prime purpose of researching the acquisition process through the example of radar.

The treatment of radar in military histories is now reviewed.

II.3. Secondary Sources: Radar in Military History.

To military historians, radar is one sensor among many. Accordingly, military histories have tended to consider the acquisition of radar-based air defence systems from one of three perspectives – first as a supporting aspect of air power; secondly, as an element in a campaign history, whether that be of the Battle of Britain, or of the Blitz; and finally and less commonly, as a component of an air defence system in its own right.

II.3.1. Military History: Radar as an aspect of air power.

As was remarked above, the study of air defence radar as an aspect of air power is the study of the overthrow of one technology (the bomber aircraft) and the doctrines formed around it, by another (radar and the fighter) with its own countervailing doctrines. The "lethal first strike" theories of Douhet[96], Mitchell[97] and Trenchard[98] were those that held sway in the interwar period. Neville Jones[99] traces their origin in the First World War, and Scot Robertson[100] their development in the RAF from 1919 to 1939, while Uri Bialer[101] and Malcolm Smith[102] show their effect on British decision-making in that period. Stephen Budiansky, himself also a writer on WW2 codebreaking[103], is the most recent historian of twentieth-century air power[104], drawing the lesson that the promise of air power prophets usually ran ahead of the reality. The contribution of radar to proving that lesson is remarked upon by the Official Historians of Grand Strategy for both the interwar period[105] and in 1940/41[106]. The recently published Air Historical Branch study *The Growth of Fighter Command* by T.C.G. James[107] is a thorough treatment of how RAF strategy began to change, built on the early warning of radar. James refers to a number of radar's individual acquisition issues and lines of development problems, but since his scope is Fighter Command as a whole, his focus is rather upon political/ military decision-making, airframes, engines and aircrew than upon radar. Nonetheless, his work is of value to the present thesis, not least because both it and his later campaign history of the Battle of Britain[108] draw from radar records now destroyed.

II.3.2. Military History: Radar in campaign histories - The Battle of Britain and the Blitz.

Turning now to review this and similar campaign histories, it is first apparent that these have covered the events of the Battle of Britain and the Blitz in considerable detail. An element of the present thesis is to contrast the experiences of developing radar for the Battle of Britain as against that for the night Blitz; it may be observed that British writers tend to consider, and write about, the Battle of Britain and the Blitz as distinct campaigns rather than as successive phases in an overall air assault. By contrast, German writers, exemplified by Horst Boog, see them as one, ending in June 1941[109]. There are implications here for the present analysis of radar. The division in British writings into two battles results in separate studies, often from different historians. In turn, a consequence is that the contrast between day and night radar as success and relative failure is rarely drawn, and the underlying reasons only rarely examined.

The relevant Official Histories are those for the RAF (especially Volume I: *The Fight at Odds*[110]) and *The Defence of Great Britain*[111], the latter being particularly worthwhile for its consideration of air defence policy. At a detailed level, the indispensable seven-volume *RAF Signals History*[112]describes the entire radar-based air defence system, and helpfully gives an introductory treatment of a number of the lines of development, in particular organisation, training and communication. However, since it attempts to cover the entire RAF communication and radar network for the whole war, both in the UK and in every overseas theatre of war, it does not deal in depth with the entire subject of acquisition of the capability of air interception, and can but briefly touch upon a number of issues which significantly affect radar.

Wood and Dempster[113] devote several chapters to describing the overall air defence system and its performance, with specific reference to radar, during the Battle of Britain, and they acknowledge their reliance on James in so doing. Two other major historians of the Battle, Bickers[114] and Mason[115] award radar similar treatment; Winston Ramsey's *After the Battle* team contribute a more visual survey[116]. The Battle itself continues to be re-fought in print on each major anniversary of 1940, with two significant publications in 2000 – Stephen Bungay's *The Most Dangerous Enemy*[117] and the collection of studies published as *The Burning Blue* under the editorship of Paul Addison and Jeremy Crang[118]. Significant contributions have also come from the assessments of the 1990 RAF Historical Society Conference[119], from Professor Richard Overy[120], and most usefully from John Ray's *The Battle of Britain: New Perspectives*[121], based on his Ph D research. Ray subsequently extended his interest to encompass the Blitz[122].

In each case, the approach is to describe the radar system as it stood in June 1940 in greater or lesser detail, and then to show its contribution to the Battle of Britain or the Blitz. The process by which radar was acquired is usually considered in an extremely condensed form, and with little reference to lines of development as opposed to a reiteration of the story of radar's "invention". By contrast, Ray convincingly establishes that the dismissal of Dowding shortly after winning the day Battle of Britain in 1940 was not due to his inability to resolve a tactical debate between his subordinates, but arose from his lack of success in countering the incipient Night Blitz – specifically, the late delivery of usable radar. However, there is only limited analysis of *why* radar was late, for Ray's major thrust is to disprove that the proximate cause of Dowding's dismissal was the "Big Wing" debate. The essence of this contretemps was whether Park, commanding 11 Group in the South-East, could and should have fought the battle by greater use of the massed formations adopted by Leigh-Mallory's more northerly 12 Group.

There are a number of useful pointers to acquisition issues among campaigns histories, but as their objective is to describe a campaign, none ventures into any depth of analysis of the acquisition of air interception capability. Published work on radar as a component of the air defence system is therefore now reviewed.

II.3.3. Military History: Radar as a component of air defence

Study of radar as a component of an air defence system, separate from campaign history, has received less attention. There are four studies of relevance, useful comparative material, and a series of works that, by concentrating upon other aspects of air defence, allow us perspective views into the contribution of radar.

Jack Gough's *Watching the Skies: the History of Ground Radar in the Air Defence of the United Kingdom*[123] was RAF sponsored, given full access to all files and should have been the definitive study of the planning, acquisition and use of ground radar from its inception in 1935. In fact it devotes less than 30 pages to the period before 1945, and those simply summarise the RAF *Signals History* already referred to. The narrative is also excessively prolix on the post-war developments in which the UK military and civilian air traffic systems and radar networks became merged. Little analytical help for the present thesis can be derived from these 1945-1970 descriptions, and the RAF Signals History remains the prime study. Much more accessible is Bushby's *Air Defence of Great Britain*[124], particularly when coupled with Michael Gething's *Sky Guardians*[125], the latter offering snapshot comparisons on a ten-yearly cycle from 1918 onwards. However, a snapshot treatment does not lend itself to any analysis of radar's five year long acquisition process, and its value for the present thesis is therefore extremely limited.

Some comparative material can also be drawn from three further groups of air defence studies – German wartime radar-based air defence as described by Bekker [126] and Price[127] , from the little-known test of this defence by the RAF in the POST MORTEM exercise [128], and from early post-war British air defences described in Martin[129]. Regrettably these offer few useful perspectives – it was noted above that the pre-war Luftwaffe acquisition process was marked by disinterest and opposition at the highest levels, and by radar's being perceived as a defensive weapon when the policy of the German state was aggressive. The post-war UK air defences also offer relatively few lessons – by 1945, radar was a mature, well understood technology, with an acquisition process to match.

Possible comparative material may also be sought from the non-radar sensors of the 1940-41 air defence system which include the Observer Corps, the RAF radio countermeasures activities of 80 (Signals) Wing (popularly called the "Beam Benders" from their success in countering the German radio navigation beams), and the British radio intercept service (the "Y" Service).

The Observer Corps, responsible for all inland information (for Chain Home did not operate inland) are given excellent treatment by Derek Wood[130]. 80 Wing and its predecessors are described by Professor R.V.Jones[131], by Colin Dobinson[132], by Alfred Price[133] and by Laurie Brettingham[134]. Its story forms an element within this thesis. It is, however, more difficult to assess the value the "Y" service and of radio intercepts. At the highest level, Dowding was not on the list to receive decoded Enigma messages[135], but these, being strategic or administrative, were of limited tactical value. The interception of German tactical radio traffic and the location of aircraft from those transmissions were extensively practised and Devereux, for instance, considers these to have been more useful than radar[136]. However, the original records have not survived, and there is limited information from which to assess this "Y" contribution – the distribution of the stations[137], memoirs of their operators such as Clayton[138] and Goldberg[139], comparative material from the German "Y" service[140] and two attempts at an overall view by Macksey[141]. For the present thesis, the essential difficulty in deriving comparative material for the present study of acquisition from these sibling sensors is that their technology was of a much more basic level than radar, and their acquisition problems correspondingly modest. The telephones and sighting instruments of the Observer Corps, and even the radio receivers of the "Y" Service, were widely known technologies in mature organisations by 1940. There are, as will be seen, individual lessons to be derived from 80 Wing[142]; but there is limited scope for any overall helpful analysis from study of other sensors in the air defence system.

In summary, the assessment can be made that military history offers useful insights, but in no case have these been assembled and analysed as an overall study. Political/ military histories referring to the story of radar are now reviewed.

II.4. Secondary Sources: Political/Military History.

It may be noted immediately that it is indicative of the relatively mature state of British radar that it rapidly became the subject of major debate between key politicians, scientists and Commanders-in-Chief. This certainly did not happen in Germany or the USA. One problem for the present thesis which ensues, of course, is that such debates become intensely personalised and can obscure a balanced view. So it is in the present case.

II.4.1. Radar as a subject of political/ military histories.

First among the contributions on this area is the unpublished 1997 Ph.D. thesis of Alexander Rose[143], later summarised in a prize-winning article[144]. Rose is primarily a political historian, his later works covering the mediaeval Percy dynasty[145] and the spy network of George Washington[146]. For students of 1930s radar acquisition, the involvement of political historians is to be welcomed as illuminating the climate within which the political approval was given for significant funding at a time when rearmament was electorally massively unpopular. Rose's thesis usefully charts this history for 1932-7, and is convincing in linking the success of radar in 1935 to politicians being persuaded of the desirability and robustness of the rearmament case. He is also to be praised for accessing the Ashmore and Tizard papers in the Imperial War Museum. However, his treatment of radar appears to rest on a limited base of less than ten secondary sources, and no radar historians appear in his acknowledgements. He does not reference the work of Bournemouth's Centre for the History of Defence Electronics[147], active at that time, nor of Blumtritt *et al.*[148], nor of any oral interviews, though several key pioneers now deceased were then still alive. Perhaps in consequence, his concept of the research process, which implies that the results were pre-ordained, and of the impact of radar ("nothing more than a sound locator *par excellence* and that was its original intention") have had no followers. There are also basic factual errors in the finances quoted, which are the more inexplicable since both the original sources[149] and a then-published analysis[150] clearly set out the true position. His work has now in part been superseded by Zimmerman[151], although in turn Zimmerman curiously does not reference Rose's work despite its being readily available in article form.

In the later debate around air defence after 1934, in which radar was intimately entwined, the notable personalities were Churchill, his scientific *eminence grise* Frederick Lindemann (later Lord Cherwell), Sir Henry Tizard, and Air Vice-Marshal Hugh "Stuffy" Dowding. Tizard was the scientist leading the innovation of radar. Lindemann, scientific adviser to Churchill, took issue with him on virtually every point, from strategy (Lindemann was a keen supporter of strategic bombing) through tactics (Lindemann advocated aerial minefields) to sensors (Lindemann proposed infra-red rather than radar). Since Churchill vociferously supported Lindemann, the latter's views could not be disregarded. In consequence, Tizard's life became more difficult, and the progress of radar slower than it might otherwise have been.

Each personality in this dispute has their advocates and detractors. Tizard's contribution was most famously (and contentiously) described by C.P.Snow[152], and more accurately by his biographers Clark[153] and Zimmerman [154]. A forceful criticism of C.P. Snow's position is most recently set out in David Edgerton's *Warfare State: Britain, 1920 – 1970*[155]. Lindemann's biographers include R. F. Harrod[156], the Earl of Birkenhead[157], and Adrian Fort[158], with a balanced obituary view in *Nature* by his former pupil R.V.Jones[159]. Churchill, of course, has had massive biographic attention, not least, so far as World War II is concerned, by himself [160], but then in greater detail by Martin Gilbert[161], and more recently by Roy Jenkins[162] and Richard Holmes[163]. It is not to be expected that much space would be devoted by Churchill in his own memoirs to the acquisition of radar, for which he was no enthusiastic advocate until mid-1939, and whose secret he came close to revealing in order to advance his own re-armament agenda. By contrast, the defeat of the German radio navigation beams, for which he could take credit, enjoys a lengthier narrative.

The debate around Dowding has been perhaps less around his undoubted achievements than on his summary termination after winning the Battle of Britain, and the reasons adduced for this "dismissal". Robert Wright, his former assistant, proposed in an authorised biography that this *affaire* was a result of political manoeuvre by senior RAF officers[164]. This theory engendered much heated discussion, for example at the RAF Historical Society and by Peter Flint[165], until the work of Ray cited above[166] clarified the most likely proximate cause as the failure to stem the night Blitz, paradoxically because of delays in acquiring suitable radar.

The main substance of all these works has been the defence of a particular personality, a perspective which tends to focus on the significance of personality rather than process. Nonetheless, in these works there are particular insights to be gained – on Tizard's role in the development of radar and its "selling" to the RAF pilots in the Biggin Hill experiments [167], and a helpful series of descriptions of the organisation and staffing of the Headquarters, Fighter Command [168].

However, the particularly significant work in this debate, because it details both the development of UK's radar based defence system and the part played in it by these personalities, is that of David Zimmerman in his *Britain's Shield*[169]. The work is generally well researched, highly readable and balanced in judgement. Reassuringly for this literature review, it also repeatedly affirms that it is the first study of Britain's first radar-based air defence system, and draws upon a number of the sources quoted here. Its focus, however, is essentially on the interplay between powerful high-level personalities, Churchill and Lindemann on the one hand, Tizard and Dowding on the other, and the development of radar for the day battle – night radar is afforded much less analysis. In consequence, the narrative intercuts between political and laboratory levels in alternate chapters. There are, unfortunately, regrettable lapses in what is otherwise an indispensable work. At the most basic level, it is indifferently edited, with incomplete or garbled sentences and the name of at least one key scientist mis-spelled on some 25 occasions. Structurally, the intercutting referred to results in a disjointed narrative where important connections are lost – for example, the impact of Tizard's resignation in June 1940 on Dowding's direction of night radar development. This effect is compounded by the narrative's moving back and forward in time without always making this explicit. Most of all, the narrative does not clearly disentangle and set out the strands of the building of the *day* air defence system as opposed to the *night* radar air defences. As a result, it is for example never clear that most of Lindemann's proposals are for the *night* defences and most of Tizard's for the *day*. One consequence is that the critical importance of Silhouette as an alternative to radar is not addressed. The impact of this omission is then compounded by the narrative's appearing rushed in its final chapters, possibly to meet a publishing deadline, and results in a contentious penultimate chapter on the night battle. In this, Bowen, the developer of airborne radar, is accused of "deception" on Dowding regarding its progress, and thereby contributing to Dowding's downfall. Sir Bernard Lovell, who contributed the introduction, therein disputes Zimmerman's interpretation[170] and without trespassing too far on the body of the present thesis, it is likely that Sir Bernard's perspective is valid. The lack of readiness of night radar, as will be shown, resulted not from any deception by Bowen, but from excessive reliance on Silhouette as an alternative, and then on mismanagement by the Air Ministry, leading to a failure on almost every single one of its lines of development. In Zimmerman's analysis of AI, as throughout his work, there are frequent, but unstructured, references to aspects of lines of development, but these are essentially secondary to a study of the impact of personalities on an acquisition process. As such, there are lessons which will be revisited, but the opportunity for a balanced study of the two was not here addressed.

Paradoxically, therefore, some potentially significant insights into the acquisition process have originated in literature dealing with powerful personalities As stated, the conclusions of this thesis will debate how far an acquisition process and lines of development can be influenced by just such personalities. At present, it may be noted that the literature of the political/ military history of the period does not contain a balanced analysis of the acquisition of radar for the day and night battles. The concluding section of this review of secondary sources addresses local, company and social histories.

II.5. Secondary Sources: Site, Company and Social Histories.

Only recently an innovative technology, the early radar-based defence system has now become archaeology. One result has been that local historians have begun to produce interpretative guides to surviving remains; and where there are sites of significance, such guides have expanded into books. Similarly, company publications or records of the war have more recently been used as a basis for corporate histories of research or manufacture, often penned once the companies cease to exist. Finally, the contemporary experiences of those involved in these undertakings, whether service or civilian, have begun to establish a corpus of social history around the introduction of radar.

II.5.1.Radar in national and local site histories.

Clearly the line of development concerned with structures has considerable resonance with site histories. The Defence of Britain Project of English Heritage gave impetus to the aim of recording and interpreting the UK's numerous 20th century military sites. One result has been a series of discussion papers on preservation and recording[171]; more relevant to this thesis are a series of Gazetteers covering the whole UK [172]. Recently, their author, Colin Dobinson, has begun publishing a major series of studies of all aspects of these defences, including radar sites, linking their history of development with their use and with the surviving remains. The series is thematically based, and underpinned by an exhaustive review of the National Archive War Diaries. The first two volumes, covering deception and decoy sites[173] and anti-aircraft defences[174]are in print, but the third and most relevant – *Building Radar*[175] – has at the date of submitting this thesis been delayed by almost four years. It is currently anticipated that this study will be published three months after the submission of this thesis, but that – its focus being ground radar sites – it is likely to contribute supporting detail on the specific line of development of structures rather than necessitate any general re-assessment.

Individual radar sites also have their local historians, often former radar operators or mechanics. Good examples of the genre are S/Ldr. Dean's booklet on the Isle of Wight radars[176] (relevant because of German attacks upon them), and Peter Longstaff-Tyrell's coverage of Pevensey[177], a Chain Home station on the key South Coast sector.

The early research sites, and their related airfield, have been addressed in a series of titles by local historian Gordon Kinsey, covering Orfordness[178], Bawdsey[179], and Martlesham Heath[180]. He relies heavily on published memoirs, including those of A. F. "Skip" Wilkins, Watson Watt's early deputy, and recollections of a number of scientific workers. As a result, his work is partly scientific development, partly social history, and tells us relatively little about the acquisition process.

The other major research location, Worth Matravers, awaits its definitive historian. An early attempt has been made by Reg Batt[181], a worker on that site. Unfortunately his loyalty has over-ridden his research, leading to partisan assertions on the responsibility for specific advances which have been factually contradicted by the historians both of GEC[182] and of a key EMI researcher, Alan Blumlein[183].

II.5.2. Radar in corporate histories.

It might be thought that the histories of private companies, in particular the major corporations involved with radar development, could make a major contribution to our understanding of the acquisition process. In reality, corporate histories often take some inspiration from the "victory volumes" produced around 1945 to show a firm's contribution to the war effort. The main contribution of these is often atmospheric photographs rather than revelatory truth. Examples are the publications of GEC[184], English Electric[185] and Metropolitan Vickers[186], each devoting many pages to radar but providing very limited insights indeed beyond pictures of workers with the product of their labours. More recent works, such as that on Cossor by Price[187], are limited in their scope by their brochure length and populist orientation.

More recently, the IEE Section 7 series of historical studies has begun to rebalance the impression that all development was carried out by Government scientists, raising the hope that information on, for example, service/ scientist interplay on concepts and doctrine might be forthcoming. The result has been more modest – the completion of the detail of a picture, mainly of laboratory or production line developments, rather than of a total process. GEC[188], EMI[189] and Pye[190] among others made significant scientific and engineering contributions. The work of EMI is especially relevant to the airborne radar debate, for the EMI equipment totally and rapidly superseded that developed by Bowen's research group. However, it required the oral input of Lovell for the present research to illustrate how various writers' lack of understanding of the night interception process caused the reason for this replacement to be mistaken, for it was not the excellence of the technical solution which was significant, but rather that EMI's improved production engineering created an operationally robust product.

Histories dealing with radar manufacture are not found frequently, or indeed at all. The state of the pre-war UK radio industry has been studied by Geddes[191], but its massive expansion into unfamiliar areas to build radar barely merits a mention in the Official Histories of *War Production*[192]and on *Labour in the Munitions Industries*[193]. Ferranti, who manufactured the early Identification Friend or Foe (IFF) equipment, have an assiduous historian in John F. Wilson, but his concern is essentially with its controlling family's business[194], and IFF merits less than a half-page. Fortunately, by contrast, one of the major Mass Observation publications focuses on another key manufacturer, Ekco, and its radar factory in Malmesbury[195]; and even more fortunately one of the managers, Charles Exton, survives and has written his own memoir[196]. That document reinforces the point that designing equipment for sustainability, and the selection and training of staff even at factory level, have a major impact – as much if not more than scientific design - on the introduction of a weapon in the field.

II.5.3. Radar in social histories.

Finally, social histories of the radar laboratories and installations have not yet begun to appear, but substantial material is available from the reminiscences collected by Colin Latham and Anne Stobbs, first for the scientists[197], and subsequently for the service users and maintainers[198]. Their relevance to the present work is the contribution they make to understanding sustainability, staffing, organisation and training. A distillation is now made of a review of secondary source material on lines of development.

II.6. Secondary Sources and Lines of Development.

As indicated above, it is now appropriate to review what these four lines of approach – from the perspectives of the history of science and technology, of military history, of military/political history, and of local, corporate and social history – contribute to the present thesis on the acquisition of Britain's early radar-based air defence system.

It is apparent that the subject overall has not as yet been addressed, with the single, partial, exception of Zimmerman. Many works contain oblique or infrequent references to one or other lines of development. However, in part because the approaches taken themselves marginalise any considerations of lines of development, a consistent and comprehensive analysis has not been attempted. The concerns surrounding Zimmerman's work have been set out above. The present thesis draws upon some of the same source material, but its approach is completely distinct in analysing the acquisition process rather than the impact of personalities, and brings into play a series of sources previously either less used or not quoted at all. As might be expected, the conclusions also differ in significant areas.

At this point, it has been identified that the approach and coverage of the present thesis, taken as a whole, is original. There remain a disparate group of sources which are each specific to a particular line of development, for example, sources related to structures, or to training. Those of these sources which make explicit reference to early radar are now reviewed.

Focussing then upon individual lines of development, neither radar's structures nor its sustainability have received great attention, from Official Historians down. The Official History of RAF *Design and Construction*[199], for example, devotes one chapter to building radar stations, but does not mention the problems with aerial masts which delayed the entire programme – although it does find space to detail the volume of wood involved. Similarly, the volume on *Maintenance*[200] barely mentions the problems of early war radar maintenance, when these problems were least known and their solution most urgent: interest focuses instead upon the complexity of training later-war service people to maintain the more interesting and complex microwave equipment. By contrast, one volume of the Air Historical Branch *RAF Signals History* is devoted to *Communication*[201]and one to *Organisation*[202], and a dedicated Official History covers *Operational Research*, the method for optimising both areas[203]. Concepts and Doctrine, in terms of strategic bombing versus radar-based fighter defence, have been reviewed above. Reference must also be made to the near-primary sources of the RAF *Manual of Air Tactics*[204], and within the Training line of development, the implementation of those concepts through the RAF *Flying Training Manual*[205]; and the tuition materials for radio operators[206], for radar users[207], and for mechanics[208].

Having now reviewed the full scope of secondary sources which may bear upon a study of acquisition of radar or upon lines of development individually or collectively, it has been identified that, at present, no published literature comprehensively addresses the areas or the subject with which we are concerned. There are a number of tangential references, and several works which have concentrated upon particular points of significance, but the topic as a whole presently remains unaddressed. Primary sources of relevant information are therefore now reviewed.

II.7. Primary Sources for the Acquisition of Radar.

The primary sources available to us are contemporary written records; memoirs of individuals involved, oral or written; surviving equipment; and physical or archaeological remains of sites of the radar-based defence system.

The shortcomings of contemporary archival records have been reviewed in Chapter 1, the salient points being that these are biased towards Government records, are incomplete and "weeded", and were often written with a purpose ranging from portraying success to attract funds, to avoiding censure for failure. As has been noted, scientists even at the time commented on the need for balance to such archival material by inclusion of personal recollection[209]. However, application of the MoD acquisition model ensures, indeed compels, the use of files which have not previously been tilled by researchers. In particular, the National Archives/Public Record Office AVIA files dealing with maintenance and calibration become a significant area of study, as do those relating to selection and training. Two almost untouched areas also contribute new insights, these being the files of the Inspector-General of the RAF[210] and the interviews of key personnel for the Official Histories[211]. The Inspector-General visited almost all the UK radar sites, and his visit notes, together with his more general observations made as formal "Minutes" have not previously been referenced. The Official Historians also interviewed every key scientist and administrator from 1943 onwards, and these near-contemporary records again have not previously been referenced. In particular, one key document, the "Touch memorandum"[212] survives in a poor negative copy but is a detailed close-contemporary record of the airborne radar programme, written by its second-in-command.

The difficulties of a second class of primary records – Air Publications (A.P.s), the "Instruction Manuals" covering everything from King's Regulations on discipline, through how to fly a Spitfire, to how to replace a valve in a Chain Home transmitter – have also been noted above. They may indeed describe the operation of a piece of equipment – that is, if the equipment is new, and installed, at the date of their publication. Edgerton[213] points out that studies of diffusion have to take into account that such new equipment might very well not be deployed everywhere, or even anywhere, at that date. Even if installed, it might not be commissioned, calibrated or working – as this thesis will show, a not infrequent occurrence. In the case of the Battle of Britain, the most frequently quoted Air Publication on Chain Home[214] is dated six months after the Battle was over, when procedures had significantly changed. Likewise, an "AP" on Air Tactics may be even more misleading. The tactics described may be an aspiration after many hours of training; they may in reality be of no application at all. Nonetheless, the general information these manuals reveal as asides is of value – when one reads that a 1930s night-fighter pilot was deemed qualified after 5 hours' night flying, mainly spent on ensuring he would not crash on landing or take-off, the idea of widespread diffusion in the 1930s of serious night-fighting tactics can be dismissed as a fantasy for all practical purposes.

A powerful source of insights and observations on both acquisition and lines of development is to be found in the memoirs of the radar scientists. Prime among them are those of Watson Watt[215], his assistant Wilkins[216], and his successor A.P. Rowe [217], which focus for this period on "day interception radar". The recollections of the airborne radar researchers, Bowen[218], Hanbury Brown[219], Lovell[220], Hodgkin[221] and Wood[222] – all written at least 50 years after the events they describe - act as the contrast for "night interception radar". Each has its drawbacks. Those of Watson Watt, apart from the prolixity of style, were partly written in reinforcement of his claim as "radar's greatest pioneer" (his own modest assessment) for an award from the Royal Commission on Awards to Inventors. Tizard, invited to write a foreword, refused to do so until the text had been heavily edited for accuracy. Wilkins' memoirs give more balanced and useful insights from the working level. Rowe, a polar opposite of Watson Watt in style and temperament, wrote his own slim volume while recovering from a nervous breakdown brought on by his wartime exertions, and without access to original papers. His breadth of vision is substantial, although his less-than-enthusiastic perspective on the early pioneers is explicit, a view repaid with interest by Bowen. Bowen's memoirs are highly readable, and judgemental, frequently of everyone but himself. Several aspects of them will be shown in this thesis to be at least questionable. However, this thesis will not go as far as Zimmerman in judging him a knave. The perspectives afforded by a line of development analysis, and review of Bowen's technical challenges, show that - like Watson Watt whom he much admired - Bowen succeeded in developing the experimental hardware, but failed to provide the military capability of night air interception, in part by disregard for the practical essentials necessary for introducing an innovatory weapon in a large organisation such as the RAF. Hanbury Brown, Lovell and Wood contribute helpful detail – Lovell in particular in his Royal Society Biographical Memoir of another researcher, W.B.Lewis[223], whose "radar life" is otherwise a mere introductory chapter in his biography[224]. The autobiographical works of R.V.Jones[225] have already been mentioned. These are especially relevant to the Blitz, German radionavigation beams, and British countermeasures, but give occasional useful insights, such as Watson Watt's dislike of Dowding[226]. The scientists developing ground control radar have left fewer traces – a recently published memoir by Duckworth[227] and unpublished material by Penley[228] are indispensable to understanding their story.

Autobiographies, as opposed to biographies, of senior service people are less common, but there do exist two of key participants. Air Marshal Philip Joubert de la Ferté[229], a well-connected and senior participant in many important decisions, wrote a memoir sadly lacking in detail on events as opposed to socialising. General Sir Frederick "Tim" Pile[230], commanding the A.A. defences, himself used to shortages and lack of support, gives a sympathetic but limited account of the difficulties faced by Fighter Command in the night battle. His major purpose, however, was to give an account of his own Command.

At the level of unit commanders, pilots and aircrew radar operators, the tendency is more to present the successes than the failures of war. This is especially relevant in the case of night-fighters, where there are few early memoirs, those of Rawnsley and Chisholm being exceptions[231]. In general, such memoirs concentrate on successes after February 1941, when the Blitz was drawing to a close[232]. Unit war diaries in the National Archives are an essential antidote to this[233], as are the original Squadron daybooks where these can be found.

Memoirs of factory workers, maintenance staff and operators are again not common, but do survive. As might be expected, however, they often have a strong social bias. The records of Ekco at Malmesbury have been mentioned. Very fortunately, one of the earliest assemblers of Chain Home hardware at Metropolitan Vickers has also contributed a detailed account[234]. Chain Home operators who have written accounts include Daphne Carne[235]and Gwen Arnold[236], and the mechanic Ray Barker[237] has also recorded his career maintaining CH. These written accounts are supplemented by the many oral accounts collected by the Centre for the History of Defence Electronics[238] now deposited at the Imperial War Museum.

A methodological caution must be inserted at this point. Radar veterans were originally selected to work in this field because of their high intelligence. That same intelligence stimulated many survivors to research and read extensively about the history, use and application of radar. They have had over sixty years to review and refine their memories. The oral interviewer must be constantly aware of how far the "need to know" security principle restricted any individual's knowledge at the time, and it may then be possible to disentangle what is genuine memory from what is a later overlay. Many interviewers have apparently been content to let the interviewee talk unchallenged, and the result is taken as accurate recollection. This author has found that a more appropriate approach may be to adopt a regression style of interview, commencing in school or university days and working forwards, constantly reminding the interviewee to base their recollections solely upon what they knew at the time. My thanks are due to Dr. Penley for acting as a willing and helpful interviewee in this regard.

It might also be added that written memoirs suffer a similar problem. Reference was made above to the difference of views between General Adolf Galland and his Group Communications Officer, Ulrich Steinhilper[239]. It is relevant that Steinhilper was infuriated by reading a retrospective article by Galland criticising German radio-communications in the Battle of Britain, for Steinhilper remembered the negativity and near-contempt which Galland expressed for the subject in 1940.

Surviving equipment has also to be treated with caution. Very few pieces of ground radar survive[240] and those which do are inactive. It must also be remembered that Chain Home, for example, survived in a modernised form until the late 1950s, and later variants differed from those of 1940. More useful are the training films used[241], of high quality and striking immediacy. Fortunately with airborne equipment, sufficient survives to have been reconstructed to working order[242], and even operating from a modern simulator gives a strong impression of the crudity of the equipment and its drawbacks.

Finally, radar sites in 1940s operational order are of course not to be found; but a number of operations rooms have been recreated, for example at Bentley Priory[243], Duxford[244], and Neatishead[245]. The buildings for Chain Home survive at Bawdsey, with an interpretative exhibiton[246], and a Chain Home Low operations room at Humberstone. Quite amazingly – since it has been disused since 1940 – one of the original Essex "Silhouette" sites survives, albeit in advanced dereliction, and both it and ten other sites identifiable only from foundations or archaeological evidence have been recorded by Essex County Council[247]; they are here published in context for the first time. It is a curious twist of fate that the early 1930s sound locators which radar superseded, being almost wholly concrete, have survived far better than any radar site, and can be seen at Denge, Kent[248]. *Sic transit gloria*!

II.8. Internet Sources for Radar History.

The internet provides ready access to both primary and secondary source material for radar history. Such material may be addressed both by accessing sites nominally dedicated to the subject though a general search engine such as Google, or by more structured searching using academic search engines. However, a fundamental problem of internet-derived information is often the lack of validation of the content of the material, and so it is with sites purporting to illuminate the history of radar. It was therefore determined at the outset of this research to make use of sites only where the content was peer-reviewed or validated by other historians, and the author therefore joined the International Electronics History Group (IEHG) of internet users to that end. Sites monitored included:

- ?? Institution of Engineering and Technology (IET, formerly IEE);
- ?? Institute of Electrical and Electronics Engineers (IEEE, USA);
- ?? Newcomen Society;
- ?? British Society for the History of Science.

The records from searches were regularly cross-checked with other researchers in the field from the IEHG, the Defence Electronics History Society, and the Historical Radar Archive.

A general search was also made, this resulting in an analysis according to their apparent purpose of the first fifty responses to a Google inquiry in September 2005 using the phrase 'history of radar 1935 – 1941'. The result showed a strong bias towards two categories – education, and "tribute" sites. Education in turn embraced categories of encyclopaedia/ compendia such as Wikipaedia; generic education sites sponsored by the media such as the BBC or Channel 4; and sites of professional bodies already accessed, such as the American Institute of Electrical and Electronic Engineers. "Tribute" sites typically recorded the contribution to the history of radar of an individual, often a scientist, but also on occasion a user, operator, engineer or serviceperson. Many of the sites were extremely brief, with similar material appearing to have been copied across a number of sites. There was a strong "hardware" bias; very few considered radar as a component of air defence, and none at all dealt with lines of development.

Where sites had been created or were sponsored by individuals, a strong secondary motivation appears to have been to advance personal theories, perhaps to demonstrate personal or national "invention" of radar. An example of such a "tribute site" is www.radarworld.org/ . In this case the tribute is to its originator's father, Hans Hollmann, author of a standard text on VHF techniques in the 1930s. This is a laudable aim in itself, but sadly the site contains a number of obvious errors and anachronisms, for example on the early British work, which negate some of the content and cast doubt on the research supporting the remainder.

The present thesis uses Internet-derived material with extreme caution, primarily as a tool for personal memoirs where the content has been or can be validated against other sources. However, to attempt to tap such value as there may be from general searches, and with the aid of the DCMT Library, a second exercise established a structure for categorising and attempting to assess the utility of some 100 websites accessed through two search engines. The aim of this research component was to identify and categorise:

?? The information contained in the website – did it relate to invention or development? National or international? Did it show awareness of radar within air defence? Of acquisition/ lines of development?

?? Source or authorship of that information – for example, were any original sources used and if so, what?

?? Where identifiable, motivation of the website – was there a "radar is a national invention" mission, or was the site more balanced?

The results confirmed that there were some (but few) websites contributing a modest amount of information relevant to this research, typically personal memoirs confirmatory of material already published, and this is used where relevant.

The thesis did, of course, make use of the Internet as an avenue of approach to academically acceptable databases through which to trace references to published work and conference papers, for example and as stated through the websites of the British Society for the History of Science, and of the Newcomen Society.

Finally, the author acts to answer radar queries over the internet for the websites of the Defence Electronics History Society, the Purbeck Radar Museum Trust, the Bawdsey Radar Trust, and Air-Britain (Historians), and maintains daily contact with those organisations' researchers in this and related fields.

II.9. Summary and Conclusion.

This Chapter has reviewed in detail the published literature on radar which offers the potential for insights into acquisition and into lines of development. It has identified the various disciplines which have generated these works, and found that none has so far addressed the areas proposed for study in this thesis other than partially. None has set out to compare and contrast the acquisitions of day and of night radar; and none has sought to investigate in detail the issues generated by the various lines of development.

There is, therefore, considerable scope for an original contribution to knowledge from the present thesis, and for the location and use of novel sources in so doing. Chapter I established the nature and identity of these sources, and this thesis now proceeds to examine with their aid the acquisition by Britain of the world's first radar-based air defence system.

II.10.

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III

ACQUIRING RADAR FOR THE DAY BATTLE

THE FIRST 1,000 DAYS: 1935-1937

III.1. Introduction.

1940 was not the first time Britain had been attacked by air, nor was the radar-based air defence system then employed the first air defence system Britain had ever acquired – arguably, it was in fact the third.

Primarily, this thesis contrasts one acquisition which took account of lines of development with a second, which largely ignored them. The first acquisition, radar for the day "Battle of Britain", was successful in delivering just enough day interception capability, just in time - the Luftwaffe conceded defeat by quitting the field. The second acquisition, radar for the night "Blitz", eventually delivered a night interception capability, but too late - the Luftwaffe inflicted 43,000 dead and significant damage to British war industries before regrouping to fight in Russia.

The purpose of this chapter is to examine Britain's pre-radar air defence systems and the first three years of acquiring a radar-based day interception capability. It illustrates how lines of development were taken into account and the consequences when they were ignored. Chapter IV will continue and develop that analysis into 1940 and the Battle of Britain itself. The conclusions of these two chapters will then be compared with those of Chapters V and VI, which detail the parallel, less successful, acquisition of radar-based air defence against the night "Blitz".

A second objective of this thesis is to assess the completeness and limitations of modern acquisition concepts through examination of the 1930s acquisition of radar-based air defence capability. In particular, attention is drawn to the interplay of personalities, process and roles, an interplay signally not discussed in recent publications on acquisition[1]. The leadership skills displayed by key personalities will specifically be assessed, and this chapter will also illustrate further acquisition lessons – the need to maintain a focus on acquiring the military capability rather than simply hardware; the need to test key interoperabilities early in the process; and the involvement of private industry on the basis of capability rather than as an article of faith.

It may be objected that applying today's concepts to the 1930s is anachronistic, and this would be so were the application one of the detail of structures, processes and concepts. The 1930s did not comprehend through-life management plans[2], though even in 1940 there were examples of re-use of end-of-life radar equipment[3]. However, it is not anachronistic to apply capability acquisition and lines of development principles to 1930s radar, because that concept and those principles were themselves derived from observation of best practice and experience over many years. In the 1930s such best practice was contributed, not by application of a conceptual model, but by the experience or vision of key individuals. However, when a process results from the experience and vision of individuals, their personal strengths or weaknesses in these areas will be uneven, and also be accompanied by the baggage of their personalities, unconstrained by the disciplines of an agreed process. As a result, analysis of the interplay between process, roles and personality reveals a rich seam of lessons to illuminate the present. In particular, this chapter will begin to illustrate the need to match the personalities of key individuals to the stage in the life-cycle of an acquisition (in this thesis, its "life-stage").

This thesis examines its subject chronologically, since it is concerned with the acquisition of a total air defence system based on radar, and a chronological treatment allows a structured and regular review of the overall system and its capabilities rather than excessive focus upon individual components.

For the historian, the lines of development approach used here brings into focus under-explored areas of the pre-1939 experience of key individuals - not only of the better-known Dowding, Tizard, Lindemann and Watson Watt, but also of those less well-known commanders whom Watson Watt regarded as radar champions[4], Freeman, Sholto Douglas, and Joubert. From their experiences during the First World War and the inter-war years reasons can be identified for each individual's particular lines of development emphases, and insights may be gained into their omissions and clashes. The chapter illustrates also how each had experience of the air defence systems of WW1 and after, and how this was of value.

It may also be objected that the pace and pressures of change in the 1930s bear little relationship to today in terms of acquisition and procurement. In these chapters are identified many similarities to today - indeed, far more than have received study. As examples:

?? Experimentation into air defence pre-1935 did not produce radar, nor did the service that held that experimentation brief, the Army. It was conceived and developed by another service, the RAF, using outside scientists, amidst departmental sensitivities and accusations of bad faith;

?? Radar's acquisition was initially handled by competing Committees with conflicting terms of reference and strong personalities among their membership;

?? Considerable political interference was present, as also was Treasury control – any notion that radar was developed without financial control should be dismissed;

?? Early and excessive enthusiasm collapsed into disenchantment when a key demonstration to senior officers and politicians went disastrously wrong in 1936, almost terminating the project;

?? Major design changes which significantly impacted upon infrastructure and training occurred after radar's proof of concept trials and "initial gate" approval, a subject which has received little study:

?? Significant supply chain issues were not foreseen;

?? When a radar-based air defence system arrived, it was so riddled with shortcomings that, to deliver the capability, older structures (such as the Observer Corps) or technologies (radio direction-finding) had to co-exist with it for years, and people had to be recruited and retrained to compensate. Commanders such as Dowding had to plan for such contingencies, while the scientists such as Watson Watt merely made excuses for them;

?? Radar was a technology which impacted all three services; in these early years, the Navy, pursuing an independent course, mishandled the acquisition, while the Army, which co-operated closely with the RAF, developed some of the most successful shorter-range radar equipments.

Modern acquisitions of systems are often measured in decades. By contrast, the UK's entire radar-based air defence system was acquired in just 2,000 days. It may be objected that today's long-cycle acquisitions necessarily involve extensive turnover among budget-holders, programme managers and equipment-capability customers for which significant succession planning must take place, and so a mere five year programme has few lessons to offer. However, examination of the 1935-40 acquisition of radar reveals that the controlling department moved from the Air Ministry to the Ministry of Aircraft Production, while the customer department changed from Air Defence of Great Britain (which included UK based bombers) to Fighter Command. The Minister changed several times, Swinton to Kingsley Wood to Sinclair, with an added short-term "Minister for Defence Co-ordination", Inskip, who materially influenced the doctrinal shift to defence from deterrence. The Chief of the Air Staff changed (from Ellington to Newall to Portal) as did their staffs. The Air Council responsibility for research passed from Dowding to Freeman; and at the next level, the Director of Scientific Research changed from Wimperis to Pye, whose job was in turn divided to allow a parallel Director appointment of Watson Watt solely to cover radar. While Dowding, as C-in-C Fighter Command the "customer", held this role from 1935 to 1940, that tenure occurred literally as the result of an accident - Courtney, his replacement, was injured in an air crash. The "champion" of radar, Tizard, held his (unpaid) role from 1935 to June 1940, but only after threatening to resign on several occasions. Turnover and restructurings, therefore, are neither a modern phenomenon nor are they restricted to long-cycle procurement; their impact on the acquisition of radar forms part of this study.

Before proceeding with this chronological study, however, it is appropriate to take into account that the reader may have a mental picture of "radar" based on the capabilities of today's civilian air traffic and military radars. 1930s radar was very far from such perfection, and it is helpful to set out for the reader a summary of how 1930s "capabilities", or lack of them, interacted with the acquisition process.

III.2. Acquiring a radar-based air defence system in the 1930s.

Before considering the detailed position of radar in 1930s air defence, it is appropriate to address the higher-level question of the generic types of defence which might be involved. Overall, the capability of air defence might broadly be divided into two categories, active and passive. Within active defences may be grouped interceptor fighters, anti-aircraft guns and missiles, and within passive defences, barrage balloons, decoy sites, black-out, and early warning to (and hardened protection for) the population. The early warning by Chain Home (CH) radar was of benefit to both categories, and for early warning purposes a crude indication of position and course of the threat sufficed. Powers[5] makes the point that active defence has four phases – detection of the threat, identification of its nature, interception and destruction. He observes that, with the technology of the 1930s, the first two – detection and identification – were likely to be ground (or sea) based. To achieve interception and destruction, active defences required an accurate and up-to-the-minute assessment of position and course, and this was provided at long range by Chain Home and at shorter range by, for example, Chain Home Low (CHL), Ground Control Interception (GCI) and Gun Laying (GL) radars.

One particular element of air defence – radio counter-measures (RCM) – achieved its objective by interfering with enemy radio-navigational aids, thus confusing bombers as to their position. RCM was less effective and hence less relevant by day (when visual navigation was more possible) and equally so for large targets such as London, where the Thames acted as a highly-visible pointer even at night. RCM was, however, extremely relevant as a defence for most night targets, and Chapters V and VI include references to this one successful component of British night air defence during the Blitz.

A generic active air defence system represented in simplistic terms is shown in Fig. 1.

The information needs of this simplistic Command, Control, Communication and Information (C3I) system from its sensors are threefold –first, position of the threat (which may initially be in terms of range, bearing and height from a known sensor position); second, positive identification whether the aircraft detected is friend or foe (IFF, identification friend or foe); and third, position of the defending aircraft (which may again initially be as range, bearing and height from a known sensor position), all so that the defenders may be directed to a favourable position to intercept the attacker now identified. It is also obviously helpful to have some indication of the number of attackers ("counting").

Time is critical in the process, as - given a 1930s context – the attacker approaches at ca. 240 mph, or 1 mile in 15 seconds. Delays in plotting positions or in communicating them are therefore of great importance for successful interception, and Chapter IV will illustrate a major dispute at Air Council level over communication delays of seconds.

Chain Home radar displays in no way resembled those of today's radars, which often present a map-like image with the radar at the centre and a radial beam sweeping around it, illuminating targets on the map as it moves (a "Plan Position Indicator" display); each target may have further information – height, nature of threat – attached to it. To gain such data from Chain Home required three successive operations.

First of all, Chain Home's display showed the **Range** of the target from the radar as a "blip" on a horizontal line, (an "A-Scope" in today's radar terminology) as illustrated in Fig. 2.

Operating a switch allowed a second reading, of **Bearing**, to be taken by turning a pointer knob over a scale marked in degrees until the "blip" was at a minimum. The pointer knob operated an electrical circuit called a "goniometer" or "gonio". There were two possible minima – one on the true bearing (say, at 40 degrees, in front of the station) and the other on the reciprocal bearing 180 degrees from it (i.e. at 220 degrees, behind the station). This ambiguity was resolved by operating a further, “sense”, control, described below.

To allow a third reading, that of **Height**, to be taken, the switch was then operated once more, and the pointer knob again moved over the marked scale until the “blip” was at a minimum. The operator then transferred the scale reading onto a manual circular calculator, and read off the **Height** of the target from another scale of that calculator. The scales on the calculators were unique to each station, and were established during the “**calibration**” of the station, a time-consuming process involving an aircraft or a ship travelling several known courses while readings were taken by technical staff and used to compile the calculator scales.

The three readings were then aggregated to establish the range, bearing and height of a potential aggressor. It will already be apparent that taking the three readings necessary to find the position useful to an air defence system might be time-consuming and prone to error; the aggressor was moving on at 4 miles per minute while the readings were taken, for example, and might change course, or height.

Further features of Chain Home radar which it is important to note are:

?? **Sense.** This refers to whether the target is in front of, or behind, the station. Simplistically, aerials called “reflectors”, positioned behind the main aerials, were switched in by “sense relays” to direct the power of the radar mainly to its front. The effect of this was that the CH then primarily “saw” out to sea. Operating the sense relay and observing the effect on the display trace then indicated whether the target was in front of, or behind, the radar. However, if the sense relay failed, then blips would appear on the trace which would be assumed to be in front of the radar (and so probably hostile), but which in fact were behind it (and so probably defenders). This could trigger “blue on blue” fratricidal attacks. Such an episode occurred in the first days of war, and is described in Chapter IV.

?? **Inland plotting – the Observer Corps.** The original intention was that there would be two chains of radars, one along the coast, looking out to sea, and a second, “inland”, chain, to control interceptions over land. An experiment at Dunkirk in Kent in 1937-8 showed that such inland stations would be overwhelmed with the number of echoes on the screen and readings to be taken. It was therefore decided that the Chain Home radar would primarily look out to sea, that there would be no “inland chain” and that the Observer Corps would be responsible for inland plots. The limited equipment of a 1940 Observer Corps post is illustrated in Fig. 3, from which it can be assessed that, at night, in poor weather, at times of cloud or in bright sunlight – all poor conditions for the Observer Corps – inland plotting could be non-existent or highly erratic. It also meant that C3I systems had to be robust enough to accept a second major data stream in addition to radar plots, to correlate these, and to utilise the results.

?? **D/F: “Pipsqueak”.** The same lack of inland radar meant that a distinct, non-radar, method had to be found to identify defending fighters’ positions, for they would often be fighting over land. The solution was to take radio direction-finding bearings (D/F) on a transmission every 15 seconds from the fighters’ leaders, a system called “Pipsqueak” which will be described in Chapter IV. It will be realised that another chain of direction finding stations had to be acquired, staffed and sustained, and that a third data stream had now to be incorporated into the C3I system.

?? **Chain Home “Lobes”.** According to the design of the aerial, the power of radar transmissions is concentrated over particular areas and particular heights. Between these “lobes” there are areas and heights where there will be little if any transmitted power, and hence no echoes back to the receiver. Chain Home had several “gaps” or blind spots; a contemporary diagrammatic illustration is given at Fig. 4. One occurred at 10-20,000 ft, where an aircraft flying a steady course at constant height might fly into and out of several lobes, thereby appearing on and disappearing from the radar screen. A second particular blind spot was at low levels, letting in unobserved such low level raiders as minelayers. This issue was eventually resolved by different radar called Chain Home Low (CHL) as related in Chapter IV. A third blind spot occurred at heights over 20, 000 ft, which proved troublesome late in the Battle of Britain.

?? **Calibration.** Until a Chain Home was properly calibrated as described above, its readings of bearing and particularly of height could be significantly in error. The results of a typical calibration exercise for a Chain Home station are given at Fig. 5. This created an especial problem at the boundary between two radars, where a single raid could be plotted as two different raids because of these calibration errors. An illustration of how this would occur, from a contemporary manual, is shown in Fig. 6. Such issues occurred in 1939-40 and an extra burden was placed on the Filter Room to resolve such plots. If the aircraft was near the coast and seen by the Observer Corps, the Filter Room might have to contend with a third, Observer Corps, plot of the same target, which complicated the problem further.

?? **Identification Friend or Foe (IFF).** The earliest hope was that a length of wire, resonant on the Chain Home wavelength and keyed by a motor, would produce a distinctive radar echo on Chain Home, and so could be fitted quickly and cheaply to all Allied planes. Experiments proved this hope doubtful. At the same time, radars were being developed on many frequencies, rendering the original concept of a single resonant wire inapplicable. A special "black box" (in reality, usually grey), the IFF set, had to be developed and fitted to every Allied aircraft and ship. This took time, as will be related in Chapter IV, and until fitting was complete, every single plot had to be identified by a centralised "Filter Room" (see below) which manually cross-checked the plots with known movements of Allied aircraft and ships.

?? **Counting.** Different numbers of aircraft in a formation produced a different "beat" of the screen blip, and with practice it was possible to estimate the number of aircraft in a formation. This was never an exact science, and mistakes were frequent.

?? **Filtering.** It will be recognised that to build up a picture of the entire battle, all these positions and sightings had to be correlated. This was achieved in a centralised "Filter Room" at Fighter Command HQ, Bentley Priory, Stanmore, before the filtered plots were placed on the Operations Room table there, and thence communicated to Operations Rooms at fighter Groups and Sectors.

The diagram at Fig. 7 seeks to illustrate a simplified representation of the complexity of the system described.

It will at once be recognised that each of the equipments and communications links which are components of the air defence system illustrated had their own individual acquisition processes, each one with its own lines of development. The very multiplicity and interaction of these "second order lines of development" will be seen to result in complex staffing, training, organisation, equipment and sustainability needs, and these will be illustrated below. The same multiplicity resulted in extreme loading on the nodal points of the communications system – and in particular, the Stanmore Filter Room.

The following two chapters describe the build up of complexity caused, for example, by increasing time pressure as war approached, by changing enemy tactics causing major shifts in equipment priorities (demanding for example "crash programmes" of CHL build and installation to counter low-flying aircraft in the early months of war), and by equipment failures or human error. The whole illustrates the value today of an acquisition model including lines of development. A cardinal issue illustrated by this thesis is that, in battle in 1940, no problem occurred whose reasons were not obvious once the problem had happened: it was simply that continuous mapping and planning of all the factors involved in producing an entire radar-based air defence system, including second-order lines of development, was beyond the capacity of the unaided mental processes of even outstandingly talented individuals.

The thesis now examines the forerunners of the air defence system of 1940, and in particular those of World War I and the interwar years. The acquisition and operation of these systems formed the learning and shared experiences of those directing the acquisition process for the air defence system of 1940.

III.3. UK Air Defences in World War 1.

At least two phases of German air attack on the UK can be distinguished during the First World War[6]. The first phase, during 1915-6, comprised night attacks along the length of the East Coast by Zeppelin dirigibles flying from Germany. The second, during 1916-8, consisted of attacks on London and the south-east, using Gotha bombers from bases in occupied Belgium. These attacks took place initially by day, but later by night.

The novelty of air assault in 1915 is less significant here than the defensive "system" which grew up to repel it. The most important elements of that embryonic system were:

- ?? Its sensors, usually human observers inland or at sea, but also wireless intercept stations and sound locators;
- ?? Its C3I system, based on the national trunk telephone network and a central London control room;
- ?? The organisation and direction of the defensive forces, both passive (blackout, air raid warning) and active (guns, searchlights and fighters).

While the novelty of the Zeppelin as a weapon of war was initially a cause of terror, greater familiarity with that threat established that, as a means of air assault, the Zeppelin had many deficiencies. It was large (200m x 25 m diameter), slow (typically 80 mph in still air, but winds reduced this significantly) and highly flammable[7]. Fig. 8 shows a typical Zeppelin, the trees at the base of the photograph adding scale. Navigation was a particular problem, compounded by darkness: one early raid, believed by the Zeppelin's crew to be on Hull, in fact attacked King's Lynn. Such errors were not rare, and British blackouts added to the confusion[8]. To locate themselves, airships would request a wireless direction-finding (D/F) position from their transmissions to base; of course, British intercept stations could then locate them equally well[9]. The British had also captured several German codes. Using these, they could identify and track the airships, and disregard decoy missions.

The air defence of Britain was initially in the hands of the Admiralty's Royal Naval Air Service, for the War Office's aeroplanes were destined for France[10]. The most successful defence at first was "intruder" bombing of Zeppelins in their sheds[11], for the few fighters in Britain had indifferent performance and armament. As landing-grounds had inadequate lighting, crashes killed or maimed many fighter pilots. Anti-aircraft weaponry was also limited - Ashmore recounts that only 12 guns defended London against its first airship raid on 31 May 1915[12], and Rawlinson contrasts this with the 215 guns of the Paris defences[13]. Both defences, guns and aircraft, lacked information on the enemy's position. The Admiralty sought to remedy this, and the police were asked to telephone reports of "any aircraft heard or seen within 60 miles of London". Later, the War Office made a similar request[14]. As police, railways, civil and military authorities, and private individuals began increasingly to interchange such information, the trunk network became overloaded. On 31 January 1916 it collapsed, and as a result several inadequately blacked-out Midlands towns were bombed[15].

By the end of 1915, 20 raids involving 37 airships had been met by 81 sorties of fighters[16]. Only 3 of these even sighted the enemy, and no combat resulted in the UK, although *L12* was scrapped after being hit by AA at Dover. Significant damage was done– over £500,000 in London in September 1915[17]- and the need for a unified and designed system of detection, location and control of the defences was apparent.

Even at this early date, scientific solutions to the problems of long-range threat detection and location, and of air interception, had been sought. The Admiralty had set up a Board of Invention and Research in July 1915[18]. Section I of the Board, which dealt with airships and aircraft, conducted research both on night air defence, described in Chapter V, and on sound locators. A Lt Richmond[19] conducted the first of these experiments in 1915-6, followed by Professor Mather, who constructed a 4.9m chalk-cut "sound mirror" at Bimbury[20]. Later, concrete sound reflectors were built at Joss Gap, North Foreland[21], and one is illustrated at Fig. 9. In terms of C3I, an overall centralised system of air defence information and control "to give the earliest notice of the enemy's approach"[22] had been recommended as early as September 1915 by S/Ldr. Babington to Admiral Scott, following a tour of the Paris defences.

The Cabinet War Committee gave the War Office unified control of Britain's air defence on 10 February 1916[23], under Field-Marshal French as C-in-C Home Forces. Arguably the first "designed" defensive system resulted. The sensors included observation reports from police, railways, and radio intercept stations such as that at Stockton on Tees[24]. The trunk telephone system became the basis of the C3I system, with seven Warning Controls, and the local AA commander distributing raid information. Around London, defending aircraft were concentrated into three flights of 39 Squadron, whose commander, Major T.C.R.Higgins, acted to improve landing grounds and tactics[25]. Further squadrons were formed across the country after July 1916, and squadron commanders controlled both aircraft and local searchlights. A training depot was created for night flying.

The effect was illustrated by a raid of 16 airships on 2 September 1916[26]. Three turned back after crossing the coast and only two came closer to London than St Albans, *SL11* being shot down at Cuffley. Its blazing descent apparently unnerved four other airship crews, who promptly retreated homewards. Airship losses increased after that date, the most demoralising to the attackers perhaps being the loss of the charismatic Commander Mathy to Lt Tempest's BE2c over Potter's Bar on 1 October[27]. With the exception of three abortive 1917 raids, the airship phase of assault was now over.

This first designed system had followed, somewhat fitfully, the principles of achieving a military capability and of respecting lines of development. Its sensors drew upon wireless intercept technology as well as human eye and ear. In an original perspective on recruitment, Rawlinson appointed blind men to operate the sound locators, because of their heightened aural sensitivity[28]. The communications infrastructure (the trunk telephone system) was incapable of expansion in the short term, and so the human organisation was built around it. The defences were organised into geographic groups, including guns, lights, aircraft and passive defences such as blackout and air raid warning, with a mobile group commanded by Rawlinson and capable of swift deployment[29]. There was training for night flying, and for sustainability squadron equipment was increasingly standardised around the robust BE2c fighter.

That system had now, however, to face an increased threat, the aeroplane bomber, which was both faster and smaller than the Zeppelin. It had to do so at a time when increased demands from Admiralty (for guns) and War Office (for pilots for France) left the defences impoverished[30]. The Germans had formed the 3rd Bombing Squadron around Ghent and began the "Gotha Summer" day offensive on 25 May 1917[31]. A

Gotha bomber and typical bombs are illustrated at Fig. 10. 16 bombers raided Folkestone, causing 286 casualties. More raids over the next three weeks culminated in a 14 plane daylight raid on Liverpool Street Station, with 594 casualties. Of 94 defending aircraft, only five even saw the Gothas[32]. None were shot down, the key problems being those of locating the enemy and communicating this information to all the defenders.

The air and ground defences were thus reorganised into a new command, the London Air Defence Area (LADA), and to head this, Major General E. B. "Splash" Ashmore, both a gunner and a pilot[33], was brought back from France. He prioritised his problems as, first, day defence; second, night defence; and third, possible resurgence of the Zeppelin[34]. Analysing the existing system against the day bomber, he identified two key issues - for fighters, that their communications broke down at the point of ground/air control, and for the guns, inaccurate height estimation. As solutions, for the fighters, and in the absence of reliable radio, he deployed large white arrows at searchlight sites (the troops there being unoccupied by day)[35], while for the guns, he developed a new system of barrage fire. The system was to make use of "directional listening apparatus" and "wireless co-ordination"[36]: Rose notes that Ashmore promoted the use of sound locators for AA control[37], and that his attention to the efficiency of his communications network was "admiringly" commented upon by Lord French in January 1918[38]. The adapted system appeared vindicated in a 10-Gotha raid of 22 August[39], when 3 were shot down (2 by guns, one by fighter), though a long-range warning from the Kentish Knock lightship which gave the guns 30 minutes to prepare must have helped[40].

The Germans then changed tactics, to attack by night. Here the same problem –location of the enemy and the transmission of that information to all defenders - proved more intractable. The passive defences were effective - under Ashmore's 1917 "Airbandit" system[41], police and "coast watchers" telephoned sightings to his War Room, where areas of a map were illuminated with different coloured lights to represent the track and timings of attack. The telephone system was used to disseminate air raid warnings, and to order raising a balloon barrage. Nonetheless, on 3 September, 218 ratings at Chatham became casualties of an air raid. Active defence was not successful - in three key raids that autumn in which 131 defending flights were sent up against 49 raiders, there were only 8 sightings, leading to just 3 combats and one success[42]. In the winter of 1917-8, only 18 combats resulted from 5 raids, and again only one bomber was shot down. The guns could achieve little, for the searchlights then in use, while adequate to track Zeppelins, could not follow the speedier, more agile, and much smaller bombers.

Ashmore turned to wireless technology. By May, some fighters had been equipped with receivers[43] (though not as yet transmitters) making ground control a possibility. The German raid of 30 attackers on 19 May suffered a severe reverse[44]. There were 12 combats, and 6 bombers were lost, 3 to fighters (of whom 84 flew that night) and 3 to AA guns, who fired some 30,000 rounds[45]. Again, it is debatable whether such losses themselves caused the cessation of bombing, for the German Spring Offensive diverted all their aircraft to France[46], but the losses may have helped.

The system which Ashmore procured reached its fullest flower on 12 September 1918, by which time there were no more raiders. Ashmore identified infrastructure, telephone lines, as the critical timing factor, and in particular the need to retain his interim system in full operation until the new system was complete[47].

That new system, utilising some 20,000 men, was managed from a single, centralised control at Horse Guards, London, where Ashmore received information from all its sensors, human and intercept, coastal and inland, and exercised unitary command over defences active and passive. The UK was divided into 25 "sub-controls", at each of which the positions of local aircraft were plotted on a large scale map. A "teller" communicated these plots to the centre, where a "plotter" marked its path with coloured counters on a large central map. One such sub-control area is illustrated at Fig. 11. The colours of the counters corresponded to timed intervals, so that outdated information was quickly removed. Ashmore and the Air Force commander followed the action from a raised dais, and could speak directly through dedicated trunk telephone lines to guns, searchlights, airfields, and, via a transmitter at Biggin Hill, with the aircraft. The entire system was regularly exercised, as were its individual components – the 200 pilots had a minimum of 25 hours' solo flying, including 4 at night[48].

It will become apparent later that this air defence system provided at least a conceptual model for developments during 1919 -1940. With this in mind, the WW1 experiences of the key personalities involved in acquiring radar for 1940 are now examined. In those years, the scientists were exposed both to the military applications of their science, and to the problems of introducing new systems. The military leaders acquired experience in the practical issues of acquiring new capabilities for fighting in the air, and specifically the training and communications needed.

Among the scientists, Tizard began the war in training Lewis gunners in the Royal Garrison Artillery[49]. He transferred as a Scientific Officer to the Central Flying School, Upavon, learning to fly and testing wireless equipment. By late 1916, he took charge of experiments at Orfordness and Martlesham, and in 1917 moved to London as Assistant Controller, Research and Experiments, becoming Controller on the death of his predecessor in a crash. In 1918, he was awarded the Air Force Cross for his test flying. He had, therefore, gained practical experience of defence problems, and of Ministry staff work. With his medal ribbon and pilot's licence, he also had credibility with pilots.

Lindemann[50], by contrast, initially experimented with both sound- and infra-red detection of aircraft and then became one of Tizard's first pupils at Upavon in 1916. He qualified as a pilot, but his experience remained in the field of equipment rather than introducing overall systems.

Of the other scientists who would form Tizard's Committee on the Scientific Survey of Air Defence, A.V. Hill[51], after 2 years spent instructing in weaponry, headed a team of statisticians and experimental officers to improve AA gunnery, one of his teams in particular developing the Sound Locator No. 1[52]. Patrick Blackett[53], a younger man, trained as a naval officer at Osborne and Dartmouth, and fought at Jutland. Henry Wimperis[54] joined the Royal Naval Air Service, qualified as a pilot, and then specialised in bomb aiming technology.

Watson Watt[55] joined the Meteorological Office, and concentrated on using radio to locate thunderstorms. This in its turn stimulated him to research the radio direction finding (D/F) techniques used in Zeppelin wireless interception. His work brought him into touch with Tizard, Lindemann and Wimperis.

The airmen, as might be expected in a war, held significant operational posts. Dowding[56], an artillery officer who had already learned to fly, early in 1915 became a flight commander in 9 Squadron, the "Wireless Squadron" which used radio to communicate fall of shot. For a period, he took command, and developed effective long range radios and air-to-ground radio telephony some 3 years *before* Ashmore, although his experiments were ruled "impractical" by the War Office. After service in France, he returned to commanding training units in the UK, finishing the war as a Brigadier General.

Among Watson Watt's "champions of radar", Freeman had also learned to fly before the war[57]. For several months he served under Dowding in the "Wireless Squadron", winning the Military Cross. He was then posted to Egypt, and later returned to the UK to command training squadrons in 1916, before being posted to operational commands in France for the remainder of the war. Sholto Douglas[58] rose from observer to pilot in France in 1915. He specifically mentions in his memoirs that he used wireless in his observations. He returned to a training squadron in 1916, and was then posted to France, with a break commanding a squadron at Northolt. After a crash in France, he established a training operation in Ireland, before returning yet again to France. Joubert[59] learned to fly in 1912, and carried out the second air reconnaissance of the war on 19 August 1914. He returned briefly to the UK before being posted to 1 Squadron in France, once more using wireless for artillery observation. He then served with the anti-Zeppelin forces in Yorkshire in 1916, before operational postings to Egypt and Italy until the war's end.

In experience terms, therefore, in WW1 those service leaders who would become key to the acquisition of radar had had experience of air defence in France or England, all had used wireless technology in its infancy, and all had had periods managing training functions. Among the scientists, several had qualified as pilots and almost all had personal experience of gunnery, Watson Watt being an exception to both. Additionally, Tizard had gained experience in Ministry staff work and planning, while Hill had developed embryonic air defence operational research.

In system terms, during WW1 an overall air defence system had been created to counter the Zeppelin, and then substantially refined to meet bomber attack. The refined 1918 system included sensors both human and technological – wireless intercept, radio direction-finding, and sound locators. Continually updated information was fed to, and the defence directed from, a central operations room which exercised unified control over all defences, active and passive. Immediate end-to-end communication was provided by a dedicated telephone system and ground-to-air radio, the whole being regularly exercised by training "raids".

Technological progress may also briefly be noted. The early crude experiments of Hulsmeyer in 1904[60] had proven the ability to detect objects by reflection of radio waves, but at extremely short ranges of 5km or less. Watson Watt, on joining the Meteorological Office in 1915, had begun to work on wireless direction finding, which would form the basis for his inspiration on radar. He points out in his memoirs that "the seeds of British pre-eminence in radar were sown not in 1935…but as early as 1915"[61]. However, the electronic technology of the time, though advancing rapidly through the challenge of war, was as yet far from making real progress a practical possibility.

Against this background, the developments of the succeeding fifteen years of peace will now be analysed.

III.4. 1919 to 1933.

Despite Ashmore's attempts to preserve at least the core of his system, demobilisation had swept it almost entirely away by 1920. There remained only a cadre of the 1st Air Defence Brigade (an artillery brigade, a searchlight battalion and a signal company) with a small AA school on Salisbury Plain[62]. However, within two years, the Committee of Imperial Defence (CID) established the concept of a Home Defence

Force sufficiently strong to protect against the strongest potential foe within reach of the UK, crystallised in 1923 as 52 squadrons[63]. Of the 52, 34 were bombers and 18 fighters, for RAF doctrine gave primacy to deterrence and strategic bombing. In practice, by 1925 the gradual implementation of the "no major war for 10 years" planning rule extended the completion date for such a force to 1936, and a repeated imposition of that rule in 1929 reset that date to 1938[64].

The 1920's did not, however, represent standstill. In 1923, the Steel-Bartholemew Committee[65] reviewed air defence, following a recommendation of the CID's Continental Air Menace Committee. It postulated a cross-Channel air attack and established two of its defence principles as

- ?? Collection, assessment and dissemination of information on friendly and hostile aircraft as rapidly as possible, and
- ?? The need for defending fighters to receive warning in time to climb to fighting height to engage the enemy.

Its concept was that, at the coast, attacking aircraft would be met by the guns of an Outer Artillery Zone to break up their formations. Following this, there would be an attack by the fighters of an Aircraft Fighting Zone, extending 35 miles inland from the coast (a depth dictated by the time for fighter ascent to 14,000 feet) and illuminated by searchlights at night. Finally, round London, attackers would encounter an Inner Artillery Zone of guns and searchlights. However, the Aircraft Fighting Zone extended only from Duxford round London to Devizes.

Sensors were clearly important to this structure, and in 1924 these were investigated by the Romer Committee[66], a further joint Air Ministry/ War Office enquiry into the UK's air defences. This recommended 18 Observer Groups to cover the country south of a Humber/ Bristol line. Each would have a control centre, linked to the fighter forces HQ, and to local fighter sector HQ's where these existed. Coastal posts would have sound locators, and note was taken (but no recommendations made) that warnings could come from ships at sea and wireless intelligence.

Acquiring even this capability was extremely slow. The Observer Corps was formed in 1924, part of the War Office for “pay, rations and equipment”. Ashmore pointed out the low priority this implied[67]. The provision of a telephone system by 1925 covered only Kent and Sussex; Suffolk, Essex, Surrey and Hampshire followed in 1926. The control rooms were manned by Special Constables rather than trained staff, plotting procedures being unchanged from WW1. Sir John Salmond was appointed the first C-in-C, Air Defence of Great Britain (ADGB) in 1925, commanding all UK based strategic bombers and, through an Air Officer Commanding, Fighting Area, the fighters, airfields, and in time of war the guns, searchlights, and the Observer Corps. The men for the guns and searchlights were to be Territorials who were not, as yet, recruited, and only after the 1929 Holt inquiry was a central air defence control room to be established at Fighting Area HQ[68].

Sensor technology was also modest. The RAF was not accountable for research in this area, for this was a War Office responsibility. The War Office’s Air Defence Experimental Establishment had focussed, in W.S. Tucker’s Acoustical Section, upon improving sound detection[69]. In 1923, a 20ft diameter sound “mirror” at Hythe had demonstrated a 10 mile range, equating to an 8 minute warning for the 75mph bombers then assumed[70]. Tucker proposed to the CID’s Anti-Aircraft Sub Committee two developments - a long-range 200ft mirror at a cost of £3,000 [71], and a complete London sensor system for £250,000, to employ 175 troops[72]. The RAF consistently supported this research, the Air Council in 1926 considering it “fundamental to the scheme of defence”[73]. Two “early warning” systems were also unsuccessfully tested. The first involved ship-mounted sound locators on board HMS Lunar Bow, illustrated in Fig. 12; these increased the range of the human ear by only 2km[74]. The second employed kites carrying sound trumpets, but this was thwarted by wind noise[75]. Both experiments were discontinued. The Navy also became concerned at the success of the US General Mitchell’s use of aircraft to sink warships, and instituted in 1924 a programme of research work to locate and counter airborne attacks[76]. Infra-red detectors were tested, but detection was beyond the technology of the time and the trials ceased in late 1927[77]. A further Cabinet report of February 1928 on detecting electromagnetic radiation from ignition systems showed that these were short-range and easily screened; “only in acoustics was there any hope of success"[78]. In 1928, therefore, the RAF was realistic in offering to cover a third of the cost of a 200 ft sound mirror, the concept being of a "line of acoustic mirrors" along the South Coast[79]. Salmond also defended Tucker against the attacks of Lindemann, by this time a member of the CID Anti-Aircraft Sub Committee. Lindemann opposed acoustic detection on the basis of his own experimental results in WW1[80].

There was at this time informed and cohesive thought on air defence in the public domain, for Ashmore's book on air defence was published in 1929[81]. His primary purpose was doctrinal - he argued that strategic bombing would be ineffective as a deterrent (as taking too long to be effective), that counter-bombing of enemy bases would be equally useless, but that defence was possible. Even though, he pointed out, the Chief of the Air Staff had publicly called the aeroplane a "shockingly bad weapon of defence"[82] in 1928, that year's air exercises had shown that of 57 raids, only 9 were not intercepted. Defence was clearly not a hopeless case. Ashmore proposed improved wireless for the ground control of fighters, realistic and regular air exercises, dedicated night fighters, and jamming of enemy radio systems, all innovations which were to be implemented in the next decade.

Meanwhile, the RAF continued acquisition of the sound mirror as the best sensor available. Tests of the 200 foot mirror in 1930 gave a range of 20 - 24 miles in good conditions, and in 1931 a central plotting room was established at Hythe[83]. The mirrors are illustrated at Fig. 13. The following year, RAF personnel began to be used to staff this room, and to be trained in the use of the smaller, 30 foot dishes[84]. However, these lines of development were interrupted by concerns over two observed difficulties with acoustic technology – it could not easily distinguish height, and more seriously could not identify friend from foe. In the crowded skies of a likely war, this would be a fatal flaw, and Salmond, C-in-C of ADGB, was unwilling, without reassurance of a solution, to go ahead with the scheme he had previously supported[85].

An unsatisfactory compromise was proposed by dividing duties according to weather and time of day, so that fighters would patrol on fair days and the sound mirror be used at night or in bad weather[86]. The use of resonant wires was proposed to solve the identification problem[87]. An RAF Conference in December 1933 detailed a scheme for 200ft and 30 ft mirrors from the Wash to St. Alban's head, A.P.Rowe (Wimperis' assistant) being present at this meeting[88]. Training RAF personnel on the 200 ft mirror went forward, and in the 1934 Air Exercises the apparatus displayed some success against lone aircraft. A new ADGB C-in-C, Brooke-Popham, supported, and the Air Ministry then backed a limited ten-mirror scheme covering the Thames estuary[89]. However, even the limited 1934 system had produced so much data that the handling system was overloaded[90]. Additionally, realisation of the Thames estuary scheme would be severely delayed by land acquisition problems[91]. Both issues would recur in the development of radar.

The interwar careers of the personalities involved in radar illustrate significant relevant experiences. In particular, Dowding[92] became Chief of Staff at the HQ of the ADGB Inland Area, actively involved in defence planning. Subsequently he was Director of RAF Training from 1926-9, and early versions of the WW2 RAF Flying Training Manual date from this period. Later, he assumed command of the UK ADGB Fighting Area (and hence the defence of Britain) before being appointed Air Member for Supply and Research (AMSR) in 1930. Here his major contributions included two significant developments, from wood to all-metal aircraft, and from biplane to monoplane construction. This move from wood was founded on Dowding's judgement that stocks of seasoned wood would quickly be exhausted in war[93], as would be borne out by its proven shortage in 1935 for building radar aerial masts. His term as AMSR was extended from 3 to 5 years, and the role restructured to focus on R&D after 1934.

Of Watson Watt's three champions of radar, Freeman[94] initially commanded 2 Flying Training School, Duxford, until joining the staff of the RAF College in 1922. Here, Joubert was a staff colleague, and Sholto Douglas a student. Freeman went on to command training establishments before becoming Senior Air Staff Officer at ADGB Inland Area in 1929. He was posted to an operational command in Palestine in 1930, returning to the UK as RAF Staff College Commandant in 1934. Sholto Douglas[95] had left the RAF for a short period after WW1, but was recruited back by Trenchard and served under Dowding, who "taught him the need for efficiency in staff duties and paperwork". He moved after a year to command flying and training units before joining the staff of the Imperial Defence College. Joubert[96], in contrast to his active WW1 operational career, spent almost this entire period in training roles, attending Staff College in 1920 then moving first to the RAF College for a year, and subsequently to the staff of the Imperial Defence College. His move in 1934 to C-in-C ADGB Fighting Area was his first flying command since 1919.

Collectively, the experience of these commanders from 1919 to 1933 would have both conditioned and equipped them to plan for the introduction of a new air defence system on the basis of lines of development. Added to their WW1 operational roles, in which all had had experience of fighter defence, of wireless and of ground control, each had now had significant experience of training and its importance; several had commanded stations in the ADGB area or held staff posts within it, and hence considered air defence problems; and all had had experience of Air Ministry planning.

That Air Ministry planning process is relevant to this analysis. Its mechanism for manpower planning is well described by John James[97]. The process began with a Task Chart, identifying the front-line units needed to fulfil the RAF's roles, and then used this to identify the support units needed to sustain them. The second stage was the production of a Manning Plan, identifying the number of airmen and specific skills needed to staff the Task Chart. To that Manning Plan were then added the time spans needed to acquire or impart those skills (recruitment and training), leading on to the need to establish and staff training schools, and thence to the need to "train the trainers". This system was deeply ingrained in the air officers, but it would be less well known to many of the scientists. Least of all would it be known to Watson Watt, for at its height, the DSIR Radio Research Department which he headed employed just 30 staff by 1933[98].

Unknown to him also would be a second feature of RAF life - its systems for stores, equipment and tools. The RAF existed to fly aircraft and to operate airfields from which to fly them. As a result, the provision of aircraft, their ground equipment and spares, and the equipping, clothing and feeding of its airmen, was operated through a known structure, the RAF "Stores Vocabulary"[99], linked in planning to the process described above. Its range of manuals listed everything from aircraft to nuts, bolts, and buttons, so in theory all that would be needed, could be ordered – though there might be a major delay between order and delivery. Beyond that Vocabulary, a local commander might be given a small, highly circumscribed, allowance to spend on local purchases, provided it was clearly demonstrated that ordering through the Vocabulary was completely impossible. Both HM Treasury and the RAF Stores Branch also operated the control that "budget approval did not constitute authority to spend", and by 1934 both had had 15 years' experience of exercising the utmost economy. Neither possessed a mindset for rapid change. As an example, it took the six years from July 1930 to December 1936 for the approved term "Equipment Branch" to replace "Stores Branch"[100]. The airmen would be familiar with the dread implications of delay associated with the response "Not In Vocabulary" (NIV), but the scientists, specifically Watson Watt who was used to freedom to spend on local purchases, were not.

Considering now the careers of these scientists, that of Tizard[101] is almost uniquely broad. At the end of WW1, he returned to an Oxford lectureship; and in 1920, as a result of his Martlesham test flying, he joined the CID's Aeronautical Research Committee, of which he would remain a member until 1943. Friendly at this time with Lindemann, Tizard helped him become head of Oxford's Clarendon Laboratories, before himself leaving Oxford to become Assistant Secretary of the DSIR. This post gave him a uniquely broad perspective across all the military and civil research in the UK. Specifically, he had direct contact with Watson Watt, whose work transferred to the DSIR in 1921, and with Appleton's use of pulsed radio signals for estimating the height of the ionosphere in 1924. In that year, Tizard recommended to the Air Ministry the establishment of the post of Director of Scientific Research (DSR). He refused the role himself, but secured it for the Deputy Director, Wimperis. Though Tizard – elected an FRS in 1927 – was appointed DSIR Secretary in 1927, he moved within two years to the better-paying role of Rector of Imperial College.

Watson Watt[102] continued his WW1 researches on direction-finding of thunderstorms, applying the then-novel cathode-ray tube (CRT) technology for displaying their atmospheric traces as soon as this became available. He was appointed Superintendent of the Radio Research Station, Slough, shown in Fig. 14, and had contact with Lindemann, Tizard and particularly Wimperis, who was Air Ministry representative on the DSIR's Radio Research Board. Scientifically, Watson Watt here acquired most of the technological skills underlying radar – use of radio for direction finding, design of short-wave aerials and receivers, display of results on a cathode-ray tube screen. What he had not acquired, for his team was small, was experience of the planning and timescales involved in programme managing acquiring a national sensor system using that technology, and putting it to 24-hour/day use in air defence. Instead, in a previously unremarked aspect of his career, he devoted time to the activities of the civil service scientists' trade union, the IPCS, from 1929 to 1936[103]. On its behalf he gave evidence to the Tomlin Commission in 1930, was the IPCS chief witness to the Carpenter Committee, and was elected Vice-Chairman in 1932 and Chairman in 1934. Trade union activities at national level are extremely time-consuming, and this study will observe how this lost time detracted from the effective programme management of radar in 1935-6.

Summarising the 1933 position, the doctrinal position of the UK, both at political and military levels, was one of deterrence through a visible strategic bombing capability, and this was reflected in RAF organisation - ADGB had more bombers than fighters. Nonetheless, thought had been devoted to defence, steps had been taken to create an integrated system resembling that of 1918, and research and project effort had been expended to develop and build sensor capabilities to detect and locate bombers. The senior airmen who would support radar had gained experience strongly emphasising lines of development concepts, with especial emphasis on manpower planning, organisation and training. Most had held air defence posts, and all were aware of wireless technology. Their counterpart scientists had in many cases qualified as pilots, and had experience of AA gunnery; Tizard at least had had experience in Ministry-level Committees, planning major defence projects. However, one key scientist, Watson

Watt, had neither a pilot's licence, nor major project experience, nor understanding of the RAF's equipment processes.

The political background at this point may now also briefly be reviewed, as indicating how proposals for expenditure in air defence might be viewed by the electorate and hence by the politicians they elected. Internationally, Hitler had become Chancellor in Germany in 1933, and was open about his intent to abrogate the Treaty of Versailles. Japan had separately invaded Manchuria in 1932, and together these events had moved the British Treasury to set aside its "Ten Year Rule", the financial planning rule for the Services that the Empire would "not be engaged in any great war" for ten years. However, the electorate were in no mood for military spending; given the economic depression of the time, social needs ranked higher, and there was a determinedly anti-militarist feeling. In October 1933, the East Fulham by-election showed a 25% swing to Labour on a "Peace or War" platform, and the national Peace Ballot recorded a similar trend. As Rose points out[104], "re-armament was not the kiss of death, but it was a brave (or foolhardy) candidate who flirted with it". In terms of air power, there were seen to be essentially three options – international disarmament; priority for a deterrent bomber force; or developing an air defence system. The Geneva Disarmament Conference gradually and publicly ran into the sand, so eliminating the first option. Investment in the RAF then became acceptable, but only gradually and always as a sensitive issue (and, it might be added, in the views of the Chancellors of the time, simply more cost-effective than investing in capital ships). Debate thus came to centre on deciding the investment balance between deterrence (bombers, favoured by the RAF's "Trenchard Doctrine") and defence, where the problem was essentially to propose a system which was credible in view of the speed of the modern bomber and Baldwin's mournful dictum that "the bomber would always get through". Financial control and political support for air defence in the early years of the acquisition of radar were never unqualified nor an "open cheque-book".

Technologically, four areas of significant development during these years merit comment. First, the concept of radar (i.e. detection and location of a target by its reflection of radio waves) was the subject of intermittent comment, research and even experiment. Marconi referred to the idea in a 1922 paper[105]; L.S. Alder of the Navy's Signal School described such a system in 1928[106]; and the War Office's W.A. Butement and S.E. Pollard put forward a research proposal in 1933[107]. All these ideas foundered for lack of interest, and, *pace* Rose, they represent isolated instances and not a continuous process of development. Secondly, the use of pulse technique, which permits high power transmissions, had been employed by Breit and Tuve[108] to measure the height of the ionosphere and was well known. Third, continuing attempts to use shorter and shorter wavelengths for communication had led to a body of knowledge in this field, even if much was concentrated among radio amateurs. Radar veterans recall using the popular Radio Amateurs' Handbook of this period as a "bible" for their own work[109]. Short-wave components had been developed, for example high-power transmitter valves by the Navy's Signals School[110]. Likewise, the use of metric wavelengths (45 MHz) for the embryonic BBC TV service will be seen to be intimately intertwined with the development of radar, exemplified by the use of entire TV subassemblies by the airborne radar team[111]. Finally, an unremarked but critical move was made by RAE Farnborough's head of radio, Leedham, to persuade UK radio manufacturers, up to this point essentially assemblers of bought-in parts, to establish their own design capabilities[112]. This would prove of great value when radar production called upon such skills.

The analysis now focuses on 1934, when air defence and sensor technology came to prominence.

III.5. 1934.

1934 is sometimes presented as a quiet year[113], in which A.P. Rowe, Wimperis' Scientific Assistant, browsed through Air Ministry files on air defence, and, finding nothing of relevance, set in motion the process which led to the founding of the Tizard Committee and Britain's acquisition of radar.

In reality, 1934 was anything but quiet, and certainly it was not so in air defence. German and Japanese restlessness, and in particular Germany's quitting the Geneva Disarmament Conference in October 1933, had caused the Government to establish a

Defence Requirements Committee (DRC) that November[114], and by 1934 Germany was identified as the likely aggressor[115]. Within a month, that Committee was recommending a £37 million, 35 squadron expansion of ADGB[116]. Relevant to lines of development, they perceived the limits on expansion as being training establishment capacity for airmen, and the staffing need to recruit construction specialists in the RAF's Works and Buildings function[117]. This was a conclusion flowing logically from the RAF's Manning Plan system described above, much as today it might flow from a structured acquisition plan. A second feature relevant to the present study is that the construction specialists would then be fully occupied in building new airfields down the East Coast to face Germany, with little capacity to spare for acquiring radar sites.

The Geneva Disarmament Conference was suspended in May, and within weeks, a CID subcommittee predicted that the Luftwaffe first-line strength would be 800[118]; the Government, under pressure from the Air Ministry and the media, stoked by Churchill[119], conceded in July an ADGB (including bombers) of 75 squadrons by 1940 (Expansion Scheme A, providing an extra 476 bombers and 336 fighters)[120]. This Scheme was a compromise – the Chancellor had supported the RAF element primarily because it was cheaper. Baldwin recognised the unpopularity of "warlike" military spending, not least against the electorate's fears created by his own phrase "the bomber will always get through", but was buttressed by Londonderry who pointed out that "the fact that all defences are fallible to a greater or lesser degree is no argument against the establishment of the most effective means of protecting ourselves"[121]. Deploying this argument, Baldwin was able to silence the opposition in debate on 30 July[122].

Against this background, in the second half of 1934 the issues, people and processes which would lead to the acquisition of radar increasingly converged. On 2 August, the CID established a Subcommittee under Brooke-Popham "for the Re-orientation of the Air Defence System of Great Britain"[123]. A significant member was Joubert, now C-in-C, ADGB Fighting Area. In the same week, Lindemann wrote to the *Times*, seeking greater scientific effort on air defence[124].

1934's Air Exercises clearly identified that "the successful interception by fighters of raiding bombers required more accurate information from the ground as to movements of hostile formations than was at the time available"[125]. The limitations of a sound locator-based system were becoming evident – it was unable to distinguish friend from foe, to handle multiple tracks, or to give sufficient warning to allow interception of bombers approaching at greater (300mph) speed and height (20,000+ ft). More dramatically, the target of the first night's exercise, the Air Ministry, was "destroyed" with no interception by the defence, and later targets such as the Houses of Parliament followed suit[126]. A.P.Rowe had been an observer of the exercises, and he noted the vulnerability of the acoustic detector to spurious noise – nearby horse-and-cart milk deliveries effectively jammed it[127]! It was apparent to him, much as it was to Lindemann, that acoustic technology had reached its limits. This prompted Rowe's investigation of all relevant Air Ministry files, 53 in number[128]. He concluded that the Air Ministry had paid proper attention to defence without early warning, to balloon barrages and to fighter design, but advised Wimperis, his manager, that further steps must now be taken to harness science to air defence, otherwise any war beginning in the next ten years would be lost[129].

Published work assumes that Wimperis proceeded to suggest the formation of a Scientific Committee simply to review an area where no work was being done[130]. This is not so, for the problem facing Wimperis, an Air Ministry official for many years, was more complex. First of all, a relevant research Establishment was already in existence – the Air Defence Experimental Establishment (ADEE), a part of the War Office, not of the Air Ministry - and research in this area had been assigned to them[131]. Secondly, the major Thames Estuary sound mirror project was proceeding under ADEE/War Office supervision, funded in part by his Ministry - training of RAF personnel, acquisition of sites, and establishment of communications were all under way[132]. Thirdly, research into wireless was explicitly not in Wimperis' brief. It was the role of RAE Farnborough[133], which as described above was already in close liaison with British radio manufacturers. Finally, the CID and its Committees had been actively progressing the restructuring of UK air defence for some time[134].

Wimperis proceeded with care. On 15 October, he consulted A.V.Hill[135], now a Nobel Laureate physiologist, about the possibility of "radiant energy as a means of AA defence" – a "death ray" - and circulated a summary[136] to his superiors, Dowding, (Air Member for Supply and Research), Ellington (Chief of the Air Staff), and Londonderry, the Secretary of State. Wimperis' proposal was to establish a Committee as part of the CID framework, with the carefully chosen terms of reference "to consider how far recent advances in scientific and technical knowledge can be used to strengthen the present methods of defence against hostile aircraft"[137]. Its members, Wimperis proposed, should be Tizard, Blackett, Hill and himself, with Rowe as secretary[138], and it would be called the Committee for the Scientific Survey of Air Defence (CSSAD). The Committee members are illustrated in Fig. 15. It can hardly have been accidental that Tizard and Blackett were members of the CID's Aeronautical Research Committee, while Hill had been carefully introduced into the frame of reference from his eminence in physiology. Wimperis was rather less making a courageous gesture in calling in outside scientists to help him, than gaining eminent cover for politically-sensitive enquiries into fields which were likely to bring him into contention with the War Office. Dowding perhaps had a similar motivation behind his response - **not** to link the Committee with the CID[139].

The CID was already alert to early warning requirements. In early November, its staff accurately predicted 1940 aircraft specifications[140], assuming a bomber speed of 250 mph, an 11 minute climb to 20,000 ft for defending fighters, and a 5 minute end-to-end air defence system communication time. They assessed the requirement as a warning disseminated when the aggressor was 70 miles away. The 200 ft sound mirror, under favourable conditions, achieved a third of this. The Committee met with Lindemann[141] (Fig. 16), whose public voicing of concern in *The Times* was noted above, and asked his ideas. Lindemann excoriated sound mirrors, suggested infra-red, and expressed confidence even that "the reflection of wireless waves might be applied to aircraft detection"[142]! His main purpose, however, was to propose a major Committee to investigate new approaches to air defence[143], a suggestion rejected by Londonderry[144] –

who did not mention the fact that such a Committee, not part of the CID, was being formed by his own Air Ministry.

Wimperis, meanwhile, prepared a briefing note[145] for the scientists of the Tizard Committee. That note interestingly followed the assessment of the ADGB Committee in postulating aggressors of 250 mph at any height from low-level to 30,000ft, and in any weather. Wimperis indicated limitations to detecting such aggressors – engine radiation could be shielded, infra-red absorbed by water vapour – and expressed doubt about radio detection.

It is, however, possible that Tizard himself may have concluded that radio detection was at least possible, for at this time he met informally with Wimperis, Brooke-Popham and Joubert to gain ADGB views. Joubert records Tizard running through detection possibilities, discarding most (such as infra-red), and concluding “I think I know the answer. I will let you know after I have made more enquiries”[146].

Within days, Watson Watt’s memorandum would set out the potential for radar, and it is helpful now to summarise both the air defence position and the British political climate.

In terms of air defence, doctrinally both Government and RAF agreed on a “Bomber first” deterrence strategy, with Germany identified as the enemy. In reflection of this, the ADGB organisation combined bombers and fighters, and was being re-oriented eastwards. It was also being significantly expanded, with resultant strain upon the infrastructure departments, particularly Works and Buildings. The ADGB’s Fighting Area defence organisation unified sensors (Observer Corps, sound locators) and defences both active (fighters, guns, searchlights) and passive (air raid warning, balloons) into a single organisation, with communications by telephone through control rooms, ADGB’s being at Hillingdon. This air defence system did indeed resemble that of WW1, but much of it was a mere “paper organisation” – in many areas, staffing, communications and equipment did not exist. There was agreement that new sensors giving at least a 50 mile detection range were needed to intercept faster bombers at greater heights, and several Committees, all but CSSAD being in the CID structure, were actively seeking solutions. The scientists now becoming involved had experience of flying and gunnery, though most had none of project planning. The airmen had experience of planning, training and air defence, and some involvement with radio. Tizard, the most senior scientist, had planned major projects, while Dowding, the most senior airman, held the dual responsibilities for Supply and for Research for the whole RAF – he had four years' practical experience of large-scale, long-cycle supply chain management and of introducing major new weapons systems.

The political perspective has been well studied by Rose, but certain of his conclusions stretch too far. For example:

> "Radar was not a radical invention that suddenly burst on an unsuspecting Cabinet, CID and Air Staff. Rather, an invention about to counter the bomber was expected thanks to the "iron law of warfare", and radar neatly slotted into the existing air defence system. It might be said that radar was nothing more than a sound locator par excellence and that was its original intention"[147]

and:

> "Officials first perceived the need for a new device or method and then applied the scientific apparatus as a sort of "mechanical Santa Claus""[148].

and again:

> "In late 1934, Baldwin, Ramsey MacDonald and Londonderry confidently ordered the subcommittees of the Air Ministry and the CID peopled by Government scientists to find a scientific defence for the bomber"[149].

This section has shown that in 1933 the demand certainly existed for a method of early warning, and that the technologies to provide radar hardware were maturing. However, as will be shown by the experience of 1935-40, and taking all the necessary lines of development into account, such demand and such maturing technologies were far from a capability of air interception, and the statements quoted from Rose illustrate some confusion between providing radar hardware and supplying the capability of air defence. As will be seen, such an acquisition involved far more than simply plugging a new sensor into an existing structure, even supposing that the structure existed in reality – which it did not – rather than merely on paper.

III.6. 1935.

In preparation for the first CSSAD meeting on 28 January, Wimperis met with Watson Watt at the Air Ministry[150]. He emphasised that the meeting was unofficial, and asked Watson Watt about “the possibility of a ray of damaging radiation which might be used in defence against air attack”[151]. Watson Watt realised that this was a resurrection of the “death ray” popular in the 1930’s and replied that he thought it highly improbable but would provide a reasoned, quantified answer[152]. Returning to Slough, he asked Arnold “Skip” Wilkins, a Scientific Officer, (Fig. 14 above) to carry out the necessary calculations[153]. These showed, as expected, that the transmitted power needed was hopelessly impractical.

Watson Watt then asked Wilkins if there was any other way in which they might help[154]. Wilkins recalled that in 1931, Post Office engineers had reported that aircraft movements had interfered with reception of short-wave transmissions, and suggested that this phenomenon might be used to detect aircraft[155]. Watson Watt then reported to Wimperis that the death ray was impracticable, but added that “radio-detection” was a “less unpromising problem”[156].

At its first meeting, the CSSAD approached its task with a strong capability focus, discussing a very broad agenda ranging from death-rays to AA gunnery[157]. it was agreed that the primary issue was the early detection and location of attacking aircraft. Tizard, as Chairman, displayed a considerable grasp of acquisition realities by emphasising that[158]

- ?? Ideas would have to be researched, evaluated and put into production well before the outbreak of war to have any positive influence on RAF effectiveness; and
- ?? Even if only a few ideas were pursued, the demand on manpower and production resources would be overwhelming.

The Committee did not have Watson Watt’s memorandum to hand – it had only just been received – but from a verbal briefing were greatly interested in the proposal for “radio-detection”[159]. Watson Watt and Wilkins were already calculating the transmitter power needed to “illuminate” a bomber and reflect a usable signal to a receiver[160].

Meanwhile, and ignorant of CSSAD’s existence, Brooke-Popham’s Re-orientation Committee had prepared its interim report by 31 January[161]. Deterrence was still the primary doctrine, but air defence was now to be extended to cover from the Tees to Portsmouth. The defence concept was of three zones – a coastal zone of observers and guns; then an inland air fighting area; next an inner artillery zone. A minimum of 25 fighter squadrons, 57 AA batteries and 90 searchlight companies, absorbing 43,500 men, would be required. A new CID scientific subcommittee on air defence was also recommended – a proposal which Lindemann, through Churchill, had three weeks earlier put to Prime Minister Ramsey MacDonald[162]. MacDonald, initially unaware of the CSSAD, was then obliged to investigate, disclose the CSSAD’s existence, invite Lindemann to join it[163], and also establish a CID Committee, the Air Defence Research Committee (ADRC) with similar powers[164]. The contention between Committees (CSSAD and ADRC) is further discussed below.

Watson Watt’s first draft memorandum “Detection of Aircraft by Radio Methods”[165] had meanwhile been sent to Wimperis, stimulating discussion with Dowding. The memorandum showed clearly that, in theory, radio location was a possibility with manageable extensions of current technology. Dowding, however, had four years’ experience of the pitfalls of theoretical calculations[166], and he also knew that he might be committing funds to a development which seemed usable only in defence – and hence was counter-doctrinal. Finally, he was already, through the Thames sound mirror scheme, committed to funding another expensive detection system, sponsored by the War Office and already under way. Refusing to listen to Watson Watt, Dowding, pictured in Fig. 17, insisted both upon a commitment that this technology could improve “offensive methods” and upon a practical demonstration[167].

The CSSAD meanwhile continued its work by meeting Brooke-Popham and Joubert at ADGB HQ on 21 February[168], adopting a non-threatening approach of informal discussion and seeking information. Joubert confirmed that “early detection (of bombers) was the main problem", the need being for a range of 50 miles beyond the coast, which would "revolutionise" air defence[169]. Brooke-Popham advised that low-flying aircraft could operate with impunity, and that the coastal gun zone was so narrow as to be of little effect. If radio-detection could be successfully demonstrated, the need for its application was starkly apparent.

A demonstration was set up near Daventry on 25/6th February[170], and made use of the 10 kilowatt BBC short-wave (6MHz) transmitter there. A picture of the event, reconstructed from contemporary photographs and drawings, is reproduced at Fig. 18. A modified receiver and cathode-ray tube display was brought from Slough, and set up by Wilkins with its aerials in a field in the beam of the transmitter. A Heyford bomber was steered on a series of pre-arranged courses on the morning of the 26th, and Watson Watt and Rowe (agreed by Dowding to be the Air Ministry observer) saw the displacement of the display screen trace which demonstrated the viability of radio detection of aircraft. Rowe reported to Wimperis[171] that detection was possible "at ranges far in excess of those given by the 200 ft mirror", and that "approximate bearing was possible", adding however that "whether aircraft can be accurately located remains to be shown". Wimperis in turn advised Dowding, who agreed research funding of £10,000[172]. Treasury approval speedily followed [173.]

Watson Watt returned from Daventry to complete his 27th February memorandum "Detection and Location of Aircraft by Radio Methods"[174], today seen as a foundation charter for radar. This, after dismissing as impractical such technologies such as sound and infra-red detection and providing the mathematical basis for the Daventry experiment, established five techniques significant to radar development;

?? The use of "floodlight" as opposed to "beam" radar for defence, explained in Appendix A;

?? The use of pulses of radio energy to measure *range*;

?? Employing range readings from cathode ray tube displays in adjacent stations feeding to a central control room, to establish *position*;

?? A method for establishing angle of elevation and hence *height*;

?? Means of *identifying friendly aircraft* (a keyed resonant array), enabling *ground control of interception*.

Importantly, the memorandum noted that these techniques represented an advance, but not an unreasonable advance, on known technology, and that Watson Watt's Slough group were competent in the techniques involved - in present terminology, it was "out of reach, but not out of sight". The use of Orfordness for further experiments was proposed. The remoteness of this Suffolk coast site, known to Tizard from WW1, ensured security; it is illustrated at Fig. 19. Watson Watt and Wimperis visited Orfordness the next day, and a group of six Slough staff moved there on 13 May. It should be noted that from the very first they encountered problems with aerial mast contractors, in this case Harland and Wolff, and that they worked under financial stringency, with little test gear [175].

The research front was advancing quickly, but the governance mechanism was more clouded. After the Daventry success, Londonderry had advised Baldwin on 14 March that "our potential capacity to defend the country against air attack had materially increased"[176]. Rose asserts also that, even before Daventry, Tizard was instructed by Baldwin to "report directly to him as well as to the Air Ministry" but the source quoted, information passed to Baldwin's biographer, appears doubtful in view of the same biographer's regarding A.P. Rowe as an aeroplane manufacturer[177], presumably confusing him with Alliott Verdon Roe of Avro, and Rose's not referencing any confirmatory reference among Tizard's voluminous papers. It appears more probable that Londonderry kept him in constant touch after March 1st.

However the stimulus arose, the Government announced on 19 March both the formation of a CID subcommittee on air defence research (ADRC) [178], and also the continuance of the CSSAD - Lindemann having been invited to be a member. Tizard was understandably confused[179]. The ADRC, parallel to his own Committee but chaired by Lord Swinton, included not only Tizard and Dowding, but also among others the Treasury Permanent Secretary, the Third Sea Lord, the Master General of Ordnance, and the First Commissioner for Works. While he may have drawn solace from the fact that Lindemann was not a member - while Tizard was, by contrast, a long-standing member of the CID's Aeronautical Research Committee - the high powered ADRC's terms of reference almost duplicated those of his own CSSAD. The resolution was practical, for the ADRC simply pursued its research through the CSSAD, thereby legitimising CSSAD's role but as a subcommittee within the CID structure[180].

The pressure of world events was increasing. On 26 March, Hitler had advised the Foreign Secretary that he had already achieved air parity with Britain and intended to do so with France[181]. Within a month, the CID had proposed accelerating the re-orientation and strengthening of ADGB, and the Chiefs of Staff concurred on 14 May[182]. A week later, the Prime Minster had also to concede that his estimates of Luftwaffe production were too low[183].

CSSAD's interim report of 16 May therefore arrived at a critical moment[184]. Earlier drafts in April focussed upon hardware issues in AA gunnery, searchlights, balloon barrages, and fighter speed. By 16 May, the final version focuses on a capability basis. The key air defence problem was clearly identified as the need for "detection and approximate location at 60 miles from the coast", and the indication was clearly given that this was not impossible. Acoustic detectors were discounted as a sensor because of increasing bomber speed. Zimmerman partly attributes May's more positive statements to Watson Watt's production of his interim programme to the CSSAD during this time[185]. This may be so, but as the move to Orfordness had taken place only three days before and no practical result beyond basic testing of the Orfordness transmitter had in fact occurred, this is difficult to credit. Zimmerman's second assertion, that "the change in tone was quite deliberate because of its intended audience" (the ADRC), is more credible.

The CSSAD may have been disappointed in their review of progress at Orfordness on a visit of 15/6 June[186]. Watson Watt intended a dramatic presentation of the tracking of an aircraft – a matter of some surprise to Wilkins and his staff, who had thus far seen nothing - and a test two hours before CSSAD's visit achieved this. However, atmospheric conditions deteriorated, and the demonstration for CSSAD could only follow the target intermittently, while the following morning little could be seen at all[187]. Nonetheless, CSSAD, perhaps to encourage Watson Watt, perhaps mindful of their report to ADRC, passed a series of supportive resolutions, and it was later found that the weekend had been one of the worst in living memory for atmospheric interference[188].

Partly in response to such interference, the Orford group increased their operating frequency to 12 MHz, redesigned the transmitter, giving priority to shortening pulse width and increasing peak power, and improved the receiver[189]. On 16 July, Rowe returned on behalf of CSSAD to review progress, and reported back that his untrained eye could follow aircraft "blips" on the display trace to 53km range, with Watson Watt able to achieve 67km[190]. His drawing of the screen trace is reproduced at Fig. 20. Within a week, Orford could also identify the number of aircraft in a small formation[191].

At higher levels, two key events occurred. The Cabinet approved Brooke-Popham's re-orientation and expansion proposals – but, influenced by the electorate's feelings and national finances, only for their first phase[192] - and Lindemann agreed to join CSSAD. Before so doing, he wrote to Tizard[193] with a list of ideas – infra-red detection, aerial minefields as a weapon, and the ineffectiveness of AA gunnery. Such techniques have some value in day defence, particularly in poor or cloudy weather, but are of most value at night. Previous writers have given insufficient weight to the fact that Lindemann, unaware of the progress on radar, was primarily interested in night attack. Lindemann and Tizard were perhaps less in disagreement than talking past each other. CSSAD had made indeed little progress on night defence, and when Lindemann joined them on 25 July[194], they devoted time to discussing aerial minefields, but conspicuously voted congratulations to Watson Watt for his Orfordness achievements.

By that time, Churchill had been invited onto the ADRC[195]. Here he was quick to propose that bombers be intercepted by a fast, high-flying and radio-equipped aircraft to follow them and guide intercepting fighters. July's ADRC concurred[196], for the tactic had been used in WW1 and in exercises by Dowding himself. More importantly, Rowe, their secretary, advised them of the Orford successes, and also of the thoughts Watson Watt had shared with him for a chain of 30 radar stations at 100km. intervals around the coast from the Tees to Portsmouth at a total cost of £200,000 exclusive of land acquisition and power provision[197]. The ADRC took the first formal step to acquisition of a radar-based defence system by instructing the Air Ministry to develop plans for establishing the "radio detection and location method" in terms of personnel and equipment[198]. A demonstration was also given to Baldwin's Parliamentary Private Secretary, Dugdale[199].

Thus instructed, the Air Ministry felt secure enough to suspend work on the Thames estuary sound mirrors on 14 August – which breached its commitment to the War Office[200]. The Air Ministry replied to allegations of bad faith by saying that the suspension was temporary[201] Indeed, the War Office had sufficient positive information to suggest that they might usefully attach staff to the Orford team – the nucleus of a group who, as will be seen, made a very significant contribution to radar development[202].

Progress during the summer was rapid. By 9 September, CSSAD was advised[203], somewhat in the fashion of a System Requirement Document, that the Orford equipment now had a 92km range with an accuracy of 1km, and had followed aircraft as low as 1,000ft. The case was mathematically made for 200ft rather than 75 ft masts, and for a chain of transmitters with such masts at 20 mile spacing along the coast, with, at each alternate station, a receiver. Position would be found by triangulation between each receiver and the transmitters co-located and on either side. The range would be 130 km for bombers at 13,000 ft (40km at 1,000 ft), with a handling capacity of 30 readings in 5 minutes. The basic cost was £3,000 per transmitter or receiver, with £2,000 per receiver extra for height measurement. Provision was incorporated for minimising the effect of interference and "jamming", but rapid frequency change circuitry could be provided as an extra safeguard at a 20% cost increase. A second, inland, chain of stations was also proposed to follow aircraft once across the coast. An Identification, Friend or Foe methodology was required, but the proposed technology, tuned aerials on friendly aircraft, had not been tested.

The paper also proposed staffing of one person at each transmitter and three at each receiver, these to be RAF Wireless Operator Mechanics, with one officer per group of "two-transmitter-plus-one-receiver" stations. A new signals unit would be responsible for the chain and "training of the operating and observing corps of the chain should begin at a very early date".

The acquisition of a research centre with living accommodation was a "first highly urgent necessity", this to house an expanded team of 12 full- and 3 part-time officers with 20-22 ancillary staff. Their Director, from the DSIR, would report "to the Air Ministry through the DSR" (Wimperis) and be consultant to the Commanding Officer of the chain's signals unit. It should be noted that the RAF was now taking control of air defence research, and doing so with the blessing of the CID, a position it certainly did not hold only nine months before.

Perhaps influenced by a deteriorating international situation (within days, Italy would invade Abyssinia) the ADRC reacted very positively, approving both the building of the chain[204] and of acquiring Bawdsey Manor, already surveyed by Watson Watt[205] , as a research centre. Bawdsey Manor is depicted in Fig. 21. In view of the presence on the ADRC of Sir Warren Fisher, Treasury Permanent Secretary, the Treasury's approval could be counted upon.

Given the significance of this 9th September document, the attention paid to lines of development may briefly be reviewed. The Government and RAF doctrine of strategic bombing deterrence was shifting, but not yet reversed. Defence was essentially a more plausible concept now that sensor technology rendered it feasible. Radar technology had been proven practical, but essentially in a laboratory form. It could not as yet measure bearing, was inaccurate on height, and had no tested identification friend or foe. The equipment had no fixed specification, and had never been production engineered. No thought had been given to sustainability or logistics, for the proposals did not comprehend the RAF Stores Vocabulary, whose inflexibility the Orford scientists were already cursing. Structural problems did not at this point appear significant – site selection criteria had been identified, as had a prospective research centre. What had not been allowed for were the time taken in site acquisition (as had in fact occurred with the sound mirrors), and potential issues in constructing the 200 ft aerial masts, both of which would wreck the programme timescales. Watson Watt had identified the organisation, personnel numbers and skill types, and the need for urgent training - but while the RAF's handling of these human resources lines of development would proceed smoothly, those for the civilian scientists would prove a major problem, with Watson Watt a prime culprit for not devoting time to his duties here. Finally, hardly anywhere in the paper does Watson Watt deal with communications or data handling – given the overloading problems that the much more limited acoustic mirrors had experienced, such problems might have been anticipated and did indeed arise.

For the balance of 1935, matters appeared to progress well. Watson Watt inspirationally solved the hitherto elusive problem of bearing-finding, by use of crossed dipole aerials and a radio-goniometer[206]. He also filed a secret patent for radar on 17 September[207]- excluding Wilkins and Bowen - and appeared to answer Lindemann's concerns about jamming at the 25 September CSSAD[208]. Bawdsey was then acquired. The Treasury approved £62,000 to construct the first five stations[209,] transferring £17,000 from the acoustic mirror scheme and hence killing it. The Air Council approved the planning for those stations – Bawdsey and Clacton to be complete by spring 1936 and ready for tests, with Orfordness, in June, while Dover, Eastchurch and Shoeburyness were to be completed for the 1936 Air Exercises[210]. This Thames Estuary chain, as eventually sited, is set out in Fig. 22.

Organisation began to surface as an issue in the context of Watson Watt's position at Bawdsey. Wimperis had anticipated appointing a Commandant[211], and had names ready. The Treasury objected that Watson Watt should be the sole Superintendent over research and administration[212]. Wimperis conceded, and Watson Watt took on the role of Superintendent, Bawdsey Research Station in December[213]. The staff, originally intended to remain DSIR/NPL employees, transferred to the Air Ministry early in 1936[214].

The organisation of the RAF was also the subject of review at this time. In July, the cabinet had approved Expansion Scheme C under which ADGB would grow to 123 squadrons (including 68 bomber and 35 fighter)[215], a total considered unmanageable when in war the AA, searchlights, balloon barrage and Observer Corps would be added to it. Accordingly a review by the Director of Organisation would by mid 1936[216] propose the abolition of ADGB and the substitution of Fighter, Bomber and Coastal Commands, a critical step in crystallising the changed doctrine and concepts for UK air defence. Joubert, ADGB's C-in-C Fighting Area, was a key participant in these discussions.

This analysis has established that the first tumultuous year of the acquisition of radar perhaps resembles major present-day acquisitions more than might be thought. A plethora of Committees with overlapping terms of reference, strong-willed personalities, competing scientific advice, on-going reorganisations, technical challenges, and major project reports produced and resolved upon under the pressure of events and of politicians, have all been identified.

The CSSAD may be seen to have maintained throughout a focus upon providing the capability of air defence; it did not deal solely with radar, but at each meeting discussed a series of issues including AA gunnery, barrage balloons, searchlights, the increasing speed of fighters, visibility problems and meteorology. "Initial gate approval", as it would now be termed, had been gained to a programme which specified human resource and infrastructure requirements for a chain of radars. At this early stage, therefore, lines of development were respected, but there were indicators of future problems. In addition, the "life stage" of the project had moved on to embrace programme management as well as research, and Treasury constraint had moved Watson Watt into taking up this extra role of programme management for which his experience and personality did not fit him, much as he desired it.

Day Air Defence Lines of Development Position at 31.12.1935.

At this point, it is appropriate to summarise the progress made in 1935 across all lines of development, and across all those radar-related elements of the air defence system that provided the day interception capability with which the Battle of Britain was fought. Those elements were six in number – long-range early warning radar (Chain Home, CH); early warning for low-flying aircraft (Chain Home Low, CHL); the sensor system inland, which was the Observer Corps (OC); the system for locating friendly fighters, "Pipsqueak" and cathode-ray direction finding, CRDF; identification friend or foe, IFF; and the ground/air communication system of radio telephony, R/T.

Each of those six elements had its own eight lines of development plus interoperability, and the status in each case is shown on a "red/amber/green" basis (a common present-day project management tool) in Diagram 1 below. The judgements made are simplistic, as will be seen from the text of this thesis, and incline to the generous, but serve to indicate both the complexity of the acquisition and also how far and how fast progress had to be made across the 54 areas illustrated. It must equally be remembered that Dowding and Tizard had many other responsibilities to occupy their thoughts, not only in applying this same technology to night interception, but also across airframes, engines, gunnery and fuel; as examples, the Hurricane and Spitfire were being procured and the jet engine developed. Attempting to visualise and track progress across the entirety of their responsibilities is, even today, a mentally-stretching challenge.

In the case of radar and on a generous interpretation, although at 31 December 1935 RAF doctrine was still strategic deterrence, Watson Watt's memoranda had illustrated in concept a defence system which comprehended the need for early warning, for identifying friend from foe, and for ground control of fighters, and proposed solutions. During 1935, radar hardware which could achieve early warning had been demonstrated in an experimental format. However, its inability to warn of low-level aircraft had not been comprehended, and hence there was no concept of Chain Home Low; its inability to operate inland had not been discovered, and so the need to use the Observer Corps for this purpose was not envisaged, though fortunately the Corps was in existence; the inadequacy of Watson Watt's solution to IFF had not been identified, and so there had been conceived neither the need for special equipment to achieve this, nor the need for CRDF to track defending fighters; and finally, the problems of constructing aerial masts and of adequate spares and test equipment support had received no attention.

To set against this, an October 1935 RAF conference had established preliminary personnel and training needs, and an embryo organisation. In terms of C3I, an operations room for plotting air raids and deciding upon responses existed at Fighter Command level, an inheritance from WW1, and it possessed telephone communication links to fighter Groups. Ground/air radio telephony on high frequency (H/F) existed in the TR9 transceiver, although this had a range of only 40 miles.

Despite all these issues, by December, a national radar-based early warning system had received approval in principle (today's "Initial Gate"), and specific approval for a 5-station chain covering the Thames approaches, with a dedicated research and training facility at Bawdsey Manor, Suffolk. No such system existed anywhere else in the world at this time; the pioneers had no prior example to guide them.

31.12.1935	CH	CHL	OC	CRDF	IFF	R/T
Doctrine & concepts						
Equipment						
Infrastructure						
Sustainability						
Personnel						
Organisation						
Training						
C3I						
Interoperability						

Table 1. Radar-based day interception capability: summary position at 31.12.1935.

The study now examines 1936, a year of technical disaster for Bawdsey's hardware, but success in the wider field of the creation of an air interception capability. The same complexities feature once more, and those lines of development which did not receive adequate attention in radar's "programme proposal" contributed largely to the failures of 1936.

III.7. 1936.

1936 was the year in which Germany re-occupied the Rhineland. It was also a year of failure for the Bawdsey scientists when demonstrating radar hardware before a high-level audience, but of some success for Tizard and Dowding in creating other critical elements of air interception capability - the end-to-end communications and air interception tactics of a fully integrated air defence system. Political interference in the acquisition process would reach its height, with the Tizard/Lindemann dispute causing the dissolution and re-creation of the CSSAD. Operationally, the creation of Fighter Command, the posting of Dowding to be its C-in-C, and the appointment of Freeman to be Air Member for R&D responsible for radar, are three moves important to that acquisition process. A fourth, the appointment of S/Ldr. Raymund Hart to head the radar training school at Bawdsey, would be almost as significant in the longer term.

During 1936, as his responsibilities extended into acquisition management (becoming today's Integrated Project Team Leader, IPTL), Watson Watt's informal management style began to come under severe strain. His career as a trade union negotiator[217] has been previously unremarked. He had been Chairman of the scientists' union, the IPCS, in 1934 and a negotiator on the National Whitley Council since January 1935 – a substantial role at any time, but hardly a suitable third job for an individual who was both trying to build up a new research centre in conditions of great secrecy, and simultaneously attempting to project manage a massive and time-driven programme, a responsibility for which he had had no training or experience whatsoever. In what should have been a series of warnings for Watson Watt, he continued to receive commitments of support which he could not turn into action – his establishment was increased from 20 to 36 in March[218], but actual recruitment lagged far behind. Structurally, Bawdsey was only partly available by January 17th – it would be 6 June before the whole site was available[219]. Both were indications of problems to come.

Intellectual thought was running ahead of practical achievement – the CID, Tizard, Lindemann and Rowe were all giving attention to air defence, and all were concerned at the need for speed and more resources. However, doctrinally, the CID's Defence Research Committee continued to accept deterrence as prime. Its scheme F, approved in February[220], placed major emphasis on heavy bomber procurement, but at least permitted an order to Hawker's for 600 Hurricanes.

Rowe, whose secretaryships of the CSSAD and of its parent ADRC gave him a unique vantage point, had worked through the Christmas break to produce a position paper[221]. He optimistically assumed that radar and new fighters had the measure of the "clear day" threat, but – perhaps stimulated by Lindemann's views - that the poor weather and night attack threat required much more research on aerial minefields, searchlights, radar applied to AA gunnery, the proximity fuse, and airborne radar. This report was circulated beyond the CSSAD - Joubert, C-in-C of ADGB's Fighting Area, agreed that scientists should come to his HQ to improve information handling and communication[222].

Lindemann had of course identified the same threat[223], but saw the solution in terms of aerial minefields and balloon barrages, and perceived Farnborough (who were pursuing this research) as far too slow. He was not alone in this view, for the radar scientists were of that same opinion[224]. Both Watson Watt and Rowe shared this desire for faster progress, but handled it in different ways. Rowe contacted Tizard personally to ask that Wimperis be given more staff, a proposition which Wimperis advanced, but which was rejected by the Air Ministry[225]. Watson Watt, perhaps influenced by his trade union role, was to engage in an open struggle with that Ministry, his employer, by seeking a role as "Director of Investigations into Communications" of equal status to Wimperis[226]. His methods would create a major issue later in the year.

By contrast, Tizard did not see the creation of a fully integrated air defence system as concluded solely because a long-range sensor, radar, was now feasible. His immediate reaction was to regard one element, the detection and location of enemy bombers, as manageable, and – thinking in terms of capability - to move on to address the related question of ground control of high-speed fighter interception. He set up tests with Joubert[227] to see if the earlier technology, of radio direction-finding (D/F), could assist. This technology may be briefly explained. Equipment had been available for some time whereby, if a fighter transmitted a radio signal, two ground receiving stations could establish its bearing and hence its position (but not its height). Cathode-ray tube displays had been recently developed to speed this process, creating cathode ray direction-finding (CRDF). The RAF had three D/F stations, at Biggin Hill, Hornchurch and Northolt[228]. Two months of tests were now carried out, from February to April, with limited success. Further tests in the summer and autumn would establish the basis for the fighter location and control element of the air defence system which won the Battle of Britain. In terms of roles in 1940, radar was simply an early-warning device locating aggressors out to sea – it was CRDF which located and helped direct British fighters to achieve interception.

Back at Bawdsey, radar was being delayed by infrastructural issues – the site did not have electricity until February[229] – and by diversion of the small team onto the CSSAD's new and broader priorities of research[230]. Bowen, for example, the Chain Home transmitter developer, now began to devote his time increasingly to airborne radar for night interception. Wilkins, left with the ground radar programme, had three priorities - selection of the sites to be purchased (eventually resolved to be Great Bromley and Canewdon in Essex, Dunkirk and Dover in Kent [231]), construction and testing of 250 ft aerial masts, and developing the equipment for the trials set for May and September. It can hardly have helped that, aided by the success in March of Watson-Watt's bearing-finding solution, the whole concept of the chain as described to the ADRC in 1935 changed. In a massive redesign, instead of alternate transmitter/receiver and transmitter sites every 20 miles, a chain of "all transmitter/receiver sites" at 40 mile spacing was now projected[232], causing all previous plans to be discarded, and with them the completion timescale.

The strain on the small team (just 3 scientists, with assistants) can be realised from this listing of tasks; but from a programme perspective the position was even worse:

?? No contractor had been identified for building the equipment. Indeed, there were no specifications upon which even to begin a dialogue. The intent was that the scientists would hand-build the first five sets for the 1936 Air Exercises, and yet the frustration of the staff at Orford with the "Stores Vocabulary"[233] – the means of ordering the necessary parts – had been ignored.

?? There were particular problems with the new, 240-foot, aerial masts; these, as now conceived, with their predecessors, are shown in Fig. 23. Watson Watt has justification for complaint here, for this research has identified that his highly competent assistant, Joe Airey, had without undue difficulty made similar masts at Slough[234] on the pattern of a mast used by the Royal Engineers in Egypt in WW1, of which a blueprint and model survive[235]. The radar team's use of a contractor (now C.F. Elwell, after the poor Harland and Wolff experience) to build the masts for the 5 approved stations would fall drastically behind schedule, compelling abandonment of the May tests and then first constraining, then rendering a disaster, the September Air Exercises.

There appear to have been three problems – mast construction method, mast material, and aerial feeder. Construction method was decided by each site foreman, these being of variable capability[236]. Materially, each mast consumed almost half a mile of wood, with several 42 ft straight lengths, and Britain's store of suitable seasoned wood was soon exhausted[237]. The feeder connecting the aerials to the equipment had to be hand-made by the scientists from copper pipe, wire and insulating beads. It is indicative that even Watson Watt took part in this handicraft, hardly an effective use of his already over-committed time[238]. Each 16 foot length then had to be mounted on the mast and joined by blowlamp to achieve the full 240ft mast height. Operating a blowlamp at such heights on an exposed mast is not conducive to precision. Unsurprisingly, both joints and feeder often failed.

These issues were not as yet visible at senior levels by the end of March, when Joubert wrote to Tizard that advances in radar meant that air defence plans made up to that point, and based on the WW1 structure, could be torn up and replaced wholesale[239], a point not referenced by those who assume radar was a mere replacement for sound locators. Tizard attended the ADGB Re-orientation Subcommittee within the week, and formally reported that radar now had a reliable range of 60 miles, with position and height finding now tested[240]. The result was that Joubert now chaired the Subcommittee to crystallise the significant tactical change implied – that interception could take place out to sea – into a new air defence structure, abolishing the coastal artillery zone and allocating its guns to a mobile reserve. He also proposed, on 9 May[241], 3.7 and 4.5in guns to replace the outdated 3in, though the related cost rise from £13m to £30m must have caused Treasury concern.

The summer months of 1936 represent a period of tumult in the world of radar. At the political level, to take pressure from the Prime Minister, Inskip had been appointed Minister for the Co-ordination of Defence[242], and rapidly showed himself as counter-doctrinal to the RAF in giving priority to air defence, shocking strategic bombing loyalists but supportive of the acquisition of new defence systems. Unfortunately, it was apparent that the radar which underpinned air defence was running severely behind plan. After 18 June Elwell's team were told to focus on the masts for Bawdsey, Canewdon and Dover only, in an attempt to have something ready for September's air exercises[243].

Dowding meanwhile vacated the post of AMRD, Freeman filling it on 1 April and henceforward being responsible for the acquisition and development of the radar chain until 1940[244]. ADGB, as foreshadowed above, was disaggregated into Bomber, Fighter and Coastal Commands, and Dowding was appointed to head Fighter Command, a role he assumed on 14 July[245]. In today's terms, he moved from being "Equipment Capability Customer" to being "Second Customer and Core Leader" for radar, a role he would hold for over four years rather than the usual three – by chance, as his replacement, Courtney, was severely injured in a crash. He would, therefore, handle the introduction to service both of the Spitfire and Hurricane, and of the radar-based air defence system sustaining them, all developments incepted in his period as AMSR.

However, during the changeover period, Tizard had to weather a major clash of personalities. He did so almost without "customer" support, for Freeman was new in post and insecure following a personal scandal[246]. Inskip inadvertently triggered this clash by indicating that he wished to speed up research and acquisition of new systems[247]. Churchill and Lindemann seized on this; Lindemann had on 29 May accused Farnborough of dilatoriness in a most fractious meeting of CSSAD, and Churchill placed this on the ADRC agenda[248]. Tizard was furious that Lindemann had gone behind his back, and demanded his resignation. He also wrote refuting the accusations. Churchill, through Lindemann, arranged a private meeting with Watson Watt[249], and the three worked on a paper alleging delays and failures in progressing defence research. Watson Watt was at this time in the middle of discussions to establish for himself a Director-level post, equal to that of Wimperis his manager, to take charge of all radar research, production and implementation. Within two days, Churchill used that paper at the ADRC [250], quoting verbatim from Watson Watt to challenge Tizard. In turn, Tizard defended well and the ADRC - Inskip and Swinton in particular - took his side. The matter was referred back to CSSAD[251]. Swinton quickly met with Watson Watt, informed him that he had been a "bloody fool", had forfeited Air Ministry support, and should accept the Superintendency of Bawdsey, for he would gain no more. Watson Watt backed down and took up that post from 1 August[252].

After acrimonious correspondence with Tizard, Lindemann sought again to confront the CSSAD on 15 July. The meeting was so fraught that its secretaries were asked to leave, and only a bland summary survives[253]. The debate appears to have been whether aerial minefields should carry absolute priority, the Committee with the exception of Lindemann believing that such a move had to await the ability to place such minefields in the correct place. Lindemann repudiated all attempts at conciliation, such that Hill and Blackett resigned after the meeting, and the CSSAD could not continue[254].

The Tizard/Lindemann clash has frequently been debated in the context of the personalities, politics and scientific credibility of the protagonists, from the writings of C.P. Snow[255] to those of David Zimmerman[256]. What appears unremarked in the thousands of words written is that, as pointed out above, the debate appears to have been one where the individuals were talking past each other. Tizard, with a strong capability focus, realised the complexity of building a system to achieve air interception even by day. Lindemann – not unlike Rowe in January – considered the day battle essentially resolved, and was proposing hardware solutions whose greater use would be at night. It was, in fact, the case that the Tizard Committee had had only limited discussion beyond searchlight illumination for night defence, and it is noticeable that after the departure of Lindemann, action was taken to advance a night solution, the "Silhouette" scheme of illumination described in Chapter V. C.P. Snow discusses[257] whether, if Lindemann had chaired the CSSAD, radar would have been ready in 1940; given the delays and shortcomings even under Tizard and described in Chapter IV, the answer would appear to be not. Watson Watt is often adduced as a witness to vouch that Lindemann never obstructed radar[258], but given their complicity in ambushing Tizard at the ADRC (not usually referenced) he is hardly an unbiased witness.

The ADRC, however, to whom a report went the following week, simply sought a CSSAD whose members could work together[259]. Swinton, who supported Tizard, proposed a new committee of identical membership except that E.V.Appleton[260], a high-frequency expert, replaced Lindemann, in an appointment which illustrated the priority which CSSAD was giving to radar. After receiving Cabinet approval, the new CSSAD was appointed on 9 September[261].

In the midst of these debates, and despite the CSSAD being in abeyance from 15 July until September, Tizard continued to develop the integrated air defence system. On 13 July he had written to DCAS[262] on the need to test direction finding in further air interception trials, and to try to identify the ranges which airborne radar would have to achieve – a noteworthy point in the context of night defence. Sholto Douglas, as Director of Air Staff Duties, wrote to Joubert, recommending Biggin Hill for these trials[263]. Early in August, Tizard, Wimperis and Rowe met with Dowding, now C-in-C Fighter Command, to discuss how best these trials might be structured[264]. The meeting proceeded extremely well. As one result, it was agreed that a scientific observer should overlook the control room of the interception trials, to see if information flow and handling could be improved. Rowe selected Dr B.G.Dickins of Farnborough for this role[265], thereby stimulating the development of what would become known as Operational Research, today's Operational Analysis.

Before considering the disastrous Air Exercises, it should be noted that Tizard had prevailed against powerful opponents, Churchill and Lindemann, who had enlisted Watson Watt himself as a supporter, and at a time when neither Dowding nor Freeman could help him. In defending himself at the ADRC, Tizard is likely to have made much of radar, and the reality of the problems of Bawdsey would now come as a major shock to him.

At Bawdsey, the equipment situation was dire as regards the aerial masts, the copper feeders and the new transmitter and receiver [266]. To have anything at all operational for September, the whole aerial workforce had been focussed upon Bawdsey's 240ft masts. With a huge effort, the equipment was ready on 17 September, the day of the exercise[267], but not tested, for there was no test equipment. Watson Watt, Superintendent for just seven weeks, had invited the whole CSSAD, Dowding and Swinton himself[268]. The equipment performed catastrophically badly, and the guests heard the noise of aero engines before any radar returns were detected[269]. The dynamics of the situation require little imagination. Tizard, so recently reliant on Swinton in a major conflict, now appeared to have supported a massively expensive but demonstrably worthless system. Watson Watt, so recently agitating for a senior role and salary, and recently plotting with Churchill and Lindemann to gain them, appeared to be a public failure at best. Dowding, having invested credibility as AMSR in the system, and about to be reliant upon it as C-in-C Fighter Command, was moved to call Wilkins a charlatan. Fortunately, Dowding stayed on after the demonstration and met Bowen, who that morning chanced to have been testing a prototype airborne radar constructed in the Manor towers. This had worked astonishingly well, and Dowding was able to see these more impressive results[270].

Nevertheless, the failure was little less than absolute. It is possible that there were three causes[271] – the new transmitter not working correctly, the aerial feeder causing major power loss, and the aerial system not calibrated. Tizard was, given the courtesies of letters at the time, exceptionally blunt in castigating Watson Watt and advising him that the project would be closed down unless the position improved[272] – a move which would involve Watson Watt's own unemployment. On the following day, Joubert, newly appointed C-in-C Coastal Command and hence provider of aircraft for the exercise, came to Bawdsey for a post-mortem and to see what could be salvaged[273]. With massive hard work, including revitalising the disused Orfordness transmitter, a much reduced series of exercises was flown on 23/4 September, with some success, ranges of 40 miles with readings of range and bearing at one-minute intervals being achieved[274].

It is extremely fortunate that for the remainder of 1936, there was pressure on the Government to support air defence, that there was good progress from the Biggin Hill air exercises, and that the CSSAD's new member was Appleton, a long-standing friend of Watson Watt – the two had co-written a series of Royal Society papers in 1923-6[275]. Appleton was to visit Bawdsey regularly during this period, and advised the postponement of radar chain planning for a year[276]. The Bawdsey team were too small, and the equipment too unstable, to form a firm basis for production planning. Watson Watt ceased his national trade union activities, although he continued to spend too much time influencing policy at the Air Ministry[277] and too little recruiting new staff and project managing. Certainly there were excuses of which he took advantage[278] – Treasury inflexibility on salaries, inadequate support from Works and Buildings – but he was fortunate that there was no other contender for his role.

At Biggin Hill, the concern was to identify how close, by ground control, it was possible to guide fighters to an aggressor force. In the trials, the "aggressors" transmitted a radio signal picked up by D/F and communicated to ground control, who in turn directed the fighters to intercept them[279]. Much complicated calculation of courses, speeds and winds was carried out by ground control to give those instructions. As a result of the trials, Tizard identified a simple solution based on an isosceles triangle, shown in Fig. 24[280]. The angle giving the course for the fighters to steer (their "vector", in the developing jargon of interception) was christened the "Tizzy angle". A further simplification resulted from one of the observers, Grenfell, realising that the angle could be accurately estimated by eye[281], thereby dispensing with complex calculations, and this was the practice during the Battle of Britain.

At the beginning of October, Hankey, the CID Secretary, visited Biggin Hill and enthused about the progress of the interception exercises there[282]. This visit coincided with the Air Staff's reporting that Germany was likely to double its already ambitious air force plans, to rival Russia's air fleet[283]. Inskip's response was that the CID should now plan for "what was needed, regardless of supply considerations", and to assume that the defences should be built to withstand a knockout blow within moments of the start of hostilities[284]. The Defence White Paper of 1936, which embodied the Scheme F expansion to 1,736 aircraft (1,000 being bombers) had already shown that finance could be made available[285]. A CID paper of 26 October[286] painted a frightening picture of such an assault, and its meeting of the 29th established that – *pace* Chamberlain's musing that money might be better spent on deterrence – UK defences should be planned on an ideal basis[287]. Dowding was nominated to chair a Subcommittee for the next three months to produce such a plan[288].

Despite the doubts generated by September's disastrous demonstration – doubts which Sholto Douglas echoed on behalf of the Air Ministry[289] – there was therefore sufficient political pressure, and lack of any viable alternative, for radar to continue. Reaction to the same display probably stimulated a restructuring of the Bawdsey organisation and greater focus on preparation for equipment manufacture[290]. Accordingly, two key recruits were brought in – Edmund Dixon, from the Post Office, to take charge of Development and Production; and Harold Larnder, to stabilise the transmitter and receiver designs. The Post Office at this time was a major commissioner of shortwave transmitters and receivers, and its staff skilled in problem analysis and specification. Dixon's memoranda[291], models of clarity, clearly show the results of this structured approach and training. Of the "old hands", Wilkins would take charge of aerials and Bowen drive ahead with airborne radar, while a group under Dewhirst would concentrate on raising the operating frequency to 23 MHz (13 metres)[292].

Two further key components of the air defence system were being set in place. The Army had, since March, seconded Dr. Tabor Paris, formerly No. 2 on sound locators at ADEE, to Bawdsey to report on the Army applications for radar[293], codenamed "Cuckoo". By September, he was able to report that a mobile early warning system usable for gun control (but not gun-laying) was realistic in the next two years, and would replace sound location[294]. In practice, sound locators would continue in use alongside radar on AA sites until 1943, but the Army's radar equipment would prove critical in keeping watch for low-flying raiders, and become the genesis of ground-controlled interception (GCI) to defeat the night bomber. Paris himself moved to Bawdsey in October to head the "Army cell" which would originate these important equipments.

The Navy had also been invited to send scientists to Bawdsey, but declined, instead increasing its own staff by one scientist to manage their own programme[295]. R.A. Yeo went to Bawdsey for six months in 1935 and in September a staff requirement was devised in terms of range – 60 miles for aircraft, 10 miles for ships. A small team experimented to determine suitable wavelengths, for a rotating masthead aerial was required to give an all-round view and Bawdsey's 11 metre choice was impractical for this. 43 MHz was eventually decided upon, but the team was too small to make any real progress.

At the summit of the RAF's air defence system, Dowding proposed a new Bentley Priory operations room, located on an experimental basis in the ballroom there[296]; this is illustrated in Fig. 25. The layout was similar in appearance to the WW1 model, but it may be noted that at this date raid plotting began only at the coast, with the plots provided by the Observer Corps, and not as yet by radar. Plotting staff received no specific training - it was simply an added duty for airmen working at Bentley Priory.

Summarising the acquisition picture at December 1936, therefore, the first point of significance was the unstable status of equipment design. The sets were still being hand-made by Bawdsey scientists; the design had not proven itself in the September air exercises – rather the reverse. Significant elements were still being developed – the reflector aerial to direct the radio beam forward of the radar, and its associated sense controls, were introduced by Wilkins only during winter 1936/7. Up to this date, screen traces displayed aircraft which could equally well be behind the radar as in front. Individuals and a Bawdsey organisation were now being introduced to stabilise the design and produce production specifications. However, as regards sustainability, neither test equipment nor maintenance procedures were even in contemplation, far less the importance of adding key components to the Stores Vocabulary.

In the more structured world of the airmen whose experience was of forward planning, the moves forward were significant. Dowding had recommended the appointment of a training manager[297] on 28 August, and F/Lt. Raymund Hart had begun to work out selection criteria for staffing, and course material for training, during this winter. Dowding had established his control room at Bentley Priory, and the Biggin Hill exercises, attended by a scientist and overseen by Tizard, himself a pilot, had established the interception and ground control techniques needed to translate radar warnings into interception instructions to pilots. Other significant components of the overall system were as yet lacking – there were no Identification Friend or Foe sets; no VHF ground/air communications; and as yet no method of tracking defending fighters unless they switched their transceivers to "Transmit", which of course obviated ground control. On a broader basis, the RAF had taken only the most elementary steps to obtain signals intelligence from the Luftwaffe, for at this date the RAF focus was upon Italy and its Abyssinian adventure[298]. The RAF also did not believe that the nascent Luftwaffe used the Enigma ciphering machine. A small function, AI 1(e), had been formed to summarise plain-language intercepts, and an equally small Air Section within the Government Code and Cipher School, but that was all. However, the CID's ADRC, advised by Tizard of radar's existence and 60-mile range, had now deputed Dowding to plan the "ideal air defences", and the Army had now begun work on radar to aid AA gunnery.

Though the doctrine of the primacy of strategic bombing still prevailed, emphasis on defence by Inskip, and the establishment of Fighter Command, focused organisational attention on, and gained resources for, integrated air defence – the Biggin Hill exercises are an example of this. Dowding as C-in-C Fighter Command was providing core military leadership, and was establishing the physical focus of the Bentley Priory Control Room. The sector controls beneath that level would now develop on its model. The staffing and training of the radar stations had also begun to receive professional attention.

Within the Air Ministry civil framework under Freeman as AMRD (thereby also Equipment Capability Customer and Top Level Budget holder), the development of Bawdsey Research Station, and the appointment of Watson Watt as an Air Ministry official, set the foundations in place. However, at ground level, the scientific recruitment programme was not receiving the attention it merited from Watson Watt. There is no evidence that he had learned any lesson about the long lead times needed to acquire sites or construct high aerial masts – his memoranda merely illustrate a desire to blame Works and Buildings, themselves fully committed with a programme of airfield building in Eastern England, or the Treasury, who to a modern eye might rather be considered rather generous with money and establishment levels.

A key point of relevance is that shared experience and Air Ministry planning disciplines allowed the airmen to maintain their focus despite their roles having changed during the year – Dowding from AMRD to C-in-C Fighter Command, Freeman to AMRD, Douglas to Director, Staff Duties, and Joubert from ADGB to Coastal Command – and despite the entire structure changing with the demise of ADGB. Tizard – who, it must be remembered, was simply an unpaid adviser – had weathered a major political storm with the support of Inskip, Swinton, Hill and Blackett. Lindemann, whose essential role was as Churchill's unpaid adviser, had not survived, but would return in 1940.

The grid below gives a summary of the position from an acquisition perspective at 31 December 1936. The problems of 1936 had been those of an overambitious programme, badly project managed by Watson Watt with his time overcommitted on irrelevancies (such as his trade union work), and in advancing his own position in his connivance with Lindemann and Churchill. Much of 1937 would be spent dealing with the issues which had resulted.

Day Air Defence Lines of Development Position at 31.12.1936.

At 31 December 1936, there was considerable doubt over the future of radar because of its disastrous showing at the 1936 Air Exercises. However, responses to the human resources needs (personnel, organisation, and training) were progressing with the establishment and staffing of the Bawdsey Training School. No need for Chain Home Low was as yet comprehended; nor had thought been given to inland observers – it was thought that an “inland” radar chain would suffice – although, as stated above, the Observer Corps was fortunately already in existence. The Biggin Hill experiments had now identified the value of CRDF in tracking defending fighters, although at this date only that one sector was equipped with such stations. The concept of IFF had been recognised by Watson Watt in 1935, although his proposed method of keyed resonant wires had not yet been tested (when it would be found ineffective). In total, the movement from 1935 was therefore extremely small.

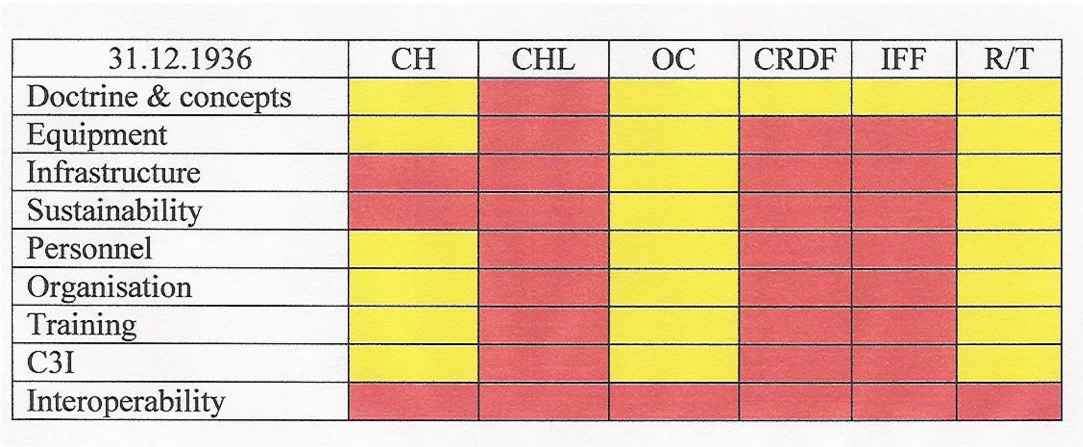

Table 2. Radar-based day interception capability: summary position at 31.12.1936

II.8. 1937.

1937 is usually regarded as a year of achievement in radar[299], although it appears so mainly because of the advances of Bowen’s group on airborne radar, here considered in Chapter V. On radar for the day battle, the story is rather that the scientists were actually producing in 1937 what Watson Watt had rashly promised for 1936. Summarised from a customer perspective of capability, radar at 1 January 1937 was under a cloud because of the failed 1936 Air Exercises. Delivery promises for the five station chain had not been kept, and the equipment at the single working station, Bawdsey, had been found unfit for purpose. There was still no IFF, merely an untested idea for resonant wires, and no secure ground/air/ground radio telephony (R/T). Fighter Command could therefore be in the position of flying standing patrols with its interception capability reliant upon the Observer Corps, radio D/F and wireless interception. There were, however, grounds for optimism – the Biggin Hill tests meant that ground control and air interception tactics were at least under development, and attention being paid to C3I. The human resources needs in terms of numbers and skills of people had been defined, and Hart's Bawdsey training school would soon be opened.

By January, then, at a high level, Dowding's working party were developing their recommendations to the CID-ADRC for the "ideal" air defence system, and at the laboratory bench the Bawdsey scientists were seeking to stabilise equipment specifications. In that equipment line of development, two processes were proceeding in parallel. The first, after 19 January, was an "Intermediate programme" of hand-building equipment for the 5-station chain originally promised for September 1936[300]. The second was agreeing the hardware specification and contractors for the 20-station chain originally approved by the ADRC in September 1935. Here new staff with wider experience played their part. Larnder suggested a basis for the 5-station chain by modifying a GPO Rugby transmitter design[301], and Dixon, the seconded GPO engineer, drew up equipment specifications for the 20-station chain[302]. On 22 January, Freeman as AMRD agreed to a meeting to discuss suitable contractors for the latter[303]. These were materially assisted by Leedham, the head of the RAE Farnborough Radio department from 1930-5, who knew the contractors in depth[304]. The earlier work of Leedham, referred to above, in persuading British radio manufacturers to develop design capabilities for military contracts, now paid off handsomely. There was general agreement that Cossor, a British firm who had TV receivers in production, should make the receivers[305]. Their designer, L. H. Bedford, had impressed Watson Watt on a 1936 visit. Contractors for the transmitter were more problematic – Metropolitan Vickers, STC and Marconi all had expertise, but the last two were eliminated on security and technical grounds[306]. Both had foreign connections, neither had a secure production facility, and Watson Watt's demand for four-frequency capability with 15 second switching time between each was not capable of achievement by the Marconi and STC designs[307]. Additionally, Watson Watt had met MetroVick's research director, Dodds, and again been impressed. Early in March, Watson Watt and Leedham visited Cossor and MetroVick, ensured security and capability of design and building[308] in dialogue with Dodds (MetroVick) and Bedford (Cossor), and allocated the contracts.

In July, Dowding presented his "ideal defence" report, and revealingly it contained no doctrinal shift - the primacy continued to be that of bomber deterrence[309]. Nonetheless, fighter squadrons were to increase from 21 to 45, while searchlight and AA batteries were to be doubled, all dependent on a "properly organised system of ground control" with Group and Sector HQ's to be constructed in peacetime. In human resource terms, the War Office could not staff its element of this increase, although the RAF could manage the fighter component, and the London balloon barrage HQ (an RAF unit) was now set in place[310].

Programme slippage and descoping was, however, continuing, for even after the stimulus of the 1936 Air Exercises debacle, Watson Watt had already been forced to concede a delay in further radar trials from January to April. On 5 February, he wrote to Wimperis with a catalogue of blame[311] (which he ascribed to the Air Ministry, his and Wimperis' employer) on a range of lines of development - slowness in recruitment, in building of aerials and huts, in acquisition of sites, and Stores not stocking items needed by the researchers. He was perhaps "getting his retaliation in first", for on the 15th, he wrote again to say that it was impossible for the full chain approved in 1935 to be ready before January 1939, and that the 5-station "Intermediate chain" would be available only in December 1937, 18 months late, with the Bawdsey-built transmitters to the modified GPO design and Cossor receivers[312].

Meanwhile, the Biggin Hill exercises were continuing, and both they and the April radar exercises concluded in the same timeframe. The Biggin Hill trials were successful[313]. The RAF could now count on an air interception capability with an 85% probability of daytime interception, using D/F techniques for location and control of defending fighters, and given only that the bombers could be tracked by radar, by wireless intercepts, by shadowing aircraft, or by the Observer Corps. The radar trials were more modest[314]. Yet again, they had been descoped to one station, Bawdsey, and even then were further severely attenuated due to bad weather. However, Bawdsey – this time provided with a complete transmitter and receiver as back-up – was able to provide range, bearing and height to 100 miles, and demonstrate this to Swinton in a very carefully managed trial on 23 April[315].

Given such a limited achievement in 1937's first trials after the 1936 disaster, the Air Ministry was unsurprisingly in doubt about ordering equipment for the chain until the hardware was robustly proven[316]. After a month's delay, money for limited progress was found by virement of the research budget, but operational commanders were more divided. Albeit it was outside his remit as C-in-C Coastal Command, Joubert wrote to DCAS on 21 May[317], supporting the chain. Dowding, who was directly accountable, was far more reserved[318], pointing out that while he was happy that radar gave a "general indication of approach", its specific plots bore no relation to actual aircraft tracks, and the D/F element of radar trials had been a failure. It is probably from this point that Watson Watt conceived an increasing dislike of Dowding. Watson Watt's ebullience was always likely to sit uneasily with the aloof "Stuffy" Dowding, who from the first distrusted words and demanded visible proof, as at Daventry. In today's terms, the Customer and the Integrated Project Team Leader were beginning actively to dislike each other. It was fortunate that Tizard was openly friendly with Dowding and that Rowe, a structured manager, would be moved to buttress Watson Watt. In the immediate case, DCAS, given the pressure on timing, recommended that the chain go ahead[319] on the grounds that it would be ready only in September 1939 from an immediate 1937 start, and on 21 June, Treasury approval was requested.

DCAS requested that approval against an unpromising background. The CID had received Dowding's "ideal scheme" formally on 17 June, but in view of its cost, merely approved it in principle[320]. The Chancellor persuaded the Cabinet to approve no major defence expenditure until the implications were worked out, and an effective ban came into place until December[321].

At this point, it will be remembered that in winter 1935/6, after radar's "Initial Gate" approval, the scientists had modified the chain concept significantly. Once again, in 1937, while the "Main Gate" approval was being progressed, the Bawdsey scientists were making significant, and rapidly varying, structural design changes to the chain. The requirement for 4 operating frequencies, and 15 second frequency changes, triggered an increase from 3 to 8 aerial masts of 240 ft (one transmitter, one receiver for each of 4 frequencies). Within a month, this was changed again, to four 360 ft metal transmitter masts and four 240 ft wooden receiver masts[322]; the eventual scale of the masts on a Chain Home site is shown at Fig. 26. As a result, the space needed at each site increased to 10 acres, and the extra "Works and Bricks" workload can be visualised. Even though Watson Watt reduced the number of sites to 10 from 15, the variability in deciding locations once more, and the fact that compulsory purchase could not then be used, would cause problems for months.

Dowding, meanwhile, was taking prudent action in case radar did not provide the capability he needed. The aspect of the system which did work was radio D/F, proven by Biggin Hill. He requested the Air Ministry (he had no budget of his own) to establish three D/F stations in each of Fighter Command's sectors[323], for effective ground positioning and control of fighters. Bawdsey, during the same period, was assessing the results of the April exercises and establishing a full control and "filter" room[324], the latter to weed out doubtful plots. Hart, who had by this time standardised radar training on a 6-week programme, took charge of this activity.

1937's second series of Air Exercises, held on 9-11 August[325], began at last – a year late – visibly to demonstrate the potential for a radar chain, since for the first time more than one station was in operation. Dunkirk (Kent) and Canewdon (Essex) joined Bawdsey and, through the Bawdsey filter and control room established by Hart, plots were successfully sent to Bentley Priory and to 11 Group HQ. Despite lack of experience at Dunkirk and breakdowns at Bawdsey, the exercises were generally successful, and the concept of a viable chain may be said to date from this point. The Treasury accordingly gave approval to the building of the full chain[326] – not a trivial decision, given a prevailing Cabinet ban on major defence spending.

A significant civilian personnel move now took place. Wimperis had retired on 1 March, to be replaced by Pye, his deputy[327]; and Rowe, Wimperis' assistant, CSSAD and ADRC secretary and Co-ordinator, Air Defence, now moved to underpin Watson Watt by becoming Deputy Superintendent, Bawdsey[328]. It says much for how Watson Watt ran Bawdsey that, though the move strengthened non-existent Bawdsey "management structure", it was resented by the scientists[329], who considered Wilkins or Bowen should be appointed. Rowe promptly replaced Watson Watt's informality with a structure of fortnightly reports of progress[330].

During October, the Air Staff prepared for Chamberlain as incoming Premier an assessment of the position if Britain were attacked by air on 1 January 1938, concluding that the situation would be dire[331]. In terms of an early warning capability, only Bawdsey, Canewdon and Dunkirk would then be complete, and the ground C3I organisation would be totally unprepared, since only Bentley Priory HQ and 11 Group possessed operations rooms. To effect any interception, from the 30 fighter squadrons only two had Hurricanes, the rest biplanes. The report may have been aimed at lifting the spending ban. If so, it was successful, albeit the emphasis would continue to be on the doctrinally-correct bombers. Nonetheless, the CID now approved expenditure[332] to bring Dowding's "ideal air defences" into being, these to be operational within 12 hours of declaring war.

The Air Ministry structure, now challenged by the need to make the approved full radar chain a reality, needed to expand its radar project management once more. In November, Pye, as the new DSIR, proposed Watson Watt as a new Director[333], equal in status to himself. Given Watson Watt's personality and track record, a debate with the Treasury ensued which would rage for eight months, until in July 1938 Watson Watt was appointed as Director of Communications Development.

Judged solely in terms of hardware, the latter half of 1937 was a time of success. Cossor produced their receiver, built to Dixon's specification, as a 7ft by 7ft 15 cwt rack. Such a receiver is shown at Fig. 27. This required the demolition of the wall of their covert workshop to ship out[334], but its performance exceeded Bawdsey's expectations. MetroVick were also making progress on a sound and efficient transmitter design with a small group in a secure laboratory[335]; an example of a typical transmitter is shown at Fig. 28. The RAF sectors had had D/F equipment ordered by Dowding, albeit slower than he wished, and from a C3I perspective their operational commands had been crystallised into the "Scramble/tally-ho/ pancake/angels and bandits" jargon[336] familiar from later films.

Finally, from the perspective of chain design, tests were to be carried out over the winter with a mobile station near Dunkirk in Kent (Fig. 22), to pick up and track raiders after they had crossed the coast. This would constitute the first test of the "inland chain" concept, postulated almost three years before by Watson Watt, and it would fail. The reason for the failure was twofold – first, geography such as hills created many non-radar "blips" on the display screen, interfering greatly with the identification of aircraft targets; and secondly the multiplicity of aircraft attackers and defenders in a small area overwhelmed the ability of the operator to read and communicate. It is extremely important, but rarely stated, that for an understanding of the organisation of the overall air defence system of the Battle of Britain, it is essential to appreciate that there were two information streams. First, there were those of the radar chain, which provided plots only out to sea. Second, inland, just as in WW1, the Observer Corps would track aircraft, with all the directly attendant problems of visual tracking in bad weather, darkness, and glare in bright sunlight. From an overall system perspective, there would be consequential issues involved, in recruiting, managing and training a large and manpower-intensive Observer Corps, in resourcing its communications, and in reconciling information at the hand-over at the coast from radar to Observer Corps. The reserve of Dowding, who now had to handle these challenges, to Watson Watt's promises, and Dowding's preparations on a contingency basis, proved wise and well founded.

The Army cell was meanwhile making vigorous progress[337] in developing radar, first of all for shorter-range early warning, and separately for gunnery.

The Army needed mobility, in order to deploy its forces to meet changing tactical situations. By September 1937, a lorry mounted early warning set was almost complete, with a 3Kw. Set on 13 metres giving a 35 mile range, the aerials being mounted on trailer-borne Merryweather towers[338]. This system was tested at Dunkirk, Kent, and was destined to be handed to the RAF as their Mobile Base (MB) radar.

Two ideas were pursued for gunnery control, the first a 6.8 metre, 15 mile range set, then at the experimental equipment stage. This gave only range data, but could be combined with a sound locator giving bearing and height[339]. The War Office was nonetheless gratified with the result, for it would allow guns to be kept at standby rather than action stations[340], and eventually it would be manufactured as the GL (Gun Laying) Mk.1 equipment. The second set was a 1 metre equipment being researched by a joint Army/RAF team under Bowen, who was managing the airborne radar work using similar techniques[341]. This employed a system of overlapping beams derived from airborne designs and described in Chapter V. In November, Dr Paris proposed a third system, for coastal gunnery[342], which once again was destined to become RAF equipment as described in the next chapter. These developments are especially praiseworthy given that the Army's researchers numbered only nine.

The Navy continued its stand-alone research on 43 MHz for much of the year, and produced an experimental set which was fitted on HMS Saltburn ready for tests in 1938[343]. However, developments were moving slowly, and in November C.E. Horton was appointed head of the Signal School with a brief to galvanise this work[344]. Chapter IV will recount the more rapid progress made in 1938.

By December 1937, therefore, Bawdsey's 40 RAF and 9 War Office scientists could show some achievement. Reviewing each of the lines of development in turn, it was true that at the highest level of concepts and doctrine, strategic bombing still held primacy, despite the increasing practicability of defence and the advocacy of Inskip as

Minister for the Co-ordination of Defence. Nevertheless, an ideal air defence scheme had been developed, costed, and (if belatedly) approved. The final move, to reversal of the "bomber deterrent" doctrine, was still in the future, but a radar-based air defence system was now the planning basis for RAF's Fighter Command.

In terms of equipment, the hardware had been specified, secure contractors chosen, and those contractors had begun to manufacture equipment exceeding specification. There were indeed complications and drawbacks - the equipment did not operate inland of the coast, where the Observer Corps would have to cover, nor could it as yet identify friend or foe. To guide the fighters, a different system, radio D/F, would have to be used – but this fact had been identified, the equipment ordered, and air exercises held to test its use to direct fighters. Nothing like a radar chain existed at this point, of course - only three stations, using hand-built, non-standard equipment, tested in exercises but once, and then for an attenuated period of time. Finally, there was an "Achilles heel" of sustainability - despite the fact that the scientists had been aware of "RAF Stores Vocabulary" problems since 1935 at Orford, nothing had been done even now to rectify this. No test equipment had been created, and no maintenance procedures existed.

Infrastructure had been identified as a key issue by Watson Watt, but his design decisions compounded this line of development's two major problems, of site acquisition and of aerial mast construction. Increased numbers of masts, of new and higher design, increased site size and hence acquisition problems. The faithful Wilkins would spend much of the winter trying to locate such sites and manage design of the towers[345], for Watson Watt had for security reasons insisted on no outside involvement, such as might have come from Marconi's.

The human resource lines of development – staffing, organisation and training - were bearing fruit – operators and mechanics were being selected and trained, and Hart's school was working to a standard syllabus. The Biggin Hill experiments had stimulated training of the pilots in ground control and in interception technique, and a standard vocabulary now existed. However, the Biggin Hill tests had not been linked to radar plots, there were only two control rooms and one experimental filter room, and control and filter room staff were neither selected nor trained for their tasks- they simply were ordinary airmen with an extra job.

Communications were beginning to receive attention. Dixon had been asked to look at automating information passing from the radar plots, and Dickens at Biggin Hill had made useful recommendations on ground-to-air information passing. The Farnborough-designed TR9 short-wave airborne transceiver[346] was being developed into a useful if limited piece of equipment. As significantly, during this year RAE began a major initiative into VHF (100-130 MHz) ground/air/ground communication[347]. VHF, with its smaller aerials, was aerodynamically suited to faster aircraft, and being essentially line-of-sight in range, was more secure from interception than high frequency communications. A new team was recruited, largely from GEC, directed by Bartlett, head of their radio group. Located just outside RAE's perimeter wire, this team would produce within 24 months the entire ground and air components of a VHF communications system. In 1937, however, people formed a greater part of the C3I system than technology – equipment was in design, not production; telephone lines had been ordered, but not yet delivered, and most control rooms (and all filter rooms) had been conceived, but not yet been built.

Day Air Defence Lines of Development Position at 31.12.1937.

Progress in 1937 had been significant, although essentially that "progress" was delivering what had been promised for 1936. The Biggin Hill experiments had now identified interception arrangements in sufficient detail for concepts and doctrine of air defence to be seen as credible, and for it to be generally perceived that, in the RAF, radar, CRDF and ground control by R/T could work well enough together regularly to achieve a daytime interception capability. The extension of CRDF across Fighter Command was a manufacturing and installation challenge, but, as being known technology, did not form a huge leap in human terms.

The inability of Chain Home to detect low-flying raiders was now at last recognised as a problem, and the winter 1937-8 "inland radar" experiment at Dunkirk, Kent would very soon identify the need for the Observer Corps to be fully integrated within the system.

Likewise, the tests of Watson Watt's simplistic IFF "solution" were proving disappointing, and work on the eventual solution would begin in 1938.

During 1937 the national radar chain achieved what today would be called its "Main Gate" approval.

31.12.1937	CH	CHL	OC	CRDF	IFF	R/T
Doctrine & concepts						
Equipment						
Infrastructure						
Sustainability						
Personnel						
Organisation						
Training						
C3I						
Interoperability						

Table 3. Radar-based day interception capability: summary position at 31.12.1937.

III.9. Summary and Conclusion.

Technological and military histories have often presented the progress of radar from its inception in 1935 to the end of 1937 as an unstoppable revolution underpinning UK air defence[348]. In this chapter, the wider perspective of the total acquisition process has shown that radar, as one sensor in an air defence system, was a temperamental, partly understood device with significant flaws, which had failed in tests before VIPs, which was being introduced by individuals with varied professional experience and very human failings, and which was subject to the vagaries of political interference, contending Committees, personality clashes, Treasury constraints and "Works and Bricks" delays. As such, it resembles many major more recent acquisitions[349].

Doctrinally, 1930s radar was a defence tool. As such, it held no absolute priority, for deterrence through the strategic bomber was the primary doctrine of both Government and RAF throughout this period – "the bomber will always get through". Even at radar's conception, before the Daventry experiment of February 1936, Dowding, then "Equipment Capability Customer", had demanded an assurance that radar could be applied offensively. In 1937, as “Core Leader”, his “ideal air defence” plans still stated that any war would ultimately be won by air offence. The break-up of ADGB, creating Fighter Command, resulted not from a doctrinal revision, but from an excessive span of control. The “bomber deterrence” doctrine was certainly under question, partly because it was visibly failing and partly because the public demanded visible defence, but that pressure was not absolute. Baldwin, then Chamberlain, viewed military spending in the light of the depressed economy and of competing social programmes. Radar offered them, for the first time, a concept of practicable defence – both the potential for interceptions over the sea before aggressors reached the coast, and also economy in the use of defending aircraft. This economy arose because previously, aircraft had to fly “standing patrols” – that is, to fly circuits along a particular track, hoping that an interception would occur. With early warning and location of the enemy, aircraft could take off later and fly directly to a favourable interception point. This resulted in crews not becoming tired out, in less fuel usage, and less wear on engines and airframes. Therefore, radar was a reasonable technology for investment, and when the results were promising, the Treasury did not refuse this[350]. Technologically, financially and politically, spending on radar became increasingly realistic and acceptable, but never in the smooth and unhindered way often portrayed.

In an analysis of personalities and the organisations in which they served, two factors are readily apparent. First, not a single person was in the same job at the end of 1937 as he had held in 1935. Tizard is just possibly an exception, albeit his “job” was an unpaid part-time advisory role, from which he had twice threatened to resign. Second, the planning and overview mechanisms – in particular, the CID, and the RAF’s planning processes – held constant, while the operational structures – ADGB, Fighter Command – changed completely.

The personalities may be reviewed in three categories – the airmen; the scientific planners; and the scientists. Of the airmen, Dowding moved from AMSR to AMRD to Fighter Command, Freeman from operations to AMRD, Douglas from operations to Director of Staff Duties, and Joubert from the ADGB Fighting Area to Coastal Command. Among the “scientific planners”, Tizard, Hill and Blackett were still

CSSAD members, albeit Hill and Blackett had resigned and been brought back. Lindemann joined CSSAD, then resigned, and was replaced by Appleton. Wimperis, who had suggested the CSSAD, had retired and been replaced by Pye. Among the scientists, Watson Watt had moved from the DSIR to the Air Ministry as Bawdsey's Superintendent, Rowe had moved from DSR staff to Deputy Superintendent, and of the early pioneers only Wilkins, Bowen and Airey were left.

Of the organisations they represented, the CID, and its ADRC, had survived the attacks of Lindemann and Churchill. This resilience was due in some part to the efforts of Swinton as Secretary of State, and Inskip as Minister for the Co-ordination of Defence. By December 1937, neither survived, for Swinton had been replaced by Kingsley Wood, and Inskip's co-ordinating post had ceased to exist. The CID's research arm, the CSSAD, began life outside the CID, but was soon absorbed and legitimised by it. The CSSAD controlled the research programme, first of Orford then of Bawdsey, through the Air Ministry's DSR, Wimperis. Within the CID's operational arm, the move of responsibility for air defence from ADGB to Fighter Command helped focus the defence structure, and Dowding had acted to give his role integrated operational control of the whole system, from sensors (radar, Observer Corps) through its nervous system (control and filter rooms, telephone links and ground-to-air radio) to defence weaponry (fighters, guns, searchlights, barrage balloons, air raid warnings).

The airmen had provably brought their experience and planning structures to the acquisition of the radar-based system. Dowding, for example, involved for many years in training, proposed the Bawdsey Training School in 1936, and contributed greatly to the Biggin Hill experiments. Freeman, as AMSR, paired the experienced negotiator Leedham with the volatile Watson Watt in visiting potential contractors, and oversaw that entire activity. Tizard and Wimperis, both pilots as well as scientists, identified and proposed pilot and ground control training with the new techniques in the Biggin Hill experiments, and secured a scientific observer to guide that process. Noticeably, none of these complained of problems with "Works and Buildings", nor with recruitment, for the system was well-known to them. By contrast, Watson Watt, the outsider who had managed only one, minor, research establishment, totally over-committed in his

September 1935 proposals, spent time on trade union matters unconnected with his already over-stretched workload, and then occupied yet more time in debating his own advancement and in finding scapegoats for failure, rather than improving his own time- and skills- management. His methods worked well in motivating a small team of scientists at Orford or Bawdsey, but they were a disaster in operational trials in 1936, lay behind the frequent descoping of the radar chain in 1936-7, and they would almost wreck the radar chain in 1939-40.

Training, of operators, maintainers and pilots, was as we have seen in capable hands. Hart's structured approach (an aspect of his background, as of all the airmen) had begun producing the ground operator staff while the Biggin Hill experiment trained the pilots and controllers. The unaddressed components – fighter controllers and filter room staff – would create problems in 1940.

The technology, in the sense of the radar equipment which would fight the Battle of Britain, was essentially designed and built by two private contractors, MetroVick and Cossor, to Bawdsey specifications devised by Dixon, a GPO engineer. There is debate on whether an earlier involvement of private contractors would have expedited the process[351], but the security of the project would then certainly have been at risk. What is more surprising is that industrial assistance was not sought on non-security items. Manufacturing aerial feeder from copper pipe is hardly a security risk if outsourced, or an effective use of a Superintendent's time if carried out in-house, even if Watson Watt was of the view that his doing so encouraged his staff. Against this, the use of contractors was not always helpful – Harland and Wolff's, and then Elwell's construction of aerial masts, were significant failures.

It has repeatedly been observed that the whole question of sustainability was never given thought. No attempt was made to design test equipment, or even to ensure that spares were available through the "RAF Stores Vocabulary", even though the scientists were aware of the problems that this might cause. The issue would eventually almost silence the radar system in 1939.

Structures had also shown themselves to be a significant issue in these early years, and again the warnings were ignored. Radar itself needed few structures to house it – huts, or simple brick or concrete buildings. However, acquisition of the land on which they stood, and construction of the aerial masts, were major problems. It is possible that the ease of entry to Orford, already a Ministry site and well-known to Tizard, gave a misleading sense of lack of problems. Likewise, on aerial masts, Watson Watt, through the inventive and capable Joe Airey, had experienced no problem with their building at Slough, and anticipated none at Bawdsey. Once the issue began to surface in Winter 1935/6, Watson Watt's only response, letters of complaint about a Works and Buildings function already struggling with a massive airfield construction programme in Eastern England, was merely unhelpful. Unfortunately, subsequent design changes, which tripled the numbers of masts and so increased site sizes, compounded the problem.

Communications in the physical sense was an area where the radar-based system could rely on much previous work. Once it was decided that ground communications could not be by radio (inherently insecure) or teleprinter (too slow), the prime requirement was telephone lines, and these had been identified as a long lead-time item since WW1. An existing CID Committee therefore handled this area with the GPO. RAE Farnborough was already working on the high-frequency ground-to-air equipment (the TR9) and now began work on VHF (TR1133). The Bawdsey scientists also set about automating information handling and passing, but there would be many false starts before this was partly achieved, by GPO help, as late as June 1940.

Overall, the history of the acquisition of the radar-based air defence system in this period reinforces the value of a formal acquisition process, for it clearly illustrates the dangers of reliance on individuals' experiences, which may be partial, and certainly are accompanied by personality issues. The acquisition process of 1935-7 was almost, but eventually not, wrecked by Churchill and Lindemann's political-level assault. It was also visibly damaged and delayed by Watson Watt's lack of programme management level skills and experience, and by his personality defects.

In the case of Churchill and Lindemann, it is the case that Lindemann was primarily concerned with night bombing, where he saw little being done – and, as will be shown in Chapter V, his assessment was correct. His obsession with aerial minefields and infra-red detection may today seem bizarre, but when the CSSAD's own remedy was to illuminate electrically the entire UK cloud base under their "Silhouette" scheme, it appears less so. Nonetheless, Lindemann's joint assault with Churchill was wholly destructive, and repulsed only by Tizard's spirited rebuttal when ambushed in the ADRC and by Tizard's support from Swinton and Inskip.

The case of Watson Watt is more complex. His vision in writing the earliest memoranda describing a radar-based air defence system, including such concepts as IFF, was unique in the world at this time. At the earliest stages of the project, his boundless enthusiasm and missionary zeal undoubtedly inspired his own team and indeed many of the co-workers (such as Rowe) and Service leaders (such as Joubert) with whom he came in contact. His personality was, therefore, almost ideally suited to this life stage of the programme. Against this, as programme management rather than research became involved, his time management was truly dreadful - energy spent on trade union matters, on personally making aerial feeders, and on negotiating his own salary and status, would certainly have paid greater dividends if allocated to improved project management, or if not that, then to recruitment, infrastructure (site purchase, aerial construction), and stores issues. His over-commitment in 1935, and disastrous demonstration in 1936, almost caused cancellation of the programme. It has been shown above that, even when he knew that this demonstration could not be ready in time, he was working with Lindemann and Churchill to ambush Tizard. As 1937 closes, Pye as DSR is proposing Watson Watt to be the Director managing the entire radar chain construction as well as research. The next chapter will illustrate the damage this caused.

As regards other personalities, the thesis has so far examined only the first half of one, successful, acquisition, and it is not appropriate to draw conclusions at this stage. It might be noted, however, that Dowding and Tizard formed an easy working relationship, as also did Churchill and Lindemann; and that relationships between Lindemann and Tizard had descended to open warfare, while those between Dowding and Watson Watt were becoming distant. Each of these relationships and personalities would create difficulties in later acquisitions, as will be seen.

Before examining radar's progress in 1938-40, it should be repeated that radar in December 1937 could provide only very modest assistance to air defence. There was nothing as yet to aid the night battle, nor indeed a battle fought on days of cloud or bad weather, nothing to help against low-flying aircraft, to aid guns or searchlights, or to tell if an aircraft was friend or foe, nothing of any use inland of the coast, and only three coastal stations, concentrated in the Thames approaches. The radar chain was merely approved, not yet built, factory equipment was being delivered and was excellent, but the only live tests had been made with hand-built non-standard equipment. Nevertheless, and thanks to the experiences and disciplines provided by the airmen and the planning scientists, the overall air defence system was present in concept, capable of realisation, and financially approved. Its broader components (D/F, interception technique, communications, and control rooms) had been the subject of live trials, and the staff for radar were being selected and trained. This study now examines the later stages of acquisition, and the successes and failures which the Battle of Britain would reveal.

. III.10.
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242. David Zimmerman, op. cit., pp. 93-4.
243. TNA/PRO AIR 2/2664.
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314. TNA/PRO AIR2/4488.

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III.11.

FIGURES.

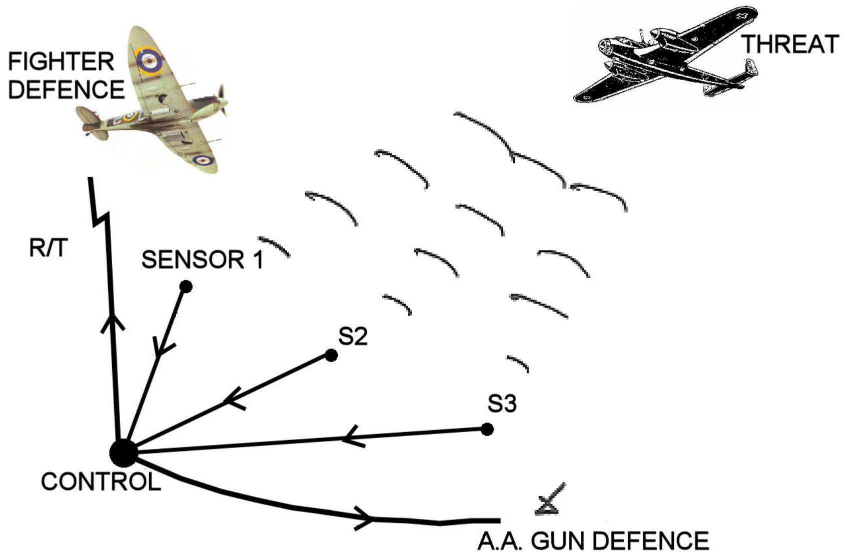


Fig 1. Generic simplified air defence system. (Author).

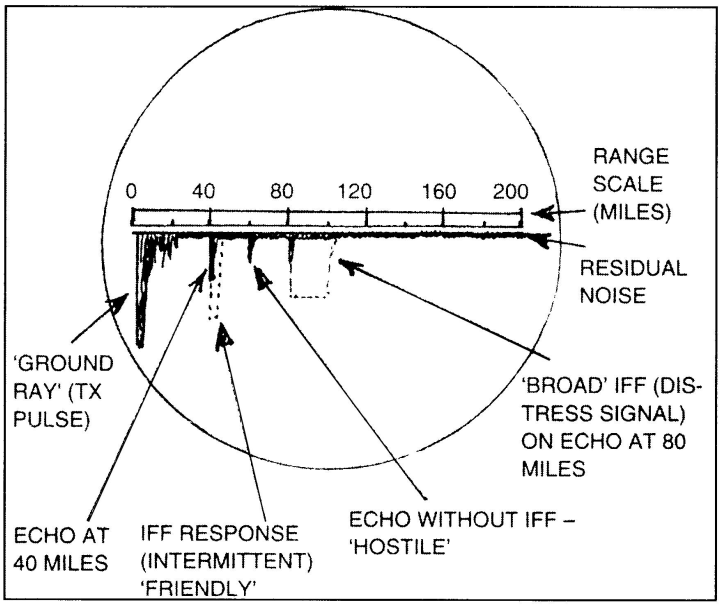


Fig 2. Chain Home display – range only (today called an "A-scope display)
(Colin Latham and Anne Stobbs, *Pioneers of Radar*, Stroud: Sutton, 1999, p.25).

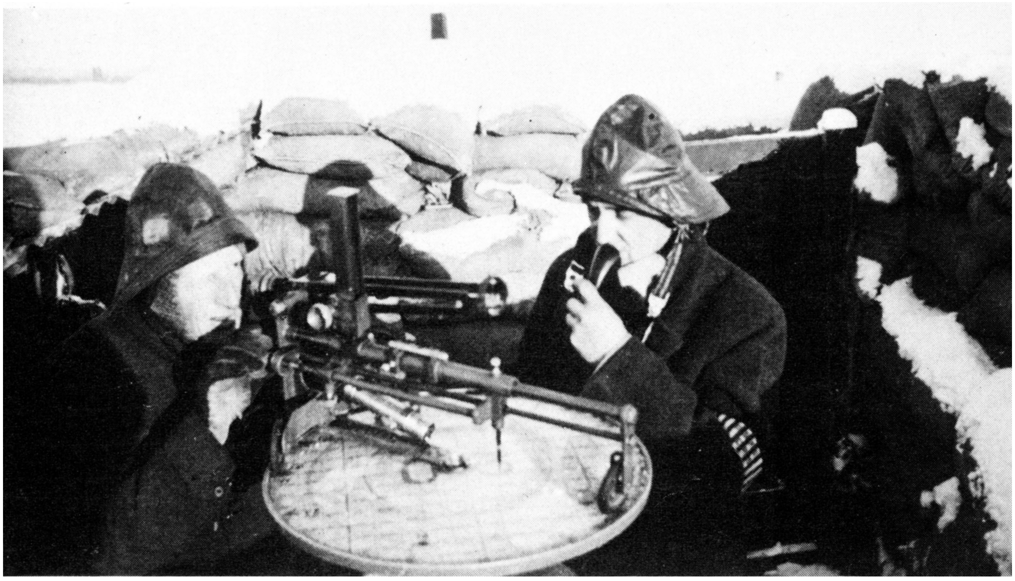


Fig 3 Observer Corps post 2/O.2, Pulborough, Sussex: Winter, 1939/40. Note the relative crudity of the sighting instrument and the fact that the post is open to the snow. (Derek Wood, *Attack Warning Red*, London: Macdonald and Jane's, 1976, opp. p.84).

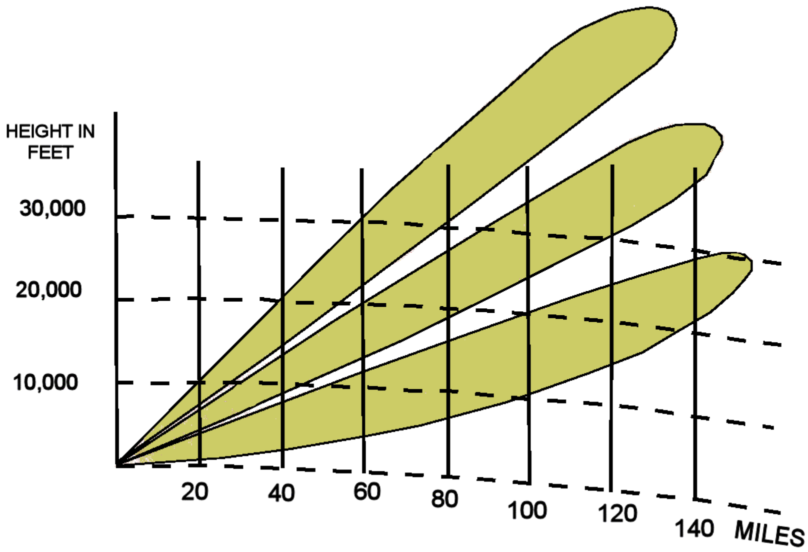


Fig 4. Chain Home lobes: the curvature of the horizontal axis represents the contemporary manual's attempt to show the curvature of the earth. In this case an aircraft travelling at a constant 20,000 ft. would be detected by Chain Home at 135 miles, lost at 100 miles and reappear at 80 miles, be lost again at 60 miles and reappear once more at 55 miles. The operator's need for skill and attention to cope with these screen appearances and disappearances can readily be deduced. (TNA/PRO AIR 10/3758).

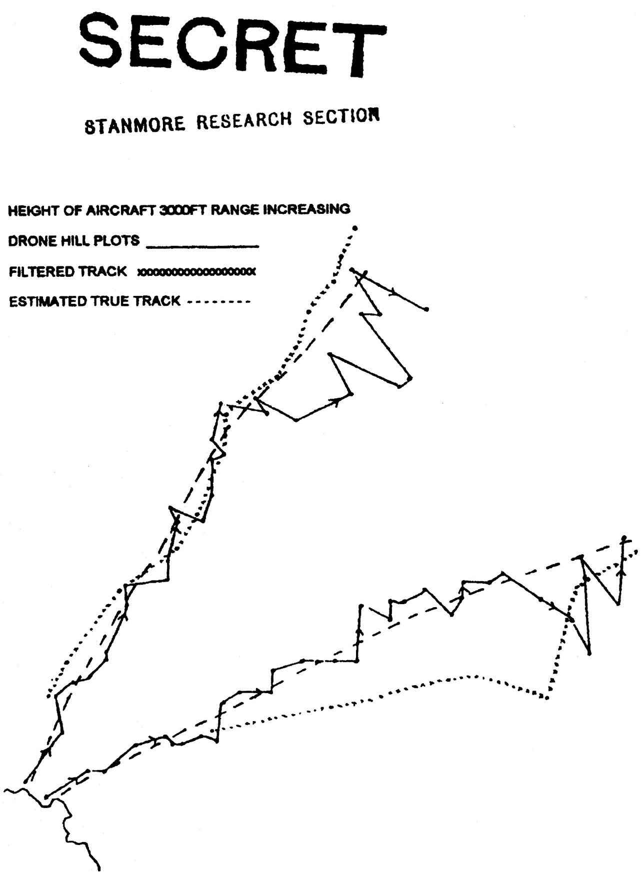


Fig 5. Chain Home calibration results for Drone Hill – the discrepancies from the aircraft's true track can readily be seen. (M. Bragg, *RDF1*, Paisley: Hawkhead, 2001, Plate XIX).

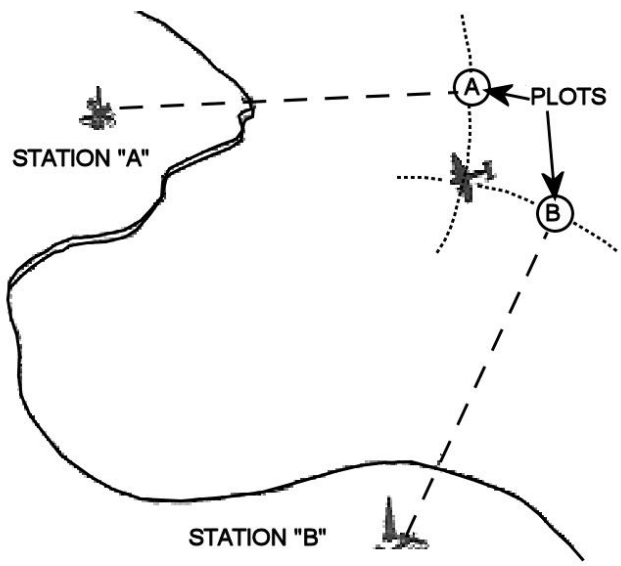


Fig 6. The result, from a contemporary manual – adjacent stations give two different plots for the same aircraft. This, together with the lack of IFF, is the reason for the importance of the Filter Room. (TNA/PRO AIR 10/3758).

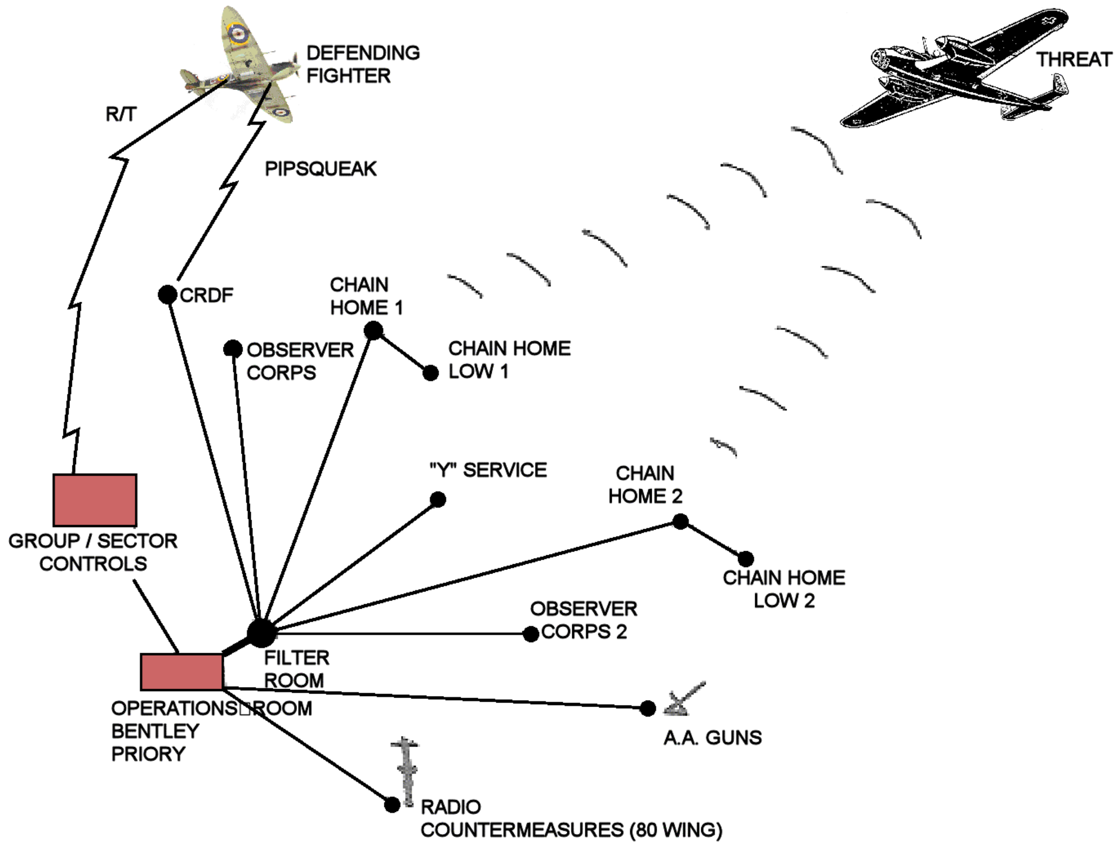


Fig. 7 Diagrammatic representation of the UK's 1940 air defence system. (Author).

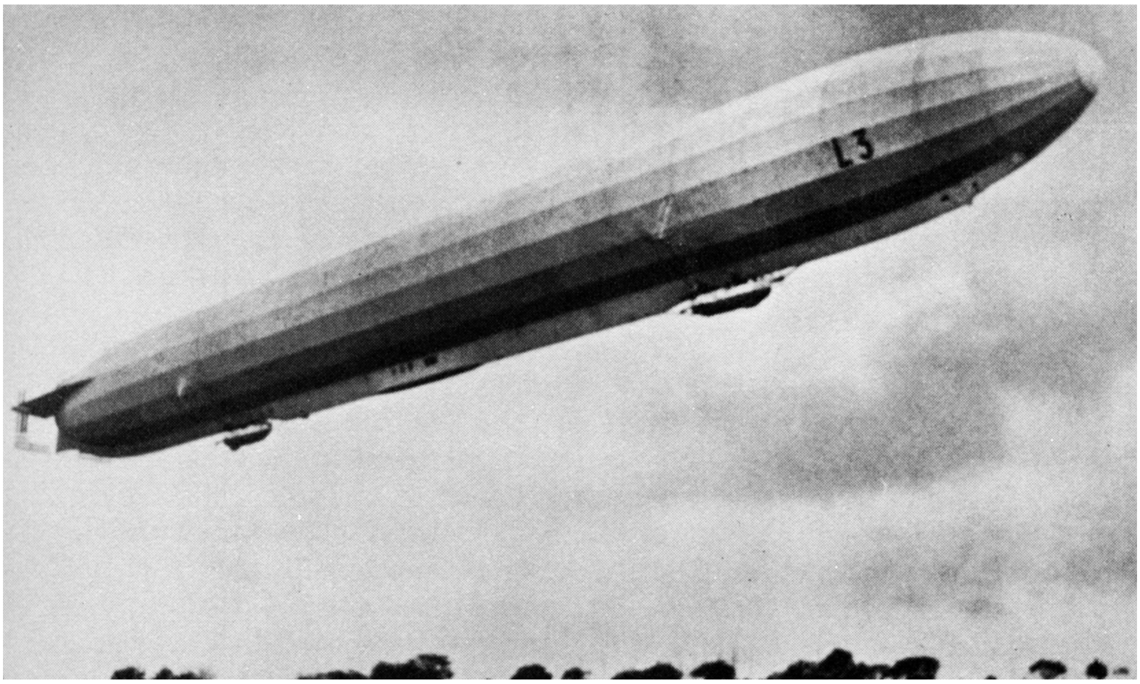


Fig 8. Zeppelin dirigible: the scale of the airship and its slow speed caused this target to be easily acquired and held by searchlights. (Christopher Cole and E.F. Cheesman, *The Air Defence of Britain 1914-1918*, London: Putnam, 1984, p.25).

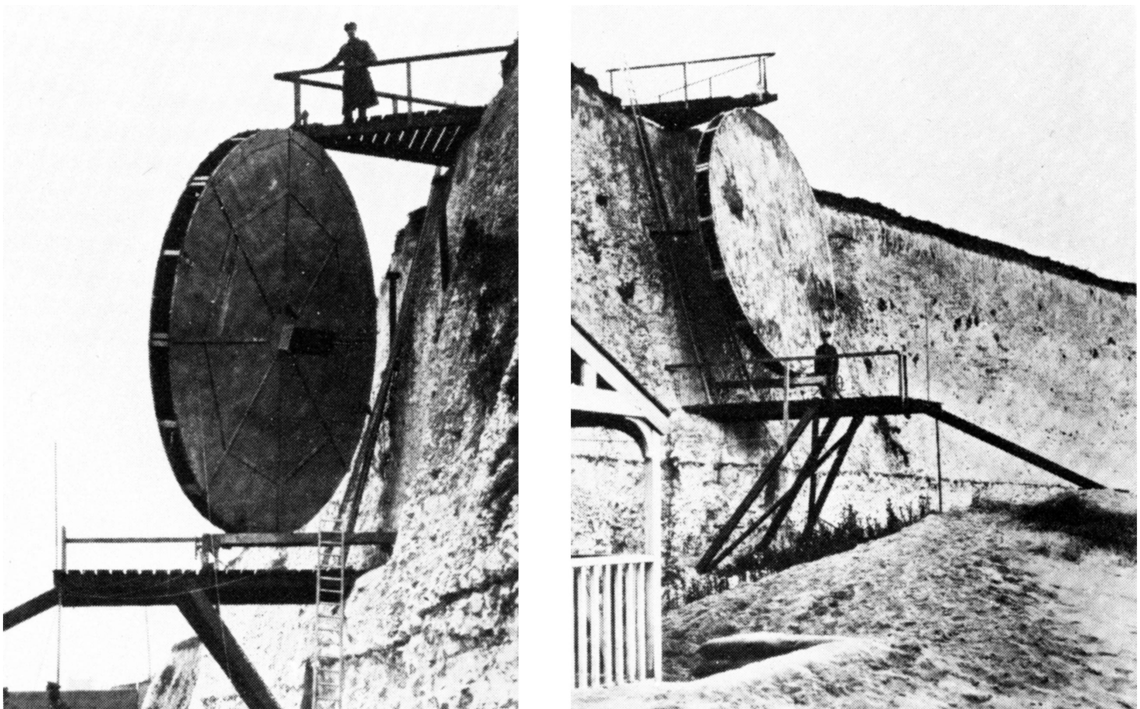


Fig 9. The "sound mirrors" at Joss Gap: acoustic early warning for slow-moving air attack.(Christopher Cole and E.F. Cheesman, op. cit, p.315).

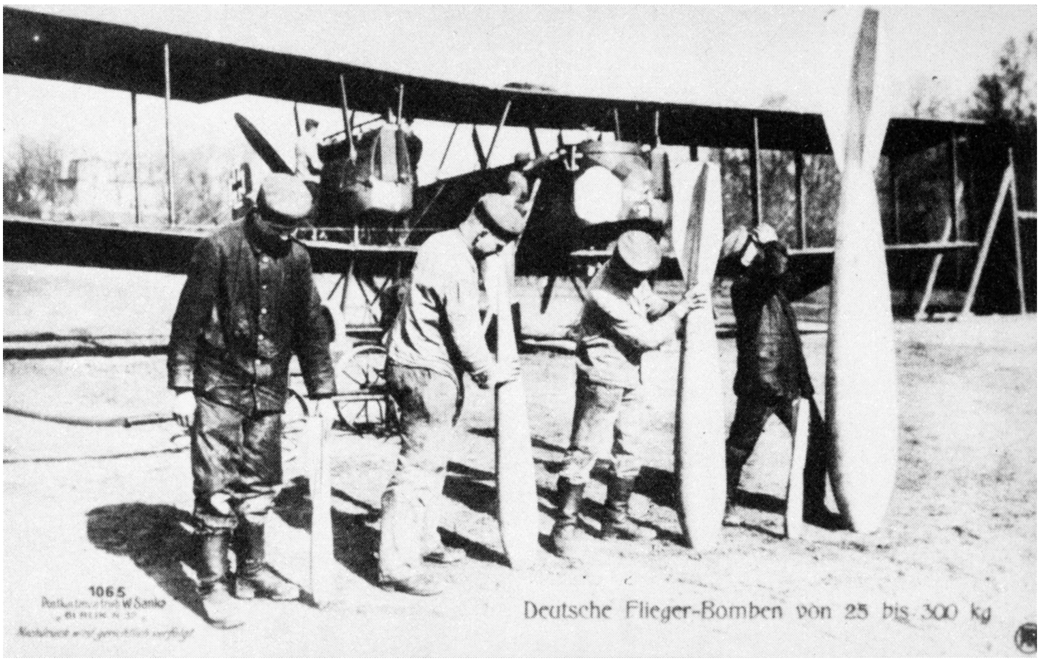


Fig 10. Contemporary postcard illustrating the WW I Gotha bomber and examples of its bomb load. (Christopher Cole and E.F. Cheesman, op. cit, p.426).

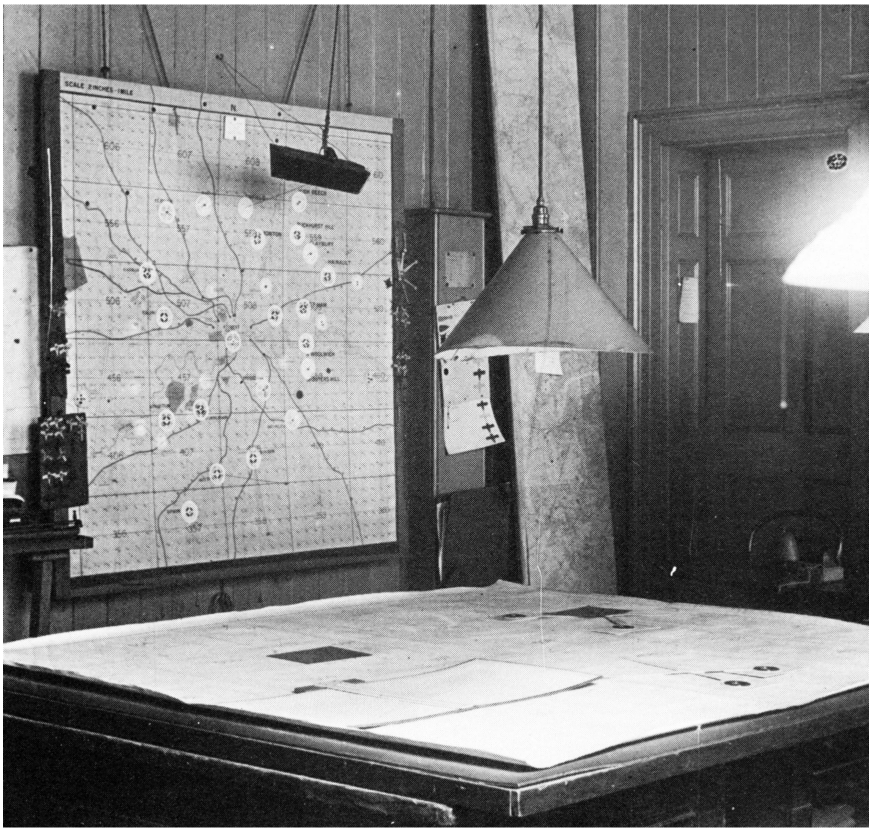


Fig 11. Contemporary photograph of 1918 air defence sub-control room (Christopher Cole and E.F. Cheesman, op. cit, p.456).

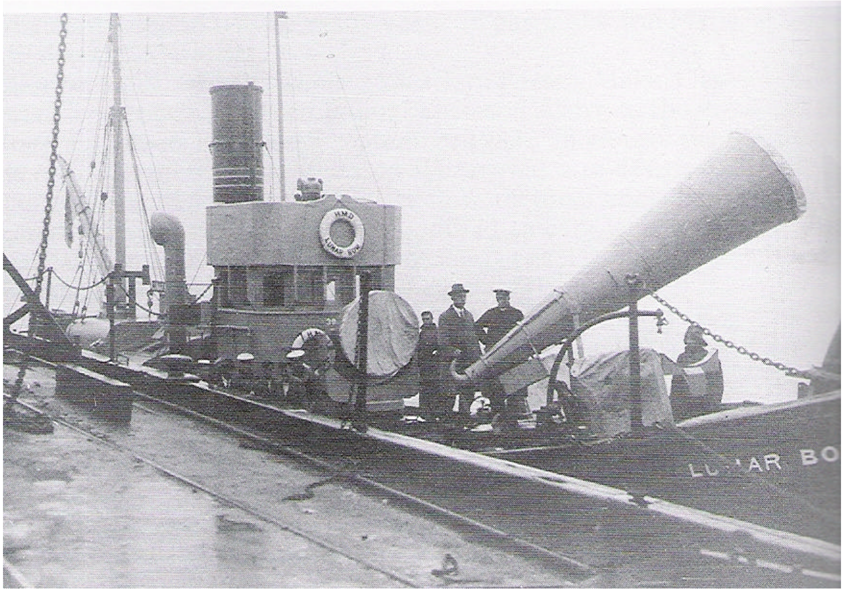


Fig 12 H.M. Drifter Lunar Bow in 1926, mounting a sound collector for acoustic detector tests at sea, intended to give long-range early warning. (Richard N. Scarth, *Echoes from the Sky,* Hythe: Hythe Civic Society, 1999, Plate 32/ Crown Copyright).

Fig 13 The sound mirrors at Denge, today under threat from shingle extraction. (Michael Bragg, *RDF1*, Paisley: Hawkhead, 2001, Plate III/ Charles W. Snowden).

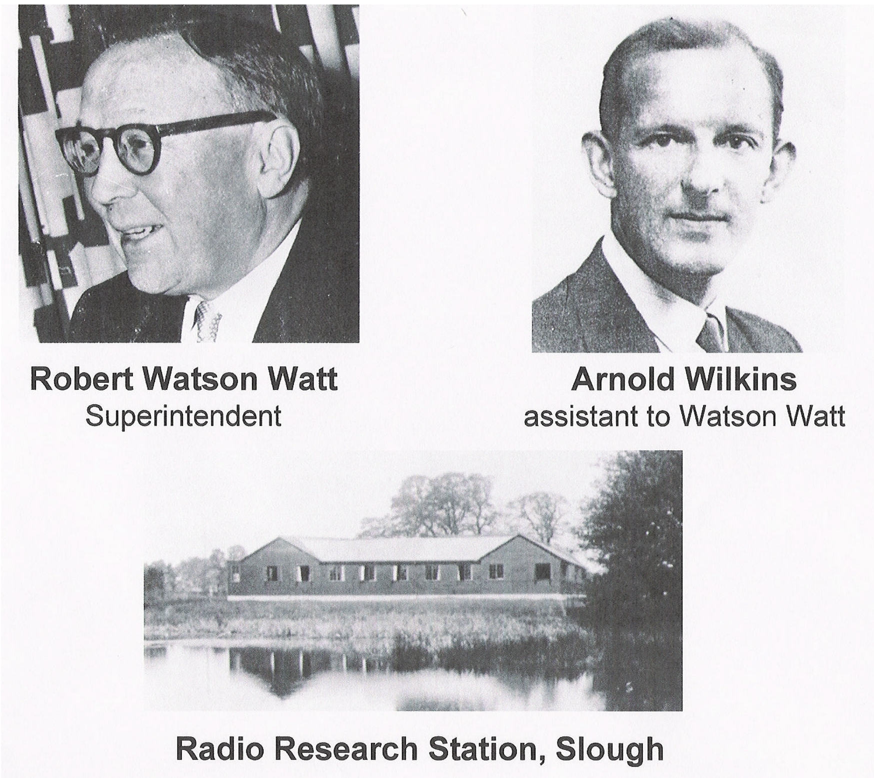


Fig 14. The Radio Research Station at Slough in the 1920s, with Robert Watson Watt, the Superintendent, and Arnold "Skip" Wilkins, his assistant. (Penley Archive A/19).

Fig 15 The Committee for the Scientific Study of Air Defence (CSSAD) known popularly as the "Tizard Committee". (Penley Archive A/17))

Fig 16. Frederick Lindemann, later Lord Cherwell. (Adrian Fort, *Prof*, London: Jonathan Cape, 2003, Fig. 1).

Fig 17. Air Marshal Sir Hugh “Stuffy” Dowding. (IWM D 1417).

Fig 18. Reconstruction of the “Daventry experiment”. The only artistic licence is that the Daventry short wave station, here just visible on the left horizon, cannot in fact be seen from the site of the experiment. (“The First Step” by Roy Huxley, BAE Systems)

Fig 19. One of the huts at Orford Ness used for radar experiments. (Fisher Archive)

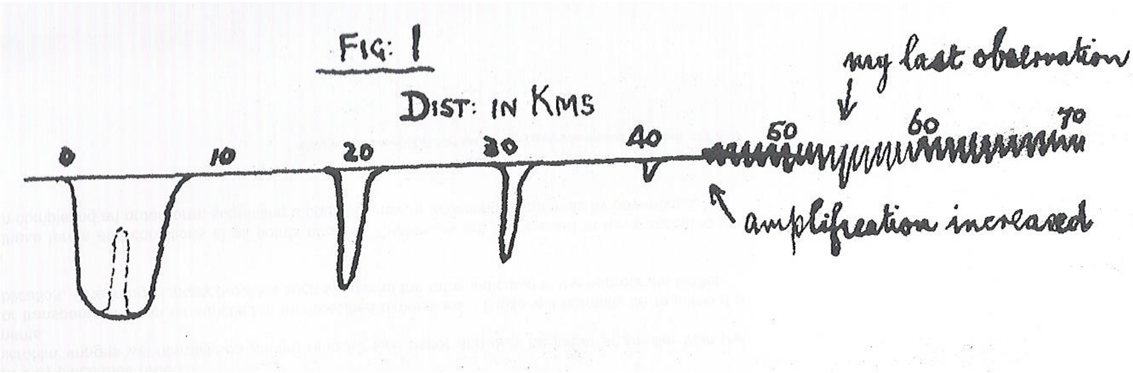
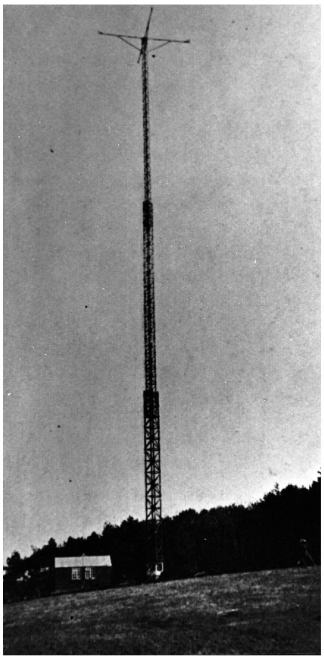


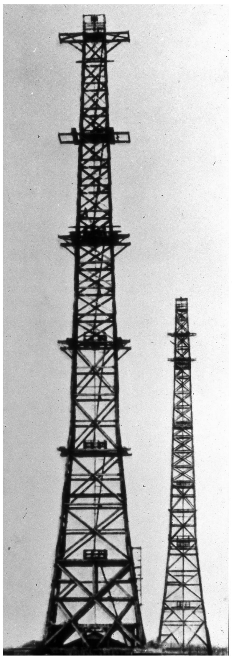
Fig 20. Rowe's sketch of the radar trace, July 1935. (TNA/PRO AIR 20/145).

Fig 21 Bawdsey Manor. (Penley Archive, A/30).

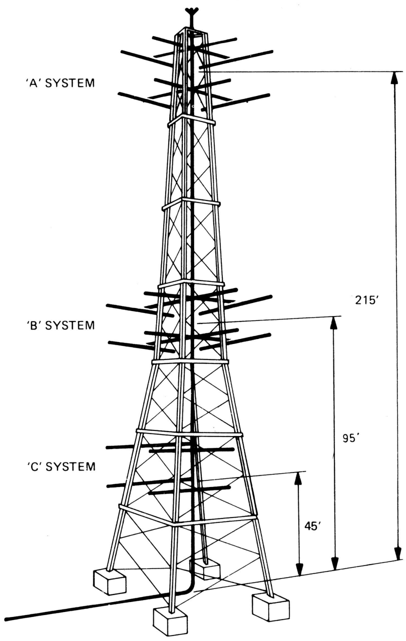
Fig 22. The Thames estuary chain as eventually constructed. (Colin Latham and Anne Stobbs, *Pioneers of Radar,* Stroud: Sutton, 1999, p.23).



250 foot Receiver Mast



240 foot Receiver Tower



Receiver Aerials

Fig 23. The masts problem. Watson Watt had found no difficulty in building extending masts (top left) but the heavier radar aerials required new, massive, structural designs (centre) which consumed vast quantities of seasoned wood. The aerial feeders which ran up the centre of the 240-foot masts can be seen upper right. These were made by hand in 16 foot sections and joined in situ by blowlamp; they gave endless trouble. The same task had to be performed for the 360 ft. transmitter masts. (Penley Archive, A/31).

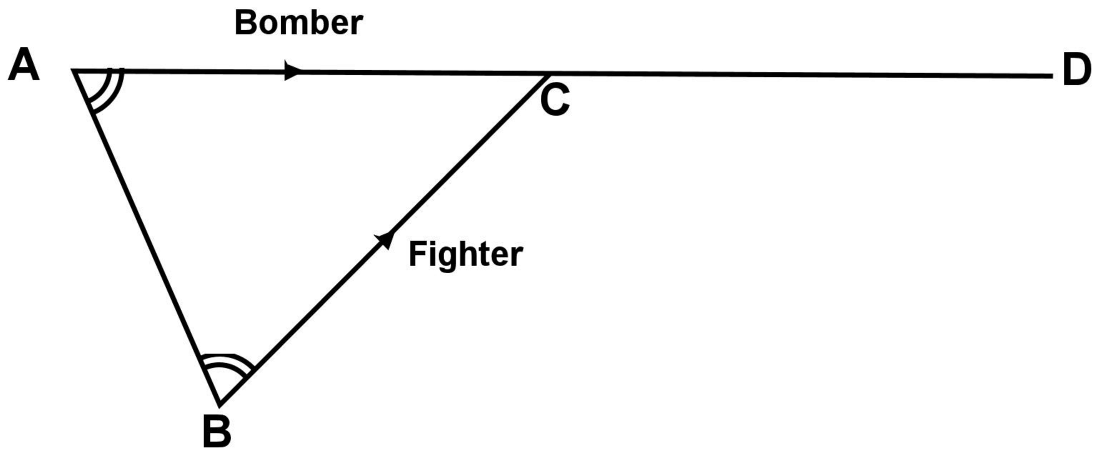


Fig 24 The “Tizzy angle”. When bombers at A on course AD, and fighters at B, are plotted, the Biggin Hill experiments showed that it was sufficient to visualize mentally an isosceles triangle ABC and use this to vector the fighters to meet the bombers at point C. (Maurice Kirby, *Operational Research in War and Peace,* London: Imperial College Press, 2003, Fig. 3.1).

Fig 25. The 1939/early 1940 Fighter Command Operations Room, converted from the ballroom in Bentley Priory. (Imperial War Museum, MH27893)

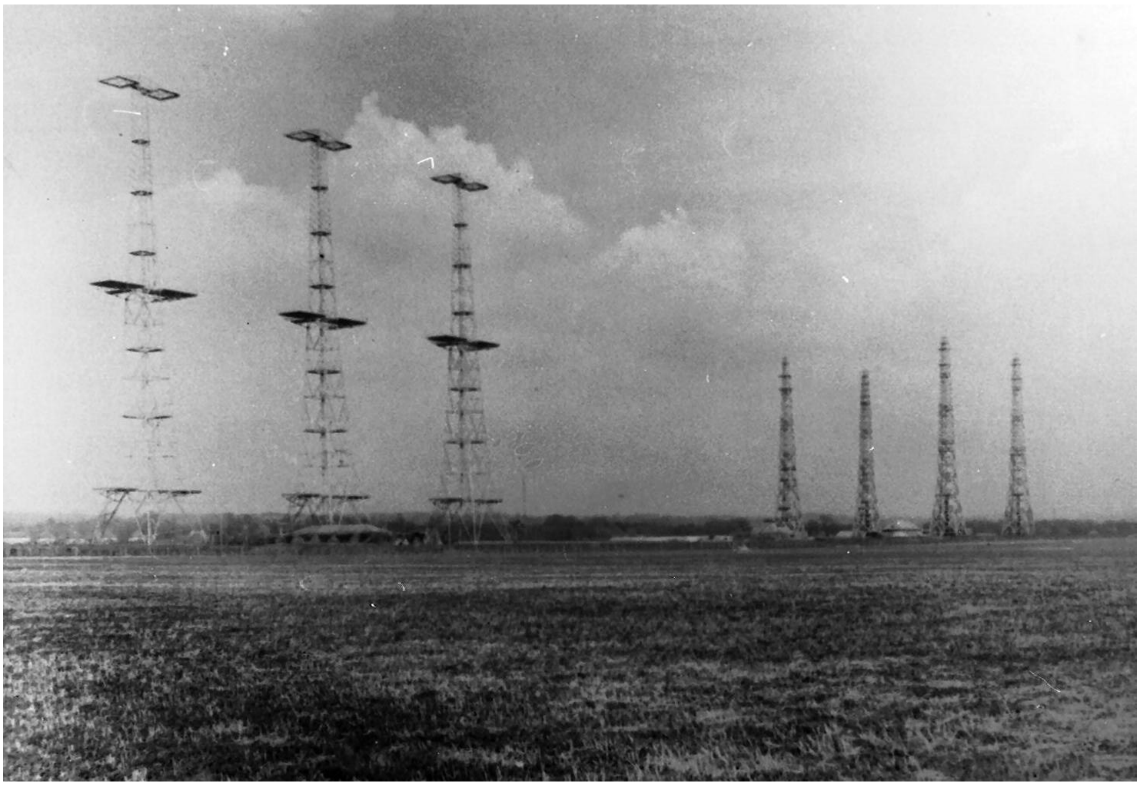


Fig 26. The scale of the new mast arrangement, 1937. (Imperial War Museum, CH 15173).

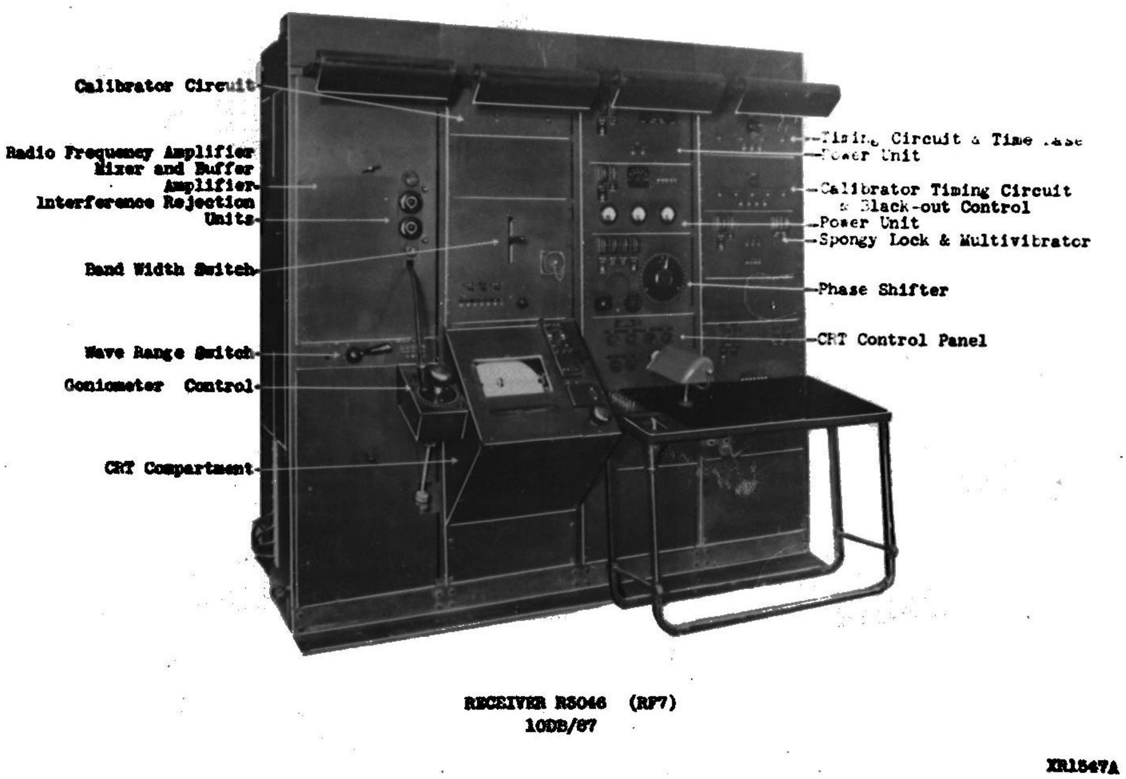


Fig 27. Cossor Chain Home receiver RF7. (BAE Intsys).

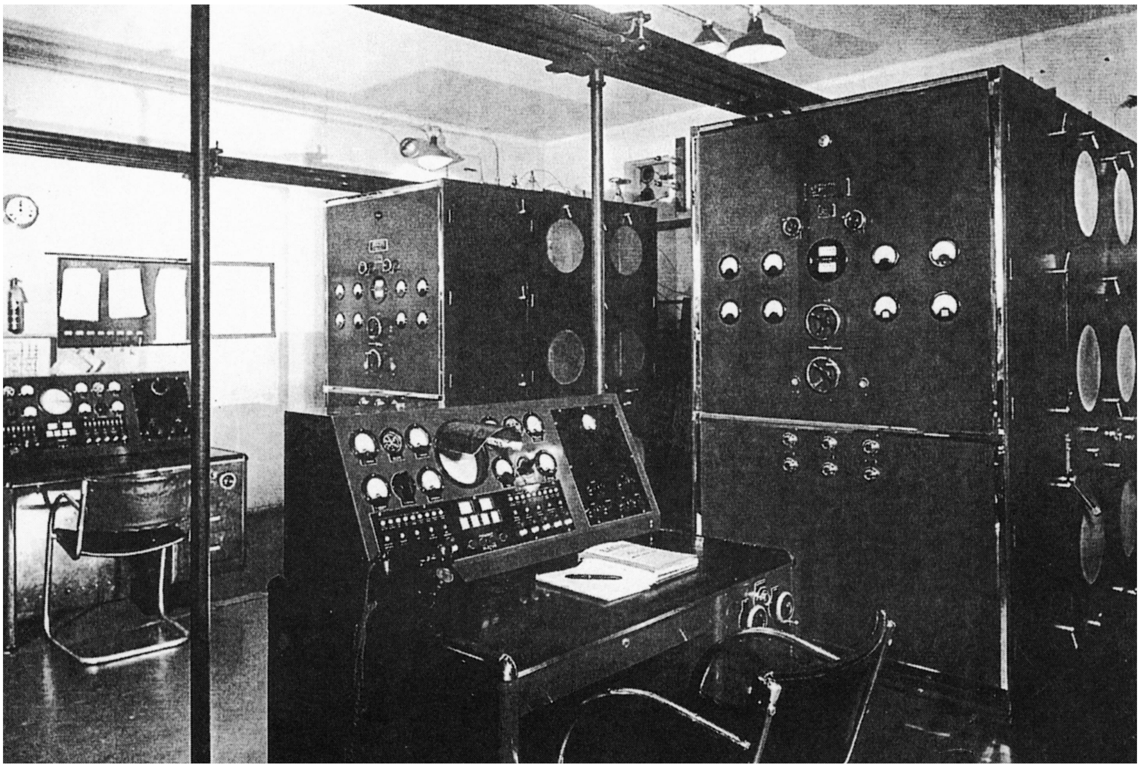


Fig 28. MetroVick Chain Home transmitter, power amplifier stages. (TNA/PRO AIR 16/935).

IV.

ACQUIRING RADAR FOR THE DAY BATTLE

THE SECOND 1,000 DAYS: 1938-1940

IV.1. Introduction.

In analysing the first 1,000 days of the acquisition of a national radar-based defence system, Chapter III concentrated upon the process of crystallising the rudiments of a system for early warning of, and controlled defence against, air attack, from a vision supported only by elementary mathematical calculations. This had involved a "proof of concept" test, the establishment of a secure research facility, the rapid production of equipment of ever higher technological readiness levels, and the development of embryonic information handling, display, communication and tactics for defence based on radar warnings.

The second 1,000 days concentrated upon the acquisition of the specific system which withstood the Luftwaffe's air assault in the Battle of Britain. This could not have been set in place without the earlier research, but it will be shown that radar's performance in battle was far from the smooth excellence implied in many histories of the period[1]. However, it will also be shown that the equipment's many deficiencies were made good by the human resource - people filtering information, acquired not only by radar, but by signals intelligence (SIGINT) from the RAF "Y" Service, and by the Observer Corps' visual reports. Credit should be assigned as much to the acquisition of this total interoperable system as to the radar hardware itself. The successful refinement of the entire system owed much to the emerging science of Operational Research, developed in parallel with radar, to identify the optimal structure, to the recruitment in particular of women to staff it, to speedy training, and to effective information handling and communication.

This success at the operational level contrasts with significant issues of personality at the command and programme management levels. In terms of personality, the unstructured ebullience of Watson Watt was not suited for the hard "detail in breadth" of programme management. His life experiences in small groups of scientists had not prepared him for major projects; and his deficiencies would become glaringly apparent as the radar chain faltered in the first weeks of war, a failure triggered by his neglect of sustainability, and specifically of spare parts and maintenance. Rapidly moved sideways into the advisory role of "Scientific Adviser on Telecommunications", he would live out the war on the sidelines as a middle manager honoured for his past rather than his present. His former job was divided into three, of which he retained one-third; his replacement as a Director, Sir George Lee, the retired Chief Engineer of the GPO, was well used to major programmes, and his replacement in dealing with manufacturers was G/Capt. Leedham, who was referenced in Chapter III as being chosen for his long RAE wireless experience to perform this role when ordering the first radar sets.

The organisation of radar, more precisely whether filtering was to be located at Group or Command level, would become a *cause celebre* between two senior airmen – Dowding as C-in-C Fighter Command, and Joubert, returned from India[2] and representing the Air Ministry because of his earlier experience with radar. The use of radar by the British, and the employment by the Germans of radio-navigation, would also become another of the battlegrounds between Tizard, radar's champion, and Lindemann, Churchill's scientific eminence grise, following Churchill's return to government on the outbreak of war. After Tizard resigned in June 1940, the combination of the lack of scientific support for Dowding, the "Filter Room Debate" and the lack of effective radar for the night battle would increasingly be key elements in ending Dowding's career.

In terms of acquisition theory, the story of radar in this period illustrates a clear series of lessons regarding those lines of development which relate to equipment, infrastructure and sustainability, in that where these were taken into account, the radar-based defence system functioned effectively, and where they were ignored, it failed. The specific problems of spare parts and maintenance have been mentioned above. To these should be added the infrastructural questions of acquiring suitable sites, and of planning ahead to source sufficient wood for the aerial towers. Most serious of all is an issue hardly ever mentioned in accounts of the Battle of Britain – the calibration and phasing of the aerials of radar stations. This time-consuming activity was essential to their effective operation, and had to be repeated every time the scientists made changes to the radar equipment, which was often. When this was not done, the plots given by the radar were either misleading or completely illusory. On 1 August 1940, for example, the South Coast stations of Ventnor, Poling and Pevensey could not give accurate bearings on raids, and the first two, together with Dover, could not give accurate height[3]. It will be shown that at least a part of the problem depended upon a single inexpensive component – aerial insulators – and that attempts to economise here almost created a classic "for the want of a nail, the battle was lost" scenario. Fortunately Dowding's system also took information from signals intelligence and the Observer Corps, and fortunately again the Battle of Britain was famously fought in clear, sunny weather, so that visual sightings were able to compensate for the inaccurate positions given by poorly-calibrated radars.

Radar scientists and engineers continued to develop their equipment up to and during the Battle itself. Important to this thesis is the fact that the equipment installed during the "Phoney War" time filled material gaps in the performance of the air defence system. Five examples of these gaps were Chain Home radar's inability to detect low-flying aircraft, its inability to distinguish friend from foe, its vulnerability to enemy jamming, the need to automate information handling, and the requirement to locate and guide British fighters while leaving their radio transceivers free to communicate with one another and with ground control. The fact that Bawdsey's Air Ministry scientists had no monopoly of skill and inventiveness is shown by the fact that the solutions to three of these problems originated outside that group. As an illustration, the radar used against low-flying aircraft, Chain Home Low (CHL), was developed from a War Office radar designed for coastal gunnery.

The system worked just well enough to be able to direct the defending fighters in the Battle of Britain to force the Luftwaffe to quit the field by day, in favour of night bombing. The massively compressed timescales for development and installation - which were, in the main, met – were summarised by Rowe, the Superintendent of Bawdsey:

> "The discovery of RDF was at least five years too late for its ordered development, thus every member of the scientific team is engaged on emergency work…..Several millions of pounds are being spent on it, and the change of policy to the production of fighters (so mysterious to Aeronautical Press correspondents) is largely associated with the discovery of RDF"[4]

The remainder of this chapter examines on a chronological basis the significance of lines of development, and of the interplay of personality, roles and processes, in the creation of the UK radar-based air defence system during the prelude to war and its test under the pressure of battle.

IV.2. 1938.

In January 1938, the RAF had exactly one functioning radar station under its control, at Bawdsey[5]. Even there, the apparatus was not the intended final equipment, but intermediate units hand-built by the Bawdsey team operating into temporary aerials. Bawdsey could give a good indication of range up to 100 miles out to sea – it did not operate inland – and some indication of bearing and height. It could not distinguish friend from foe, was vulnerable to jamming and accidental interference, and could not detect low-flying aircraft at all. Training RAF personnel in its operation and maintenance had begun, but had been given to only a handful of men. The necessary spares could not easily be ordered, as they had not been added to Ministry stock lists. Equipment contracts and specifications had been issued, but deliveries had hardly begun. Acquisition of many of the sites where the equipment was to be installed had not yet taken place, and none of the specifications for site buildings had been issued. The detail of the most complex of the structures, the aerial masts, was still undecided, since attempts by contractors, Harland and Wolff and subsequently C.F. Elwell, to build them in reasonable time, had failed disastrously.

More positively, Rowe, the Deputy Superintendent of Bawdsey under Watson Watt, and hence responsible for R&D, was aware of the problems and working on them. During the course of 1938, most would be resolved, or at the least have solutions proposed.

The area which initially proved most troublesome was the selection of suitable sites for radar stations. Since the previous autumn, Wilkins had been touring the south and east coasts proposing sites and then finding alternatives when objections were raised on environmental or amenity grounds[6]. Sites suitable for Chain Home radar stations were typically on high ground, overlooking a smooth fall to the coast. Given that the installation would include eight huge aerial masts (four 240 feet, and four 360 feet, tall), the objections were perhaps understandable. Much of the land was owned by the National Trust or by major, well-connected, land owners, who could force delay in acquisition or drive up the price. The Duke of Norfolk, for example, objected to the site at Poling near Littlehampton, as towers could be seen from his Arundel Castle[7]. In the Isle of Wight, the local authority proved equally stubborn over the selection of Ventnor, but seemed to have been mollified by an Air Ministry letter reassuring them that the risk of enemy attack was "very unlikely"[8]. In fact, Ventnor, illustrated in Fig.29, was to be the heaviest bombed of all the radar stations, being put off the air for a month on 12 August 1940. However, Michael Bragg has shown that the story of a general instruction "not to interfere with grouse shooting" is a myth, perhaps derived from a particular case at Danby Beacon, Yorkshire[9]. In the main, objections appear mild compared with those today, and slowed rather than stopped the acquisition process. Great respect was, for example, shown by the media to a "D" notice prohibiting mention of the towers on the radar sites. This was imposed on 1 February 1938 and almost entirely respected[10].

The RAF took over two further stations, Dover, and Canewdon (Essex), early in February[11], each coming under the control of a Warrant Officer heading a team of 6 men trained at Bawdsey. Here also the equipment in place was not yet the commercially-manufactured solution, but a unit hand-built by Bawdsey. In fact, it would not be until two months later that Bawdsey was able to provide even the dimensions of the transmitter and receiver equipment so that standard site buildings could be specified, though by contrast Tizard visited MetroVick and considered progress “good”[12]. Given the pressure on the Works department, who were struggling with a massive airfield building programme for the east coast, nine months were usually required to issue drawings[13] and even then this did not allow for design changes dictated elsewhere, such as the need to add gas-proofing.

These questions of infrastructure were to prove less significant than four major issues - of tracking aircraft inland of the coast, of distinguishing friend from foe, of accurately locating friendly fighters, and of guiding them to a successful interception without denying them the use of their radio transceivers. Watson Watt’s original vision had been that a second chain of radar stations would be based behind the first, much further inland from the coast[14]. This “inland chain” would follow aircraft overland. To identify friend from foe, British aircraft would carry a length of wire, resonant at the CH frequency, which would be “keyed” by a motor[15]; the resulting pulsing reflected signal would create a pulsing radar display “blip” identifying them as “friendly” to the radar operator.

Unfortunately for simplicity, both concepts proved wanting in practice. The experimental inland radar station constructed at Dunkirk in Kent clearly demonstrated that the sheer number of radar echoes received made it impossible even to plot the multitude of tracks[16]. Tests, initially by Dewhurst, then by R.H.A. Carter, with the keyed resonant wire showed that it worked only when the aircraft was in a certain attitude such as directly facing the radar, and when the wire was an exact half-wavelength long; even then the pulse amplitude was small[17]. The two resulting problems were that an aircraft could be identified as friendly to a radar head-on, but as hostile to radars obliquely on either side; and that radars were being developed on many different wavelengths[18], such as the Army’s GL, meaning that a British bomber would not be shot down by the RAF, but would be fired upon by British AA.

The Dunkirk experimental station was dismantled, and the setback led to four urgent projects:

?? Building up the Observer Corps to carry out overland plotting;

?? A device to identify friendly aircraft on the radar screen;

?? A mechanism to plot the position of friendly aircraft continuously, and

?? Some means of communicating to friendly fighters while leaving them use of their radios.

The Observer Corps had, until 1931, eked out a pauper's existence sustained by the enthusiasm of Major-General Ashmore, whose First World War career has been described. Concentrated in the south-east of England, its members held the unusual status of unpaid special constables (given up reluctantly only in 1939) and at this stage had no uniform[19]. As the 1930s progressed, the RAF assumed greater responsibility for the Corps, new sighting equipment was issued in 1935, and the Corps built slowly into a national entity structured into five Areas managing some 21 Groups. The 1938 Air Exercises tested some 265 Observer Corps posts on the scenario of an attack from Germany, and identified the need for an improved telephone network. Though the Corps was in general more professional than its German equivalent, the Flugmeldungdienst, would be found to be in 1945[20], there remained many engaging eccentricities – one Scottish manse allowed siting of a post on the undertaking that a "decorous atmosphere" was preserved; and an isolated public telephone box in Wales became Post 25/L1 by the addition of six feet of extension wire to allow the observer to use its telephone while standing outside the box to scan the sky[21].

The second need, Identification Friend or Foe (IFF), was clearly delineated by Nutting, the RAF Director of Signals, in April 1938[22], and was heavily emphasised by Dowding. Rowe dedicated two teams of two men each to find the best solution[23]. Both worked with the radio circuit called a "super-regenerative detector", whose key feature was that, when triggered by a pulse of radio energy (from CH), it could also act as a transmitter and return a more powerful pulse to the interrogating radar. This showed as a distinctive trace on the display, although the design was temperamental in operation. Within the year, the design was to be stabilised by F.C. Williams at Bawdsey[24]. However, there would be practical difficulties of mass production, for one such "transponder" would be required on every friendly ship and aircraft. There would also be a need to redesign the system mechanically to incorporate an explosive charge, to deny the IFF's secret to the enemy. Taken together, these ensured that IFF would be deployed only during 1940, and then only gradually. Its lack would bedevil the interpretation of radar data throughout the Battle of Britain, and mean that yet more strain would be thrown on the Filter Room staff to avoid "blue-on-blue" fratricide.

A third solution was required to locate, plot and control defending fighters. This was found outside the radar field altogether, by use of the fighter aircraft's own short-wave transceiver, the TR9, fitted on fighters since 1932. The Royal Aircraft Establishment designed a new Mark, the TR9D, fitted with two channels, one being maintained on a fixed, accurate frequency by a quartz crystal[25]. A clockwork "Master Contactor" switched the fighter leader's TR9 to transmit on that frequency for 15 seconds every minute, leaving the other 45 seconds for the leader to talk to his formation. These 15 seconds were just long enough for ground listening stations to obtain a direction finding (D/F) bearing on the plane, and three such stations working together could obtain a "fix". It was then possible to plot that fix with the radar plot of the enemy's position, and guide an interception based on the Biggin Hill experiments of 1936, provided of course that the interception was within the TR9's 35 mile range of Sector Control. The system was christened "Pipsqueak" after the 1 KHz note transmitted during those 15 seconds[26].

To achieve this, it was of course necessary to establish a chain of ground listening and radio direction finding stations. A problem of "technology clash" occurred, for the fastest method of taking a D/F bearing on a transmission utilised cathode ray tube displays (cathode ray direction finding, CRDF), and the nation's pool of relevant specialists was already used on radar work. The solution was to order D/F stations to which CRDF could be retrofitted, and 29 such stations were ordered on 14 April[27]. For the control of defending fighters, this order was as significant as the ordering of the radar stations; indeed at the end of 1938 Watson Watt considered the lack of D/F stations and staff the most serious gap in the UK's defences. The ability to control fighters directly from a radar station (Ground Control Interception, GCI) would not become a reality until the winter of 1940, as will be described in Chapter VI.

During this same period, intensive work forged ahead at Farnborough to equip the RAF with VHF ground/air communications[28]. The merit of these systems was their long range (typically 100+ miles compared to the TR9's 35); their clarity and freedom from interference; and their relative security from interception. The teams under Bartlett had been augmented by Clegg, for ground receivers, and Cockburn, for ground transmitters. Most had previous industrial experience from GEC and EMI, so that production engineering was a natural part of their thinking. Their products would be ready for test early in 1939.

The growing complexity, scale and urgency for the acquisition of radar highlighted that the organisation for delivery was inadequate[29]. In early 1938, Watson Watt as Superintendent of Bawdsey was responsible for the R&D there, for its programme of constructing radar equipment, for the training of RAF operators and maintainers, for the selection of sites and the erection of aerial masts, and for general advice to the RAF and the War Office on the use of radar in the UK and abroad. He reported to Pye, the Air Ministry Director of Scientific Research (DSR) who had succeeded Wimperis. Though Watson Watt had been buttressed by the appointment of Rowe as Deputy Superintendent, the breadth of his own role was plainly anomalous – the Superintendent of RAE Farnborough, for example, did not make airframes or train pilots. Another area of contention was ground/ air communications. This was specifically excluded from Pye's or Watson Watt's remits, for it was part of the role of the Director of Technical Development (DTD). As we have seen, however, it played a key role in the radar-based defence system due to "Pipsqueak".

Pye himself had recognised these problems and in November 1937 had recommended the establishment of a post, parallel to his own, to take up the task of delivering the entire radar system[30]. He perceived it as a role which necessitated a person whose career had been devoted to this technology. Watson Watt was clearly the prime candidate, given that Tizard was much too senior and Rowe too junior.

Watson Watt, of course, had views on the matter, as also did the Treasury. Those of the Treasury were straightforward - that there should not be two Directors of Research in any service function, no matter how pressing the need. Watson Watt was equally firm that he saw his job as primarily one of research, or as he had put it in 1936, “Director of Investigations into Communications”[31]. The position was eventually resolved largely in favour of the Treasury, with the deliberately vague title of Director of Communications Development (DCD) being presented to Watson Watt as necessitated by security[32]. Reassured that he would continue to be responsible for research, Watson Watt turned his attention to continuing disagreement about his own salary, a point of correspondence for many months. On the question of security, it may be observed that several openly published articles speculated about radio, and even television, detection of aircraft in the late 1930s, and an example is given at Fig.30. Each of the potential combatants possessed radar of sorts, but each thought that it held an advantage, none wished to confirm its existence, and none therefore made any comment.

His elevation to Director status left open the position of Superintendent of Bawdsey, and here Pye performed a major service by ensuring that Rowe, still a Principal Scientific Officer, was appointed, over the heads of many Deputy Superintendents at other establishments[33] and incidentally over the heads of the radar pioneers Wilkins and Bowen. This promotion was achieved against Treasury opposition, but proved to be one of the most successful of the war, for Rowe held the role of head of radar research until the end of the war. By 1945 he headed a staff of 3,000, among which were many talented scientists, including some ten future Fellows of the Royal Society. Though Rowe became a figure of fun to some[34] and an enemy to a few (including, as Chapters V and VI relate, Bowen[35]) he is recognised now as an outstanding scientific manager[36], sensitive both to the needs of his service customers and to the rapidity of change in a technology he had done much to originate.

Watson Watt, by contrast, was to hold the post of DCD for less than 18 months. His inability to control the scale of the projects for which he was responsible, and his inattention to such items as the need for the proper planning of a wartime evacuation site for his staff, would cause his demise in the first months of the war. The scope of his vision, as will be shown below, was often accurate, but his management was not; in today’s terms, he could “see, but not do” major projects.

The start he made was, however, sound. The major remaining infrastructural problem were the manufacture and erection of aerial masts, and the making of aerial feeders (by threading wire through copper tubes, it will be remembered, with which Watson Watt helped personally). Recognising that such amateur expedients were over, the Air Ministry established a unit specifically to handle these tasks. No. 2 Installation Unit (2IU) was set up at Kidbrooke, in an RAF depot already dealing with the erection of high-power radio aerials and masts[37]. A part-Service, part-civilian organisation, the unit would become a critical component of the UK radar effort throughout the war.

In a second positive move, Edmund Dixon, the seconded GPO engineer already referenced above as giving shape to the equipment specification and construction programme, turned his attention to the total organisation structure needed for effective radar-based air defence. In June 1938, he produced an extraordinarily wide-ranging paper[38] embracing sensors, information and communication flows, filtering and decision points – the entire C3I system for radar in UK air defence. Watson Watt approved the paper – essentially the foundation charter for Operational Research – in July 1938, and Dixon, shortly to be joined by Harold Larnder, established, with Dowding's full commitment, the first scientifically-based observation of a radar-based defence system at work. From this, together with extensive work carried out during 1938 with the GPO on communications, would flow many of the improvements to the system which would give it effectiveness in the Battle of Britain[39]. In the short term, it hastened work on IFF and on the TR9 "Pipsqueak" system. However, the problem of calibration, and the need to repeat it with every change made by scientists to the equipment, remained a problem, as will be shown later in this chapter.

In the first week of August, Dowding mounted what he described as the "first realistic air exercises" for Home Defence[40]. Five radar stations had now been handed to the RAF and staffed by servicemen, Bawdsey acted as a filter room to identify friend from foe (IFF being still in the laboratory), the Observer Corps handled all inland tracking of aircraft by visual observation, a very few key fighter stations had some radio D/F, and there were even fewer Operations Rooms in which to receive and plot Fighter

Command's battle picture, and to control their local interceptions. The first Fighter Command HQ Operations Room, converted from Bentley Priory's ballroom, is illustrated at Figs. 31 and 32. The entire exercise was watched and assessed by Dixon's and Larnder's O.R. group, and led to extensive O.R. work being carried out by E.C. Williams on control room procedures and G.A. Roberts on communications systems[41].

Dowding was pleased with the results, but not without criticism. In particular, he identified three gaps in the system[42]. These were the inability of CH to track low-flying aircraft; the erratic nature of height readings, crucial for a successful interception; and the blocking of the filter room by excessive numbers of reports. In general, his conclusion was a need for more air exercises and training, both needs with which Rowe agreed.

A specific equipment-based solution was required for the detection of low-flying aircraft. Watson Watt requested Rowe to take steps to detect aircraft flying below 8,000 feet at a range of 80 miles[43]. Rowe in turn reminded Watson Watt that at present wavelengths the laws of physics would require aerials to be at an altitude over 2,000 feet, and he suggested tethered balloons to carry aerials[44]; when tested, this did not work. The Air Force radar team were saved by a very fortunate chance, and by the War Office team at Bawdsey. The War Office group, working on the challenge of radar to direct coastal gunnery, had produced hardware which was also able to detect low-flying aircraft, and do so very well. As described in detail below, this was taken over by the RAF to become, first, Chain Home Low (CHL) radar against the low-flying threat, and eventually in a developed form the Ground Control Interception (GCI) family of radars which would eventually prevail against the night bomber. This was indeed a most serendipitous chance, although RAF veterans are inclined to point out that the War Office team had already incorporated many ideas from the RAF airborne radar group in their coastal gunnery radar[45]!

Meanwhile, events had rapidly overtaken the successful results of the 1938 Air Exercises. In less than a month, Britain was plunged into the Munich crisis. Hitler's annexation of the Sudetenland brought Chamberlain to Munich and to the decision whether to go to war. Watson Watt took the view that the state of unreadiness of the radar chain was a significant factor in Chamberlain's conceding to Hitler's proposal, in the famous piece of paper brought back to London by air by Chamberlain. However, Watson Watt is alone in this view. Historians are prepared to concede that radar was merely one element in a general level of unpreparedness for war at that time[46].

From a radar perspective, perhaps the most visible achievement was that Chamberlain's aircraft was tracked every mile of its flight into London. However, the effect of Munich was to redouble the pressure to complete the full 19 station radar chain, and have it calibrated and ready to meet an opponent. The urgent operational requirement of the Air Ministry now was to have a 19 station chain in use at 1 April 1939, rather than 1 January 1940. An "Intermediate Chain" was required[47].

In turn, this requirement created two further demands, of equipment and of manpower. The manpower issue was acute in two categories – staff to man the stations, and scientists and technicians to commission and calibrate them. Training of operators created a short-term issue, while diverting scientists from research caused a longer-term problem within Fighter, Bomber, and Coastal Commands, for there would be fewer people to research interception radar for night fighters, and no-one to research navigational aids for the latter.

In terms of equipment, the first assessment of the practicability of the timescale for an "Intermediate Chain" was carried out by Watson Watt[48]. He assessed that - given 7-day, 24-hour working by all involved, contractors included – this was just feasible by April 1939, except that neither the final manufactured equipment nor the tall aerial masts could be ready for all 19 stations by that date; indeed, MetroVick were reporting delivery delays at this time. Instead, six stations would have their final equipment, and the remainder a simpler transmitter, the Mobile Base 1 (MB1). The origins of this Metropolitan Vickers equipment was the War Office "cell" of scientists at Bawdsey, as described in Chapter III, and the development and use of it were now handed to the RAF to become their "Mobile Radio Units" (MRUs) used throughout the war[49] .There would only be one transmitter aerial and two receiver aerials on most sites. Bawdsey staff would have to carry out all the installation, testing and calibration. Although, then, Bawdsey had grown from 40 to 61 scientific staff during 1938, over half were working on the Intermediate Chain, leaving just 30 to handle 13 major projects[50] – and 8 of those 13 projects were to remedy deficiencies in Chain Home.

Training of service personnel faced equally major problems. By October, Hart and his school had trained just 60 of the 280 personnel which it was estimated the Chain would need for continuous operation, although Tizard was "much impressed" with their quality[51]. To meet the newly accelerated demand, it was decided to open a new school at Tangmere[52]. However, by November, fresh calculations by Tester, Hart's deputy, showed that between 450 and 600 trained personnel would be needed, and Watson Watt expressed his concerns to Tizard[53]. By April 1939, that estimate would double again, and exceed 1,200.

Clearly, the pool of suitable Servicemen could run dry. This likelihood was not helped by the minimal grading of the operators. A significant issue was the desire of trained men to move on rapidly to such higher graded posts as barrage balloon operator, or to trade (i.e. skilled) jobs[54]. In response, a new source of personnel was identified in the proposed use of women as operators. Watson Watt considered that this proposal was his, and he is recorded as having advanced it as early as December 1937[55]. The idea, however, was hardly new, for women had been employed in similar roles in the First World War. The three Bawdsey secretaries, the Misses Booker, Boyce and Girdlestone, pictured in Fig. 33, acted as "guinea-pigs" for training[56] and a trial placement at Dover, delayed by Munich until February 1939. Their performance was judged to be a complete success, equalling that of trained and experienced male operators after just four days[57]. Dowding's deputy, Keith Park, confirmed that women could be recruited into that specific role, although he noted that they might then be in locations "likely to be the object of enemy attack"[58] as indeed proved to be the case.

The long term solution to the shortage of Bawdsey scientists was equally inventive. Rowe had written many times on the difficulty of recruiting, into secret work where they could not publish papers, capable scientists at the poor rates of pay and promotion prospects prevailing[59]. For example, only one in four of his new appointees in 1938 had been recruited above the most basic level. Recognising that the Treasury was unlikely to concede wholesale regradings, Tizard resolved upon a different approach. Gaining Air Ministry approval to induct a greater number of scientists into the radar secret, he then approached key research centres such as the Cavendish[60]. In 1939, selected scientists were lectured on radar by Watson Watt, and then spent a summer month at various Chain Home stations. The personnel position would thus be resolved before the outbreak of war, albeit at the price of the influx of new recruits at senior grades causing disaffection among the radar veterans. However, the short term problem was not resolved, and the cost in delayed research would be months of delay in the introduction of radar for the night battle and a year's delay in navigational aids for bombers and Coastal Command.

Army development of radar proceeded with great rapidity, surprising even Watson Watt. Detailed specifications for anti-aircraft radar were produced in April 1938, shortly after a visit by Tizard, to guide the development of the "extremely promising" GL (gun-laying) set, and Watson Watt argued for large-scale production facilities to be readied[61]. An experimental set would be available by February 1939[62]. However, six months before that date, on 18 August 1938, the Army requested and the Treasury approved the extension of production facilities at MetroVick, Cossor and GEC for 1,000 GL I sets, illustrated in Fig. 34, at a total cost of £4,612,500[63], and also an expanded R&D site to be located at Christchurch; Tizard considered the AA achievements "remarkable". On 21st December, specific approval was given for 500 GL sets[64.] A second Army team, under W.A.S. Butement, focussed on coastal defence using 200 MHz equipment copied from Bowen's airborne radar hardware[65]; the two teams worked closely together. Production capacity increases to produce 40 such coastal defence sets was approved by the Treasury. The equipment so developed would become most versatile, acting as a foundation for the RAF's Chain Home Low and GCI sets as well as for coastal defences. The Army was also immediately sensitive to the potential training needs – the first "training of the trainers" began in June 1938 at Bawdsey and the first lower-level instructors' course followed before the end of the year.

As was described in Chapter III, the Navy had been slower to develop radar for its own use until late in 1937. Coales and Rawlinson[66] provide three potential reasons why this was so – the wavelengths used by Chain Home necessitated aerials too large for shipborne usage; the Navy had an excellent organisation for electronic equipment supply, lacking in the RAF and Army, and their Signals School had provided the transmitter valves for CH – the logic being that the Navy could procure equipment rapidly if radar became proven technology; and the Navy had unique design constraints of heavy seats, gun blasts, and long voyages without maintenance[67] . Trials of the Signal School's 43 MHz equipment in HMS *Saltburn* early in 1938 proved successful and two better engineered models, christened Type 79Y, were installed in the cruiser *Sheffield* and the battlecruiser *Rodney*, giving aircraft detection up to 50 miles; the aerial system is illustrated in Fig. 35. A second team, under Coales, developed 600MHz (50cm) experimental equipment at Southsea Castle. The Navy, at this time, was more focussed upon increasing its research team of eight than upon acquiring a comprehensive air defence capability; the personal papers of Shayler[68], one graduate recruit, confirm the modest scale of the activity.

At first glance, therefore, 1938 appeared to be a year in which attention was paid to lines of development and solutions, even if not timely solutions, found to the problems within each. At the level of concepts and doctrine, a clear direction existed for the creation of an effective air defence system founded upon radar - strategic bombing was no longer the sole option, and November's "Scheme M" provided 42 fighter Squadrons for Home Defence. Radar equipment was in manufacture and being delivered, the critical adjuncts of IFF and Pipsqueak were being developed, and CRDF was on order even if not delivered. Infrastructure obstacles, of finding suitable sites and of constructing aerials, had been largely overcome by Wilkins' hard work early in the year and by the establishment of No. 2 Installation Unit, described above. Calibration had also been recognised as a significant issue, albeit one with no immediate solution in sight, but the "iceberg" of sustainability, of maintenance and spare parts, remained unseen at this stage.

Organisationally, the creation of the post of DCD within the Air Ministry and the appointment of Watson Watt to it appeared, from his first actions, to be sound, as did that of Rowe to head Bawdsey. Dowding and Tizard continued to act as an informed customer/supplier team with the highest mutual respect for each other, while Freeman as AMRD – the budget holder, and Watson Watt's ultimate head – was fully supportive of radar in all its aspects. Dowding as customer was careful to test the system in all its components and as an integrated whole. In particular, through the filter room, he was concerned to identify all aircraft whether plotted by radar out to sea or by the Observer Corps inland, and, by integrating his Command's activities with those of other Commands and services, avoid shooting down friendly aircraft. Tizard was equally concerned to find solutions to the problems identified, and supported the development of Operational Research so to do.

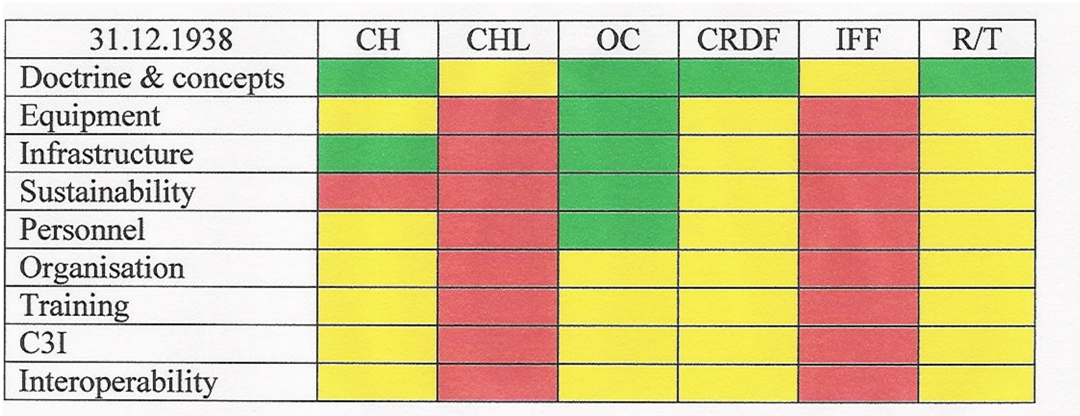
Though training and staffing were both under pressure in 1938, solutions appeared to have been found – in the Services, the establishment of a new training school, and the employment of women as operators, and in the case of scientists, the contacts with the Cavendish Laboratory and the induction programme planned for 1939.

In retrospect, it can be identified that Watson Watt's lack of programme management skills would cause him to founder in 1939, and that the diversion of scientists from research onto implementation work would delay night interception and radio navigational aids. Neither would have been obvious at the time. Watson Watt appeared to have made a sound start, and Bomber Command did not then consider itself in need of navigational aids.

Two final refinements of the system closed the year. The need for contingency equipment (in the event that the radar station was bombed) had been identified and was met by orders for a second set of equipment for each site[69], and a Filter Room had been constructed at Fighter Command HQ, Bentley Priory, next to the Operations Room; this was handed over in December[70]. Group Operations Room sites had been chosen for 11, 12, and 13 Groups by May, and programmed for completion by March 1939[71]. The Bawdsey filter room reverted to experimental and training status.

Day Air Defence Lines of Development Position at 31.12.1938.

At this point, the concept of effective day interception capability being achieved by radar, the Observer Corps, CRDF and ground control by R/T was accepted, and IFF and CHL were under development, albeit at a very early stage. The Chain Home infrastructure was finally being addressed by Wilkins and No 2 Installation Unit, and most other CH lines of development were progressing on plan; the hidden problems of sustainability remained beneath the surface. The requirements of the Observer Corps, being much simpler, were more easily satisfied, and the CRDF and R/T elements posed no major problems, with VHF now being developed to replace H/F.



31.12.1938	CH	CHL	OC	CRDF	IFF	R/T
Doctrine & concepts	green	yellow	green	green	yellow	green
Equipment	yellow	red	green	yellow	red	yellow
Infrastructure	green	red	green	yellow	red	yellow
Sustainability	red	red	green	yellow	red	yellow
Personnel	yellow	red	green	yellow	red	yellow
Organisation	yellow	red	yellow	yellow	red	yellow
Training	yellow	red	yellow	yellow	red	yellow
C3I	yellow	red	yellow	yellow	red	yellow
Interoperability	yellow	red	yellow	yellow	red	yellow

Table 4. Radar-based day interception capability: summary position at 31.12.1938.

Progress in the last months before the outbreak of war in September 1939 is now analysed.

IV.3. January to September, 1939.

The system which Bawdsey was struggling to install by 1 April 1939 was, in air defence terms, anything but comprehensively efficient and effective. This Intermediate Chain Home (ICH), was undefended, housed in wooden huts, employed low-powered transmitters and only three, low, aerial masts, and was capable only of giving a warning that there was “something out there”, providing its range and approximate bearing. The system could not distinguish whether that “something” was friend or foe – IFF was still in the laboratory, and it could not easily direct defending fighters to intercept the "something", for by April only one of the 17 Sectors had the three Radio D/F stations needed to take a fix on defending fighters, and none of the TR9D "Pipsqueak" sets had been delivered. Indeed, Chain Home could not yet give accurate bearings or height indications, and it could not detect low flying aircraft at all.

Nonetheless, the bones of the system were there. When in January the Air Staff received approval for 50 squadrons of fighters, it was on the basis that air defence was now a solidly-based doctrine, and their first action was to seek extension of the radar chain to the west and the north[72]. Wilkins had already surveyed sites to the west, and locations on Portland and on Prawle Point, Devon were approved[73]. It might be noted that this was not in any anticipation of the collapse of France - Dowding and the Air Staff agreed that this westward extension was purely precautionary, not the necessity it became after June 1940. By contrast, extension to cover the Fleet anchorage at Scapa was an indisputable priority, and a site at Netherbutton, Kirkwall was approved for urgent action[74]. By June, and by dint of re-use of salvaged equipment from the temporary station at Ravenscar, Yorkshire, rudimentary cover was provided[75]. Dowding was also concerned about the possibility of aircraft flying up the Irish Sea and past Cumbria, where the Observer Corps had few posts. Stations were therefore approved for the Isle of Man and for Stranraer[76], of a simpler design than for the prospectively heavily occupied East Coast stations.

Efforts continued to improve the CH equipment for those East Coast stations, both in terms of power output and of information handling. The limiting factor on power was the transmitter output valve. The decision was taken to induct GEC into the secrets of pulse modulation and of radar valve design. In a short time, they had adapted a valve used for television transmitters, the ACT10, to the specification needed and the resulting VT58 valve became a wartime standard[77].

Information handling was a more complex problem. The requirement was for a device to automate the various readings taken from the tube face – range, bearing, height – to minimise the numerous errors. L.H. Bainbridge-Bell, one of the Orford pioneers, was presented with the problem, and devised an electromechanical device[78] which was linked to the Chain Home controls and which, when guided to the spot on the tube face by the operator, presented the target's position by illuminating a numbered and lettered grid. The use of the Optical Converter was gradually extended to all the Chain Home stations during 1939 and early 1940. Unfortunately, this device depended heavily on a number of strings and pulleys being kept in tension, and these conditions did not apply at operational stations. Sites without this device were obliged to use, for height calculations, a manual circular slide-rule calculator devised at Bawdsey[79] and adjusted for the unique calibration of each radar station. Using this doubled the time taken for a plot, and so was unpopular. Research began on an electrical calculator, illustrated at Fig. 36, taking advantage of the GPO's experience in switching systems. Developed largely at Dover by G Roberts and the GPO engineer Marchant, the calculator would be installed at all CH stations, beginning with Poling, from early 1940 onwards[80].

Ground/ air communications, by contrast, were moving into a situation where the "best was the enemy of the good". It had been known for some time that VHF communication would be a major advance on HF. There was no interference from commercial stations on VHF, and, as VHF communications were line-of-sight, they would be longer range to and from aircraft at height, and inherently more secure from interception and jamming. For some time, under DTD, RAE Farnborough had been developing a VHF transceiver[81], as described above. Watson Watt had also investigated simpler designs in both Holland and France, but found them inferior[82]. Now, Watson Watt and the Air Staff were agreed that VHF sets should be installed with the utmost speed, at least in the Hurricanes and Spitfires of 11 and 12 Groups. Instructions were given that the sets should be manufactured and installed by September 1939[83]. However, the disruption caused was significant. Because fighter location was carried out by "Pipsqueak", the challenge was not merely to replace the sets in the aircraft and their related ground stations - *the entire ground D/F network had also to be replaced*. It will be shown that it proved impossible to achieve this in time, and a number of tactical expedients were adopted such as placing mobile repeater stations close to the coast to increase the range of control. In fact, by the Battle of Britain, only half the VHF sets had been installed and had to be stripped out again as the attrition of Dunkirk and of the onset of the Battle itself ran down stocks[84]. The Battle of Britain was at first fought on HF, for it was too complex to have mixed HF and VHF communications.

International events did not, of course, wait on UK supply chain problems. On 10 March, Germany occupied the rest of Czechoslovakia. To forewarn of a surprise attack on the UK, Dowding placed all the radar stations handed over to him on a 24 hour watch[85]. The immediate impact of this was a significant increase in the demand for trained operators and maintainers – numbers required now increased to 1,265, where only six months before the total trained numbered just 60. Although the planned radar school at Tangmere had not yet opened, it was demonstrably inadequate to this new demand, and a much larger school at Yatesbury was scoped and agreed, with training in the meantime to be provided at the CH stations themselves[86]. Approval would be given in May for women to be trained as operators, following the success of the Bawdsey secretaries. Interestingly, it was the Treasury who suggested the use of WAAF - the Air Ministry had been inclined to use civilians[87].

The deteriorating international situation focussed thinking on several fronts – the inadequacy for air defence of the chain of radar stations delivered by April; the need to protect those stations in war, and to evacuate the Bawdsey scientists; and the need to provide back-up Operations Rooms.

By immense hard work, there was a radar station of sorts on each of the 19 sites by the target date of April 1939, although Ottercops and Rye were not as yet operational; as Rowe wrote to Tizard "I shall never quite understand how it has been done"[88]. The inadequacies of these stations has been listed above – none of the 350 foot towers had been built, there being only three temporary, lower towers per station, while the transmitters were low powered Mobile Base (MB1) equipments, housed in unprotected wooden huts; the receiver hut at Ventnor is shown in Fig. 37. No equipment existed to detect low flying aircraft, none was yet installed for IFF, and only one sector of 17 had D/F equipment to use Pipsqueak, while even there the hardware was being changed to VHF. Nonetheless, the delivery of any kind of early warning system at all was a miracle, especially when the winter of 1938/9 is taken into account – infrastructure work, especially erection of high masts and towers, was (and still is) uniquely dependent on the elements. It had been so in this case, but by January, 90 days from the deadline, half the stations had had no aerials at all, and the critical calibration and phasing process depended on these being in place.

Watson Watt's first demand, therefore, after distributing due praise for the major effort of delivery achieved by Bawdsey and No. 2 Installation Unit, was an insistence that all outstanding items of calibration and installation be completed during May[89]. A "clean-up" of this magnitude once again brought all Bawdsey research to a halt.

Dowding was aware of the strain brought about by the 24 hour watch at all stations, and sought from the Air Ministry a relaxation of their ruling that he must intercept all unidentified flights, at the latest by the time they crossed the UK coastline. There being at this stage no operational IFF - its satisfactory demonstration had taken place only on 4 March 1939, displaying to a delighted Dowding a range of 100 miles at 14,000 feet[90] – the necessity was to keep the entire chain, including the critical Filter Room, on 24 hour watch for every single flight which might even appear to approach the UK from 100 miles distance. Such a span, of course, encompassed a huge swathe of commercial and pleasure flights on the Continent and over the North Sea, all of which had to be tracked and potential threats identified. Dowding simply did not have the manpower to do this, but the Air Ministry would not change its stance[91]. Dowding was left to do the best he could, and to use the issue as a lever to gain priority for IFF manufacture.

Given the importance of IFF to the air defence system, it is appropriate to recap its history. Watson Watt's original concept of a keyed resonant wire having proven inadequate, Bawdsey worked on a dedicated IFF transceiver (a "transponder"), triggered by Chain Home's transmission to return a powerful, pulsed, echo. Such a device would mean that fighters had no need to scramble on the approach of every aircraft, but only for unidentified or enemy planes. Dowding was impressed at the cheap, light, set he was shown in March[92], and an Air Exercise later in the month confirmed IFF's high priority. Bawdsey produced a design by June, but to do so had to constrain the equipment functionality to operating only on the CH frequencies. The first 30 were hand-built by

Ferranti and delivered on 30 August. Poorly constructed, they did not perform well, but for want of anything better 1,000 were ordered.

IFF was but one problem. A report by Rowe on 19 June[93] set out clearly that the Chain was not, at that time, fit for purpose if that purpose included interception. As yet, the Chain provided only early warning. There were some glimpses of the necessary improvements appearing – at the beginning of the month the first complete factory-manufactured transmitters began to be installed, and the first of the 350 foot towers was completed, at Bawdsey.

Planning for the realities of war raised three questions. To where could the Bawdsey scientists be evacuated? How could the Chain be supported thereafter? And how would the radar stations themselves be defended?

When the roles of Bawdsey were examined to assess the suitability of likely evacuation areas, its unusual span of responsibilities became sharply apparent. Bawdsey carried out R&D, when the exigencies of the service permitted, and this would require one home. But Bawdsey also carried out installation, support, maintenance and spares for the Chain, and these needed to be housed also. Finally, Bawdsey carried out training. However, with the Yatesbury site being commissioned, it was decided that the facilities at Bawdsey could remain where they were without undue risk.

Research had to be evacuated to a distant "safe" location. Rowe preferred Poling[94], which would become one of the heaviest bombed sites after the collapse of France. By February 1939, the likeliest R&D evacuation area was Newquay. However, Newquay was not well situated to provide rapid maintenance and logistic support to a chain of radars stretching from Ventnor to Scapa Flow. Accordingly, there was developed the concept of a Base Maintenance HQ (BMHQ) [95] physically separate from the research scientists. The GPO had already configured telephone lines from the Chain stations for a contingency Operations Room at Leighton Buzzard, in the event that Fighter Command HQ, Stanmore, was hit. This, it was resolved, would also be the most satisfactory location for BMHQ in the event of war. In turn, BMHQ would manage detached, small, support groups, each with a car, testgear and some spares, to be based at Pevensey for the South, Bawdsey for the East Coast, and Staxton Wold for the North.

For Bawdsey's R&D functions, the wartime location was then apparently solved by Watson Watt's locating a suitable site at the University of Dundee[96]. It will be seen below that Watson Watt's inadequate (indeed, almost non-existent) arrangement here would prove a disaster.

The defence of the radar stations themselves was a more straightforward issue to resolve, although with unintended consequences. The stations were near the coast, and invasion was in prospect. There was therefore the need to protect each station against both ground and air attack. The Army provided the resources to achieve this – 60 men under a Captain to defend against possible ground attack, and 40 under a Lieutenant, with light anti-aircraft, to defend against air attack[97]. The RAF thereupon considered that a commissioned officer in the rank of Flight Lieutenant[98] should command their own operating personnel, where previously this had been the responsibility of a Warrant Officer or a Flight Sergeant. Perhaps fortunately, the RAFVR proved capable of providing enough suitable personnel, although a yet further burden fell on the training organisation.

Perhaps because Dowding had instructed regular exercises with the radar chain since February, Fighter Command had become increasingly conscious of the inadequacies of the radar chain in its Intermediate form. The most significant of these operationally were the vulnerability of the Chain to jamming, its inaccuracies in measuring height, and the need to fill in gaps in its coverage. There were two such gaps – low flying aircraft could not be detected, and the fact that coverage was lost as an aircraft flew between the lobes of a station's transmission (as described in Chapter III). The disconcerting effect of the latter was that an aircraft on a straight and level course could be followed, then disappear from the screen, and then reappear minutes later. Accordingly, on 28 June, Fighter Command requested Bawdsey and No.2 Installation Unit to upgrade all 19 stations with extra "gap filling" aerials, height finding capability, and anti-jamming circuitry by 7 August[99]. Once again, all research stopped but the target was met, much to the amazement even of Rowe.

It is helpful to recall the other radar-related activities taking place at this point. Watson Watt had delivered his radar briefing to the Cavendish scientists in February. The chosen individuals arrived in July for their induction into radar, and were then "thrown in at the deep end" by attachment to a Chain station[100]. To their credit, most flourished. The first WAAF training course also took place at Bawdsey at this time[101], when training resources were stretched to their limit. Infrastructural work was also being carried out at all 19 sites[102], with foundations for the new, taller, aerial masts being dug and the masts erected, the new concrete protected buildings for the new transmitters and receivers being built, gap-filling aerials and anti-jamming circuits being installed, and the underground Group Control Rooms being constructed, the first, for 11 Group, being finished on 5 August. In turn, this had necessitated a re-laying of many telephone lines, itself not a trivial task. In the communications chain, work was proceeding on re-equipping 16 ground transmitter and 24 radio D/F stations with the new VHF equipment, while GEC and Ekco were struggling to build the airborne transceivers and Ferranti to hand-build the first 30 IFF sets.

The solution to the low-flying aircraft problem was now to be found, but not from the Bawdsey Air Ministry team. Their solution, of balloon-suspended aerials, proved inoperable as well as vulnerable to fighter attack. However, the War Office group at Bawdsey had developed a 1.5 metre coast defence (CD) radar[103], intended to locate ships at sea and direct the fire of defending gun batteries. For this purpose, height finding was irrelevant, and the radar was required simply to assess range up to 25 miles, and bearing to 2 -3 degrees. At a 1.5 metre wavelength the aerials were far more compact than Chain Home, and the War Office scientists had developed equipment where transmitter and receiver were mounted in separate huts some 50-75 yards apart, the front of the huts mounting several dipole aerials. The signals to these could be switched on and off electrically ("beam switching") and this allowed bearings to be taken to an accuracy of a degree. Observation showed that the apparatus detected low-flying aircraft; trials at Dover[104] showed a range of 32 miles at 1,000 feet, 25 miles at

500 feet and 15 miles at 50 feet, a result sufficiently impressive for Tizard to overrule Watson Watt's and Rowe's balloon experiments. A month later, Watson Watt recommended buying 24 such "CD/CHL" sets[105], 20 for placing between the CH stations to pick up low flyers and 4 as spares.

The impact of CHL in lines of development terms was major. First of all, it doubled the need for sites. Fortunately, CHL, mounted in two huts and with no need for eight massive masts, required minimal construction and had a small environmental footprint. A typical CHL is illustrated at Fig.38. Sites still had to be acquired, but objections were fewer. Second, CHL's manufacture could have begun to place an undue load on the radio industry, a point discussed below. Third, doubling the number of radar stations also doubled the maintenance needs, particularly because the technology of CHL (a 1.5 metre, VHF, equipment) differed from that of CH (a 10 metre HF equipment). Fourth, the number of operators needed doubled again, as did their training requirements. Finally, the need for data communication from the CHL stations had to be resolved - some simplified reporting had to be devised, as otherwise the centralised filtering system would become overloaded.

Fortunately, manufacture appeared a non-issue at that time. Metropolitan Vickers seemed able to produce the necessary transmitters, illustrated at Fig.39, without major issues, and the receivers took advantage of a chassis developed for television purposes by Pye Ltd[106], which had become by this time a standard unit in the embryonic air interception (AI) and air to surface vessel (ASV) radars being developed by Bowen's small team at Bawdsey. The Pye receiver chassis had proved so superior to that of Cossor's, who made the CH receiver, that Pye was commissioned to produce the CHL receivers. Since television broadcasts would cease before the outbreak of war, Pye welcomed the work to keep their production lines running. Production was not therefore seen as an issue, but maintenance and spares would add to the growing problems in this area. For communication of results, it was decided that CHL stations should send their plots (of bearing and range only, as CHL had no height-finding capability) to the nearest CH station which would resolve any overlap with its own plots before forwarding a consolidated result to the central filter room at Fighter Command[107].

Organisationally, the origins of CHL as a War Office equipment would have unforeseen consequences. In July 1939, the Ministry of Supply (MoS) was formed to relieve the War Office of development and production responsibilities; among other areas, it took over the War Office Bawdsey scientists. In August, that group was ordered to move to Christchurch, to centralise with other Army scientists[108]. Given the criticality of CD/CHL work at Bawdsey, Freeman, as the Air Member responsible, had to protest to the MoS to delay the move[109] although, within a month, Bawdsey itself would evacuate. That incident was trivial, but the MoS' desire to run its own production would later help ensure Watson Watt's own downfall.

Up to this point, Watson Watt had faced no interservice challenge to his management of radar acquisition. Manufacturing Chain Home was a matter of craft-building 40 transmitters and 40 receivers, these figures including 100% reserves. The Navy had gone its own way, but it was seen above that their team was modest and their requirements highly specific. The Army had been content to use Watson Watt's research and suppliers, perhaps because the primary user, AA Command, would in time of war be operationally controlled by Dowding. However, as war loomed, these arrangements would be severely threatened. The Navy would identify an urgent need for a chain of Coast Defence radars based on the Army's CD set, to detect both U-boat and low flying mine-laying aircraft. The Army, who had tested their experimental GL AA radar in February and signed off the pilot models in July, would have 39 delivered by December to be followed by 344 in 1940[110], and had begun work on the GL II model shown in Fig.40, which incorporated elevation finding. This move to mass procurement became, as will be seen below, a significant acquisition issue on the outbreak of war.

Further Army and Navy developments may briefly be reviewed. The Army had formally introduced radar as a concept to AA Command at Cambridge in March 1939, and its first production equipments went to the Military College of Science and training establishments to "train the trainers" of the operators and mechanics[111]. Searchlight units were not included; at this time and much later they depended upon sound locators, whose usability was much improved by the Visual Indicating Equipment (VIE) developed by the innovative Alan Blumlein of EMI[112]. The Navy had realised from their successful 1938 installations of Type 79Y on *Sheffield* and *Rodney* that more and smaller sets would quickly be needed. A marine radio production expert, J. Rawlinson, was quickly put to the task, and by 30 June the first production equipment, Type 79Z, was installed on HMS *Curlew*[113]. 40 of this "engineered" version of Type 79, illustrated at Fig. 41, were on order at the beginning of the war. For smaller ships, Coales' team successfully tested their 50 cm. set in HMS *Sardonyx* in June, and a modified Army GLII was installed on HMS *Carlisle* before the end of the year as Type 280[114].

Before that time, Chain Home would be the target of one of the first electronic intelligence (ELINT) flights against radar. The Germans had been experimenting with radar since 1934, but radar was viewed as an essentially defensive technology, and in Germany's national atmosphere of expansion had low priority. Its main developments were encouraged by the Kriegsmarine, to aid gunnery in poor weather or at night. By contrast, the Luftwaffe focussed on radionavigational aids, based on its experiences from the Spanish Civil War. A defensive chain of Freya radars, in origin a Kriegsmarine gunnery radar handed over to the Luftwaffe when it proved able to detect aircraft[115], was located on the German North Sea coast. These operated at a frequency of 120MHz (2.5m) with a pulse repetition frequency of 1 KHz; a typical "Freya" is depicted in Fig. 42. In mounting their ELINT operation, the Germans were anticipating a similar system. The Zeppelin LZ130 "Graf Zeppelin" was used as a platform, because of its stability, endurance and carrying capacity, and on 4 August flew the length of the East Coast, tracked by Chain Home all the way. An RAF photograph of the "Graf Zeppelin" while on this mission survives and is shown at Fig. 43. For reasons which are still not entirely clear, the operation concluded that Britain had no radar-based defences of any significance. Latham's study of the mission[116] hypothesises that:

?? The search took place on the wrong frequencies, in the 100 MHz range rather than the 20-30 MHz band actually used by CH;

?? CH was"floodlight" radar which illuminated an area in front of it, rather than "search" radar which scanned an area. Search radar can be heard to "paint" a target, but floodlight radar gives no such indication of its presence, for its signal is continuous;

?? Fortuitously, the British had locked their pulse repetition frequency to that of their mains electricity. The result – a continuous signal with a pronounced "mains hum" sounded like the national power grid rather than a radar.

The lack of positive information from this mission was one factor which would make it easy for the German commanders in the Battle of Britain to decide not to press home air attacks on the radar stations, a tactical decision with adverse consequences for their strategic assault.

Within days of this ELINT mission, on 8-11 August, the last peace-time Air Exercises were held[117]. It is important to recognise that Dowding had been operating monthly minor air exercises, with the support and urging of Tizard and Watson Watt, since early that year. Training was, for him, an ingrained habit. In addition, the exercises had been overseen by Bawdsey's O.R. scientists, who since June had become an autonomous group within Bawdsey, headed by Larnder. Dowding had also organised regular conferences between the scientists, the Air Ministry staffs, and the War Office[118]. He was in a well-informed position to make decisions on the future tactics to be employed.

In the Air Exercises, radar was effectively backed up by the Observer Corps, who had trained and practised hard during 1939 as the onset of war became increasingly probable. A series of exercises from January onwards caused the Corps to refine its procedures. To cut down the number of sightings to be plotted, the Corps was greatly aided by an instruction to plot only those raids confirmed by radar, in itself a highly significant vote of confidence in the new system. "Lost Property Offices" were established where scientists traced raids at the boundaries of each CH's area, or where tracks had disappeared without explanation[119]. Some proved problematic: Edward Fennessey recalls that his Corps assistants included one with a speech impediment, one stone deaf and one who had lunched too well in the Mess[120]. Nonetheless, the August Air Exercises, employing 1,300 aircraft and 33,000 men, and with the attackers having complete freedom to decide how and when to approach the UK, led Dowding to conclude that "radar worked extremely well"[121] and Warrington-Morris, the head of the Corps, that the "plotting at centres was excellent"[122].

It was to be the last peacetime trial. On 3 September, war was declared, and at its outbreak, as has been shown, the radar chain was still some way from being a fully component of a seamless and efficient air defence system. However, the considerable efforts made to identify problems in the system by the systematic application of Operational Research, and continual exercises to train all the personnel under operational conditions, had rendered it effective as an early warning system. The cost had been the diversion of the scientists from research whose results would be sorely needed within months.

Day Air Defence Lines of Development Position at 03.09.1939.

The position at the outbreak of war reflects the fact that much had been done, but much remained to do. In doctrinal and conceptual terms across all elements of the day air defence system, and in terms of interoperability across four of the six elements, the system had been tested and was operational. The missing elements, CHL and IFF, were being manufactured; R/T was a working entity, albeit on H/F rather than VHF, and was fully supported, even though all its maintainers were not in place; and the Observer Corps was a functional and exercised body. Though CRDF was not present in all Sectors, its organisation and the fact that it was known technology made its roll-out a relatively straightforward matter.

The Achilles heel of sustainability of the Chain Home stations – spare parts and support - was about to become evident to its unsuspecting users.

03.09.1939	CH	CHL	OC	CRDF	IFF	R/T
Doctrine & concepts	[green]	[green]	[green]	[green]	[green]	[green]
Equipment	[yellow]	[yellow]	[green]	[yellow]	[yellow]	[yellow]
Infrastructure	[green]	[red]	[green]	[yellow]	[red]	[yellow]
Sustainability	[red]	[red]	[green]	[yellow]	[red]	[yellow]
Personnel	[yellow]	[red]	[green]	[green]	[red]	[green]
Organisation	[yellow]	[red]	[green]	[green]	[red]	[green]
Training	[yellow]	[red]	[green]	[green]	[red]	[green]
C3I	[yellow]	[red]	[green]	[green]	[red]	[green]
Interoperability	[green]	[red]	[green]	[green]	[red]	[green]

Table 5. Radar-based day interception capability: summary position at 3.9.1939.

Radar's experience in the first months of war – the "Phoney War" – will now be examined.

IV.4. September 1939 – June 1940: The "Phoney War".

On the outbreak of war, Watson Watt had (unknown to himself) less than 100 days to serve as DCD. The man who engineered his departure was Air Marshal Joubert, recently returned from India and appointed as Air Co-ordinating Officer, RDF in the Air Ministry, yet Watson Watt's memoirs, which explicitly refuse to praise Dowding, list Joubert as one of Watson Watt's chosen champions of radar[123]. The consequences of this personnel change would be far-reaching. The reasons which caused it have much to do with the neglect by Watson Watt of lines of development issues which he might reasonably have foreseen. The background therefore merits further analysis.

On the outbreak of war, Tizard's key committees– the Committee for the Scientific Study of Air Defence, and the CID's Air Defence Research Committee – ceased to exist as their members moved to take up wartime posts. The Air Ministry, anticipating war, had taken care to engage Tizard as Scientific Adviser to the Chief of the Air Staff, Newall[124]. It has not been previously remarked that these moves deprived Watson Watt of his "top cover", as Tizard was now no longer working for Freeman, Air Member for Development and Production, but for his superior, Newall, and with a much broader remit. Appleton, who had been the CSSAD member most supportive of Watson Watt, now had no forum for his advocacy. The pressures of war also left none of the latitude for error of peacetime. Tizard, who had risked his reputation on radar, had now to be dispassionate in assessing Watson Watt – and Watson Watt had not only let him down in the 1936 Air Exercises, but had even plotted with Lindemann and Churchill against him in that same year. War had also brought Churchill, and with him Lindemann, back into public office, Churchill now being appointed First Lord of the Admiralty.

From the first, Watson Watt was under pressure. There would be four critical incidents involving radar in the first weeks of the war, and these added to the mounting pressure from the War Office and the Admiralty to manage their own radar acquisition independently of Watson Watt. These four incidents were the mismanaged evacuation of Bawdsey to Dundee, the fratricidal “Battle of Barking Creek”, the failure of radar to cover the fleet anchorage at Rosyth, and the visible inability to maintain the Chain on-air exemplified by the Drone Hill breakdown.

On 3 September, the Bawdsey staff evacuated to their war stations. The Base Maintenance HQ at Leighton Buzzard was occupied without great problem, and the Chain stations were already on a war footing. Two views exist of the move from Bawdsey. Bowen[125] paints a picture of a chaotic flight to Dundee, and describes Rowe vanishing before war was declared. However, Bragg demonstrates[126] that this view is at best exaggerated, for the surviving documentation shows that 74 tons of crated equipment had been collected from Bawdsey and loaded at the local goods station for onward transport to Dundee on 2 September. Given that this could hardly have been packed in a day, or even a week, preparations at Bawdsey must have been well in hand in the weeks preceding the war. Bowen, out-based at Martlesham airfield, presents a partial picture perhaps influenced by the unpreparedness of Dundee and by his own poor relationships with Rowe.

Dundee was, by contrast, completely unready to receive Bawdsey’s scientists[127]. It appears that Watson Watt had completely underestimated the space and facilities required by Bawdsey in his discussion with the University authorities. By considerable efforts they were able to clear two small rooms. Eventually, it was the local Teachers’ Training College which reorganised itself to house the scientists, though equipment remained in crates in the yard for many winter months. The airfield facilities at Perth proved even worse and totally unsuitable for Bowen’s AI and ASV work[128]. Rowe, who in the short term put a brave face on the problems but poured out his real feelings to Tizard[129], described in his memoirs the few months spent at Dundee before the group relocated to Worth Matravers, Dorset, as the “unhappiest and least productive of the war”[130]. Bowen was even more pungent about the shorter period his group spent at Perth before moving to RAF St Athan, Wales[131].

In the infamous "Battle of Barking Creek"[132] on 6 September, the "sense relays" at Canewdon radar failed. These relays, high on the aerial mast, switched aerial elements so that the radar echo from *forwards* of the aerial was received at the highest gain. Relay failure meant that a signal from *any* direction was received with equal gain, so that echoes from targets *behind* the mast would appear on the display identically to echoes from targets *in front of* it. Behind Canewdon was an RAF fighter station. On the morning of 6 September, unidentified echoes appeared on the display. Fighters were scrambled to intercept, and further echoes appeared on the display. More fighters were despatched, and the apparent incoming raids seemed to increase in severity. Eventually, with a major raid apparently in progress, the fighters made contact and three aircraft were shot down, two by fighters and one by AA. As the defenders returned to base to refuel, the attackers disappeared from the display, until peace was restored.

From this detailed description, the problem will be apparent. The "raid" was illusory. In the absence of IFF, fighters behind Canewdon's aerial had been mis-identified as attackers in front of the radar, and successive waves of fighters appeared as new adversaries. The tragedy was that the fighters had shot down two RAF aircraft, killing the pilots. Dowding demanded an explanation. Watson Watt, without full inquiry, tried to defend radar by insisting there had been an enemy raid and remained firm in that view for over a week[133]. In his defence, there was apparent supporting evidence from an Army GL radar at Landguard Fort close by[134], and from the Observer Corps[135]. However, when a scientific investigator climbed the mast and discovered the relay problem, mistakenly thought by Canewdon's operators to have been fixed long before the "raid", Watson Watt eventually apologised. Nonetheless, the bond of trust was shaken, by a maintenance issue.

The effect of running the CH stations on a 24 hour watch was causing problems elsewhere. The Cavendish scientists kept notes of their CH station assignments, and these showed that at many stations the equipment was overheating towards the point of breakdown The inevitable consequence occurred on 16 October[136]. The Luftwaffe raided naval units at Rosyth. The area's CH had failed, and was unable to warn or guide the defending fighters. The Observer Corps performed well, but obviously could not give the same warnings as radar. The fighters consequently arrived too late, and significant damage was caused to several RN ships.

Shortly afterwards, Drone Hill CH went off the air with transmitter power valve trouble[137]. There were no spares closer than Driffield, 100 miles south. In a chapter of accidents, Driffield believed that the TRE scientists now at Dundee, having always given CH support and now being closer to Drone Hill, would do so again. When disabused of that notion, Driffield tried frantically to get spare valves, both from its own store and from Ottercops, to Drone Hill, which was off the air most of the day. Base Maintenance HQ, Leighton Buzzard, clearly identified lack of spares as the problem, and copied Dowding on that conclusion. Dowding was not unsympathetic, for he believed Air Ministry insistence on unnecessary 24 hour working was one culprit; but he did seek a comprehensive solution. He asked for an investigating Committee[138], chaired by Tizard, whom he trusted.

These operational incidents added to the visible failure of the Dundee accommodation arrangements made by Watson Watt. Particularly visible was the disruption to Bowen's work, on airborne radar[139]: this had two important customers, Fighter and Coastal Commands, and worked visibly to, and closely with, the Navy and the War Office.

Into this arena returned Philip Joubert, associated with radar from its inception as Chapter III above describes. On 1 November, he was attached to the Air Ministry as Air Co-ordinating Officer, RDF, with four primary duties[140]:

?? Examining the operational, technical and administration details of RDF and advising the Air Staff of deficiencies;

?? Remedying these deficiencies with the utmost despatch;

?? Advising DCD (Watson Watt) on RDF expansion to meet RAF needs, and

?? Advising the Director of Signals (Nutting) on reorganisation and training.

Plainly, Tizard's Committee on RDF was a major focus for Joubert's first month in office and Joubert spoke to Tizard on 30 October. During that time, he proposed that Dowding should not control the radar chain. Nutting raised the query "Is it not time that

Mr Watson Watt was relieved of (wider) responsibilities and confined himself to research and design…”[141] Those responsibilities were indeed wide, and accurately described by Joubert[142] as:

> “scientific advisor to the Air Staff and to Commands on applications of RDF, ..advisor to Naval and General staffs in corresponding fields, .. director of research and development on communications for the Air Ministry, .. director of production of RDF equipment for all departments, .. chief engineer for design and installation of RDF stations at home and abroad, .. chief maintenance engineer for those stations. He has also been responsible for research, development and initial provision of operations room equipment for the communication and display of RDF and other operational data in Command, Group and Sector Headquarters. He has also, in effect, been RDF adviser to the French Government.”

Tizard meticulously heard evidence from all parties and presented his first, interim, report on 28 November. Relying to some extent on an RAF Signals review of 1 November[143], he listed the general defects of the chain – no detection of low-flying aircraft, nor of those above 25,000 feet, only 7 of 20 stations with the high power transmitter, none with the specified RF6 receiver, or operational on more then one wavelength as a defence against jamming – with specific shortcomings of particular stations, of technical reliability and of training. Tizard concluded that DCD, Watson Watt, had too wide a span of control. He raised also the question of a separate Command “solely for the purpose of organising the various means of tracking aircraft”.

In his final report of 1 December to Newall[144], Tizard again postulated the “eventual separation of the chain …. from Fighter Command”, specifically stating that Joubert wanted that separation immediately, but that Dowding had strong counter-arguments. Newall took the stance that a Group within Fighter Command (60 Group, as it became) should take over installation and maintenance from DCD[145], while DCD would remain in charge of R&D, production, and interpretation of the Air Staff’s requirements.

The case for Watson Watt to retain even these duties was, however, fast becoming unravelled. Two factors would fatally undermine it:

?? The strain on manufacture, installation and fitting of airborne equipment by Bowen's group, as will be seen in Chapter VI. This had essentially broken down with the move to Dundee, and affected both Fighter Command (for night-fighters) and Coastal Command (for ASV radar).

?? The combined strain on production and installation created by the need for simultaneous expansion, both of the early warning Chain and also of the Chain Home Low-flying (CHL) radar. CHL was needed to stop mine-laying German aircraft striking naval anchorages, and also – since the CD set was essentially the same apparatus – both to guide War Office coastal gunnery, and, when used by the Navy as the CDU (Coast Defence, U-boat) set, to warn of incursion by surface craft and U-boats.

Both the War Office and the Navy now demanded control over their own RDF production[146], which would have adversely impacted RAF orders. Given that CHL equipment was not even an RAF Bawdsey "product", it will be useful briefly to amplify its history.

Unlike the RAF, which sought equipment for long-range early warning in order to have its fighters at the right height for interception, the Army needed simply a height and a bearing for coastal gunnery. By definition, its targets would be at sea level, and its radars could be simpler. Likewise, because range needs for coastal gunnery were shorter than those for aircraft early warning, shorter wavelengths could be used and the aerials be far smaller. The War Office scientists worked closely with Bowen's airborne radar group, for they shared a need for small and portable equipment. In particular, they adopted the Pye ex-television receiver chassis[147], and developed beam switching for their smaller aerials (the "split-beam" system for accurate bearings) [148]. From mid-1939, this War Office Coast Defence (CD) radar had been tested and found effective against low-flying aircraft. With few modifications, it became the RAF's CHL radar. Watson Watt had originally opposed its use, but Tizard and Dowding had overruled him.

Now a new and pressing Navy need had become stimulated by the need to defend anchorages, particularly in Scotland, against both surface and air attack. The loss of the *Royal Oak* to the torpedoes of Prien's U-47 in October had shown the urgency of that need. The energetic Admiral Somerville, recalled from retirement to head the defence of that area, had seen Coast Defence radar[149] at Bawdsey in mid-September and wanted this, slightly modified, for use against U-boats (and titled Coast Defence U-boat, CDU, radar) with the utmost urgency. A second German method of attack reinforced Naval demands with a further need to detect low-flying German aircraft, for these had begun to sow mines, including the new magnetic mine, in coastal waters[150]. Until the de-gaussing countermeasure was in place, the minelayers had to be shot down. CH could not detect them, but CHL could. This demand was also pressing - by 10 December 10 naval vessels had been lost. Somerville was insistent in his demands, and he was supported by Churchill in his new role as head of the Admiralty.

Extreme unorthodoxy was the order of the day in responding to these demands. A team of newly-joined scientists from the Cavendish Laboratory, Cambridge, under its head, Cockroft, simply drove the Bawdsey radar back to Cambridge[151] and, aided by Pye Ltd., began to copy it. They relocated to the War Office site in Christchurch, where their methods of acquiring parts would introduce the phrase "filching and scrounging" to the Official History of Army Radar[152]. Having thus created enough sets for Coast Defence they departed to Scotland, where their exploits included, on Fair Isle, "hauling the material by oxen up a gradient of 1 in 4"[153]. Their next move, to create a CHL defence, included simply taking from MetroVick a number of Army GL transmitters which had been put aside for faults to be remedied and repairing them, taking receiver parts from Pye to hand-build receivers[154], and finally looting the stores left behind at Bawdsey. The aerials were a marvel of improvisation - two twenty-foot gantries straddled the transmitter and receiver huts, with cradles bolted to turntables on those gantries. The 26 foot by 13 foot aerials were fixed within the cradles, and both were turned by a bicycle chain drive from a static frame where two airmen (the "binders") tried to keep the aerials moving in synchronism by watching a centre-zero meter and moving the hand-cranks quickly or slowly as required[155]; the arrangement is pictured in Fig. 44. They installed the first CHL at Fifeness on 1 November, to be joined in December by sets at

Dalton and then by Dunwich; Happisburgh, Shotton and Easington followed before 1 January. None had even the simplest of testgear, neither a wavemeter nor an Avometer[156]. It is perhaps worth commenting that this group of scientists did not complain of their Christchurch site, though it was even sparser than Dundee. The Official History is positive in recording their setting-to and digging ditches, sustained by food from “Joy’s Transport Café”[157].

The equipment, of sorts, was in place, but a series of major issues with Finance branch for the unorthodoxy, even illegality, of the payments for the parts came to Joubert to resolve[158]. Observing this semi-piratical improvisation, the War Office and the Admiralty unsurprisingly thought they could manage matters better themselves. Freeman, as the Air Council member responsible, received their written requests so to do in mid-December[159]. Enough was enough; he proposed dividing Watson Watt’s role in two, establishing two Directorships, one for R&D Communications and one for Communications Equipment Production.

Joubert, however, had a further problem to handle. Watson Watt, stimulated by Fighter Command’s head of O.R., Larnder, had ordered yet another crash programme of CHL installations[160]. However, Dowding had not been consulted and threatened to disown this new chain. Exasperated, Joubert now recommended that there be a third post, of Adviser to the Air Ministry on Telecommunications, free from *both* R&D *and* Production responsibilities; those would be the responsibility of the two Directors proposed by Freeman. Watson Watt, he considered, should be that Adviser, for his “knowledge and expertise were unique”[161]. The Air Council sought the approval of the Treasury on 4 January, proposing Sir George Lee, recently retired as Chief Engineer of the GPO, as one Director[162] and the experienced Leedham, who was referenced in Chapter III as ordering the first radars, as the second. Considerable pressure had to be put upon the Treasury, but their assent was eventually gained. Watson Watt took up the role of Scientific Adviser on Telecommunications (SAT), and was to remain in similar middle-management advisory roles throughout the war[163]. His executive role had ended within 100 days of the outbreak of war, through neglect of comprehensively pursuing progress across all lines of development.

As Air Co-ordinating Officer for RDF, Joubert de facto was now charged with the planning and managerial roles for delivery of the radar-based air defence system. His time was to be divided between strategy, as in his recommendation for a "Communication Command" to control radar (a view in complete opposition to Dowding), and fire-fighting, as on the CHL programme and payment issues. This dual focus was to occupy his life for much of 1940.

Delivery and implementation in the winter months of 1939/40 were to be crippled by the appalling weather of the worst winter for 40 years. The Germans continued to fly low level missions against east coast shipping, and Joubert continued to push ahead the second, 7-station, CHL programme[164], in part due to his distrust of the contingency – a screen of trawlers to radio back low flying aircraft movements, an echo of WW1. By mid-February, all 7 CHLs were operational, but the resulting strain on manufacturers and installers meant that CH work was delayed, and that the War Office would have to wait until 1941 for delivery of its Coast Defence (CD) radar, for the whole of Pye's output was taken up by CHL orders. Correspondence shows that Joubert was clearly under pressure in his dealings with Lee[165], the newly installed DCD, and relationships suffered to the degree that Freeman became involved. Watson Watt, in his new role, did not help by insistently pointing out the CH problems that flowed from priority being given to CHL[166], for CH was far from a perfectly functioning entity.

By the close of 1939, at least two of the 360 foot masts had been installed on the 18 CH sites, and the receiver buildings were ready for the specified RF6 receivers[167]. However, a review of the Chain coverage in January showed the requirement for further extension of the Chain. Coverage was now needed along the south-west coast, the Scilly Isles, the Liverpool/Clyde coast, and the naval anchorages of Devonport and Scotland. Before the end of February, a policy meeting chaired by Dowding and attended by Joubert, Lee, Watson Watt, the War Office and the Admiralty identified a need for a further 13 CH stations above the 18 in use, and 22 more CHL stations[168]. Desperate expedients were necessary to achieve this quickly. For Chain Home, a new aerial array which was strung between the masts, rather than mounted on them, permitted a reduction in the number of masts needed. One mast was therefore taken from each of six completed sites to use for the new stations – one, from Rye, was reported to have been erected only seven days before being dismantled for re-use[169].

It is instructive at this point to illustrate the total loading which was being placed on manufacturers and the spares/maintenance supply chains. Radar was now being procured in quantity for the RAF, Navy and Army. Additionally, the IFF secondary radar, the CRDF location equipment and the VHF ground/air communications sets consumed much the same resources and skills. The total strain on the manufacturers was significant. The extra CH and CHL stations have been described. In addition, the Army had 344 GL1 sets being made, with the higher power GL1* (GL1-star) and more functional GL II sets authorised for production[170]. The Navy was trying to make up for lost time. In April, it issued orders to GEC, Cossor and Marconi for 200 of Coales' 50 cm set Type 282, to be delivered by *November* – and then expanded the order to 900 sets in June[171]. Trials of the RAF's VHF communications system at Duxford in October 1939 proved successful, with a 150 mile range to the TR9's 40 miles, and in November 1939 orders were issued for 13,260 sets by March 1941, a massive increase which Tizard had foreseen and had advised Watson Watt to meet industry to discuss[172]. Three months later, the ground equipment was ordered – 72 mobile ground stations for R/T and 77 for the VHF "Pipsqueak"[173]. GEC, the prime contractor, began deliveries in March 1940 building up to 150/week within a month. IFF was the province of Ferranti; their 1939 order for 1,000 IFF Mk I began to be delivered with 100 hand-built in early November, mainly for Bomber and Coastal Command[174]. The Mark II set, with extra frequency coverage, was being developed almost in parallel; 10,000 were ordered in September 1939, and the first 50 hand-built sets were delivered in May 1940. By that point, in a classic case of "dysfunctional diffusion", the fact that the IFF set could also be used as a navigational beacon had been discovered by S/Ldr. Lugg at Leuchars[175], and demand increased yet again. 21,000 sets would eventually be manufactured. As was commented by the Navy, the Services were "relying on the good relationships built up with the manufacturers"[176], but it was also to be expected that manufacturers had to build up workforces rapidly and the equipment was often delivered with faults or minus essential components. Likewise the strain on individuals acting as a focal point for manufacturer relations was immense – Rowe went so far as to intercede with Tizard to reduce the pressure on Leedham, who currently held that role[177].

The human resource issues were consequently extremely worrying, both in terms of the supply and the training of operators and of mechanics to use and service this rapidly growing radar base. The first party of WAAF to train as plotters at Leighton Buzzard arrived there on 4 September. The success of their training was shown by the enthusiastic response from Poling, where the first "graduates" were posted[178]. A WAAF operator "on the tube" is pictured in Fig. 45. However, Bawdsey – which had only one receiver on which to train its trainees – could produce a maximum of 27 operators per course, and a basic calculation showed that 1,300 WAAF would be required. Again, desperate measures were adopted; the course was to be cut to two weeks[179], although this decision would not remain in place for long.

The problem of maintenance staff was even more pressing, and much larger in scale. The extra burden of maintaining CHL forced an urgent review of the manpower supply/demand position; of 1,000 mechanics needed, only 250 were available[180]. Yatesbury had opened on 18 January to train technicians, but almost immediately closed again with personnel being sent home on 3 weeks' leave due to freezing weather and incomplete facilities. Joubert had approved external recruitment, targeted at radio service mechanics, to fill the gap[181]. Realising the exigencies of military service from this Yatesbury experience, many of the new recruits resigned, leading to acrimonious correspondence between Joubert and the Director of Training[182]. The situation improved only slowly.

Staffing problems of a different nature occurred with the Observer Corps. Unbelievably as it may seem, at the date of their mobilising for war on 24 August 1939, the Observer Corps members were unpaid, had no uniforms, and no official status beyond that of unpaid special constables – their mobilisation documents were signed by the Chief Constable of their area[183]. For a national force, this was clearly unacceptable, and a solution granting them up to £3/week against proven loss of earnings was rushed through. Their uniform issue was not solved until the Fall of France, when in the event of invasion it was feared that they might be shot as *francs-tireurs*. Granted a single-status uniform with a midnight blue rank band, they were alternately mistaken for Brigadiers or for members of the War Graves Commission[184]. Despite the maladministration, from the beginning they performed their inland tracking role with great credit, in the opinion of Dowding[185].

There continued to be equipment problems with CH stations. Chief among these was height measurement. The hand-held calculator was not a user-friendly device, and staff invented their own, incorrect, rules of thumb to avoid using it. Dowding advised the Air Staff that, as a result, there were further problems over and above the known issues of CH's inability to detect low fliers, and aircraft at heights over 25,000 feet. Now, he pointed out, even between these limits height reading was very approximate - "the situation is much worse at 10,000 ft., and when we come to 5,000 ft. there is practically no part of the coast north of the Humber where height can be read at all"[186]. The electrical calculator being developed from Roberts' and Marchant's work at Poling would materially help, but was as yet still in manufacture. The entire chain would be fitted just in time for the Battle of Britain, the 21st calculator being fitted on 30 June[187].

Problems were also caused by incessant visits of staff from Fighter Command and from Dundee to the CH stations[188], either to observe or to modify the equipment. Many of the scientists did not realise that their modifications necessitated a complete recalibration of the station, typically taking the technicians and mechanics a full week. A series of terse letters[189] curtailed such scientific visits.

However, by far the most contentious issue between Joubert and his customer, Dowding, was the question of filtering. This process – the comparison of plots across all stations to eliminate duplication, and the comparison of all plotted aircraft with known flights from all Commands, so as to identify positively every track – had become critical in the absence of IFF. Though CH was far from perfect, it was a great improvement from 1938 in equipment terms; yet O.R. showed that the overall system performance was worse[190]. Such a result could only follow from organisational or people problems.

Filtering had been identified as an issue from the earliest O.R. reports in September 1939, and a significant study was published by Williams, one of the expanding O.R. function's section heads, on 11 January[191]. A series of specific incident reports also outlined the need to compare tracks from adjacent stations, to avoid duplications or, worse, both stations missing a track by each assuming the other would plot it. The continued absence of IFF, identified by Dowding to Tizard as one of the three major issues facing Fighter Command[192] (the other two were lack of AI radar, and of an armour-piercing machine gun) had been caused by delay in its manufacture in order to design in demolition charges to deny its secrets to the Germans. Eventually, by February 1940, 258 aircraft, mainly bombers, were fitted with IFF. By the end of May, most of Bomber and Coastal Commands were equipped, but only by the end of the Battle of Britain had almost all RAF aircraft been fitted[193]. Even then, this was far from the end of the story. Serviceability of the early IFFs was poor, with little maintenance training and no test gear until Spring 1940, training aircraft not being fitted, and battle-damaged aircraft often having an unserviceable IFF. Filter rooms would therefore remain of cardinal importance.

The filtering debate focussed around two schools of thought[194]. The first held that centralised filtering at HQ created a delay and an unnecessary potential blockage in the system – it could be overwhelmed by the volume of traffic in the system. Joubert's conclusion was that filtering should be decentralised to Groups. The second view, held by Dowding, favoured centralised filtering. The process of filtering, they pointed out, had to be done somewhere – hence it was no more of a delay to do it once, at HQ, than do it in several Group locations, between which more boundary problems would arise. In addition, more filter rooms would have to be built and staff trained, and there was now no time to do either. Indeed, it was only in March 1940 that Fighter Command's own Filter Room relocated from the adapted room at Bentley Priory, illustrated in Fig 46, to the purpose-built underground room shown in Fig. 47.

It was common ground to both groups that the quality of existing filtering staff was not very high. Radar had gone beyond the stage of being run by enthusiastic scientists - it had become a comprehensive system, run by individuals of defined grades, skills and duties. Williams' study had proved the error of assuming that the dedication of pioneer airmen filterers would pass by osmosis into their successors. However, the issue was of longer standing. Hart, now at Fighter Command HQ, had commented on the same issue the previous November[195], and had proposed to recruit civilian filterers to bypass the low military grading placed on the role, but had been refused by the Air Ministry[196]. Tests were then conducted with three physicists acting as filterers, which proved to be outstandingly successful[197]. The case was presented for filterers to be of officer status, and this was eventually conceded after considerable delay in March. The first 15 trained officer filterers took up their roles on 10 June[198], and the Official History is of the view that their contribution was essential.

The organisational location of filtering – Command or Group level - was a much more intractable problem. The day following Williams' 11 January report, Newall called a meeting to discuss the Air Staff view that the time lag involved in filtering meant fewer interceptions[199]. A day later, Dowding discovered[200] that the draft minutes recorded that he had agreed that:

?? Fighter Command HQ would pass plots to Groups as soon as the direction of incoming aircraft was known;

?? He would consider passing RDF plots directly to Groups, who would then communicate them to Command;

?? CHL plots should go to Sectors, who would take action without reference to Groups or Command.

Dowding pointed out in plain terms that this misrepresented his position:

> "My system is now being criticised at the Air Ministry by officers who do not know the circumstances in which the system was created and are even unaware of the existing facts. …..These (proposals) put forward at the meeting, viz., filtering on existing Group operations tables, I can only describe as fantastic"[201].

The target of his barbs would have been immediately recognisable. Joubert had been in India after his spell in Coastal Command in 1935-7, far away from radar development. The point is significant because the debate would continue during the Battle of Britain, and would result in Dowding alleging in writing to Churchill that Joubert had no understanding of the importance of “differentiating between friendly and enemy aircraft”[202].

In January 1940, the Air Ministry suggested further meetings and Dowding replied:

> “My contention is that the Air Council have the right to tell me what to do, but should not insist on telling me how to do it as long as I retain their confidence”[203]

This “back me or sack me” response closed the correspondence for the time being, though Joubert added a file note that “the Air Ministry should continue to control closely the development and application of RDF”[204].

The problem will be analysed further below, in the context of whether the centralised filter room, staffed by selected officers, could cope in the Battle; but two unremarked elements may be noted. First, the processing of plots by the Electrical Calculator meant that plots could be passed to the Stanmore Filter Room at 7 plots a minute, faster than they could be recorded[205]. Second, the CH expansion, and the multiplication of CHLs, was already causing Group filtering functions to be established in Scotland, the North-West, and the South-West[206].

It remains to note that the unhappy experiences of the research staff at Dundee were coming to an end. Within weeks of their unsatisfactory move to Dundee, an alternative location at Worth Matravers, Dorset was identified and reconnoitred on 21/2 October[207]. Approval was given in December for a move there, but Rowe wished the time for an orderly move with everything in place before the physical relocation. That process took time, partly due to inclement weather, and the move took place on 3-6 May, just in time for the 10 May invasion by the Germans of the Low Countries and France to return the scientists to the firing line.

That same invasion, following upon the April invasion of Denmark and Norway, also precipitated the resignation of Chamberlain and the elevation of Churchill to Prime Minister. With Churchill came Lindemann, and within a month, Tizard departed from the Air Ministry[208] in circumstances described in Chapter VI below. In those same weeks, Churchill had created the Ministry of Aircraft Production to take control of the Air Ministry's development and production activities, and the vigorous Beaverbrook was appointed as its head. To this new Ministry would now report Rowe and the Worth scientists, Lee, as DCD, and Freeman, in charge of the whole "supplier" activity. In the Air Ministry remained the "customer" function - Joubert, Watson Watt, as SAT, and Nutting, Director of Signals. The "end user", Fighter Command, under Dowding, retained its O.R. function and 60 Group, its maintenance and installation activity, now significantly expanded to meet the needs of the growing Chain.

There are, therefore, two views on the state of radar as it entered the Battle of Britain, and these are worth quoting at length. First, an operational assessment by Watson Watt, written 25 years later, looks at the position on the ground[209]:

> " The CH stations entered the Battle with good and dependable indoor equipment; aerials not yet as good as we would have liked; calibration seldom complete….range finding good; direction finding fairly good; height finding as always a delicate and difficult operation; counting an art still in the learning; continuity in individual tracking impaired by still half-developed procedures in heavy traffic conditions; filtering and display still being learned in the only available school, that of full-scale utilisation; supply of suitably minded and adequately experienced observers, recorders and plotters very acutely limited."

Second, Joubert's contemporary high-level and organisational view[210]:

> "The situation … is considerably worse. Sir Henry Tizard's resignation has been effective and there is "war" between Sir George Lee and Mr Watson Watt. Mr Rowe is in open mutiny. Further, Mr Watson Watt has departed from the arrangement made some months ago whereby you decided that he was to advise the Air Staff on telecommunications, and is now inserting himself into Sir Frank Smith's organisation. I understand the latter has now taken over all Sir Wilfred Freeman's responsibility for RDF production. My position has become impossible. I have responsibility without authority and the RDF sheep, harried by the Lindemann wolf, are rushing madly in every direction. No-one knows who to go to for orders…..".

Day Air Defence Lines of Development Position at 01.07.1940.

On the eve of battle, the air defence system was generally in a good state to face conflict, but with a number of weak points. Both CHL and IFF equipments had been rushed into service; in the case of CHL there were many non-standard, hastily-assembled “lash-ups”, and in that of IFF, too few equipments to fit all aircraft – hence Dowding’s concern about identification and the need for tight control of filtering. Chain Home would have calibration problems throughout the battle, and the impact in terms of uncertain plotting, exacerbated by the inexperience of a number of the rapidly recruited and barely-trained personnel, threw further strain on the filtering process. Nonetheless, held together by its people, the system worked just well enough to prevail.

01.07.1940	CH	CHL	OC	CRDF	IFF	R/T
Doctrine & concepts	Green	Green	Green	Green	Green	Green
Equipment	Green	Yellow	Green	Green	Yellow	Yellow
Infrastructure	Green	Green	Green	Green	Yellow	Green
Sustainability	Yellow	Yellow	Green	Green	Yellow	Green
Personnel	Yellow	Yellow	Green	Green	Yellow	Green
Organisation	Green	Green	Green	Green	Yellow	Green
Training	Yellow	Yellow	Green	Green	Yellow	Green
C3I	Green	Green	Green	Green	Yellow	Green
Interoperability	Green	Green	Green	Green	Green	Green

Table 6: Radar-based day interception capability: summary position at 1.7.1940.

The performance of the system under the pressures of battle is now examined.

IV.5. July to October 1940: The Battle of Britain.

The Battle of Britain, on conventional reckoning, opened on 15 July 1940. The 2,000 days effort since Watson Watt’s memorandum on radar would now be put to the test. The test, it may be observed, was hardly the one predicted, for:

?? The attack would not come from Germany against the East Coast chain, but from France, against the South Coast chain;

?? The attack would not consist of bombers only, but of bombers heavily escorted by high performance fighters;

?? Because French airfields were much closer to the UK, the early warning would be much shorter than anticipated – the seconds shaved off interception timings by the practice and training triggered by the Biggin Hill experiments, and the role of O.R. in optimising the system's efficiency, would prove crucial;

?? Again because of the closeness of the French airfields, the short range Chain Home Low (originally an Army radar) could plot the Luftwaffe taking off.

?? the German tactic of stacking formations on top of each other would compound the Chain Home stations' difficulties with providing heights, due to inadequate training and lack of calibration, and

?? In addition to radar, signals intelligence (SIGINT) proved extremely useful in identifying likely German formations, targets and intentions.

An illustration of the radar coverage achieved by this date is shown at Fig. 48, and an enlargement of the area over which the Battle was mainly fought is set out at Fig. 49.

Once battle was joined, the delivery work of the scientists was not over. The focus changed to the delivery of systems for the night battle, including attempting to fit single seat fighters with rudimentary radar-based interception aids[211], and these will be discussed in Chapters V and VI. Work had also begun on centimetric radar[212], which would prove a major step forward after 1941. Of rather greater relevance to the immediate threat, scientists were also testing the ability of CH to detect wooden gliders[213], since the British military had been greatly impressed by the ability of German glider-borne troops to capture the previously impregnable Belgian fort of Eben Emael.

It should be observed in passing that the earliest radar-based interceptions of bombers flying over the North Sea had been by *German* fighters intercepting *British* bombers attacking *German* fleet anchorages in day raids in September 1939[214]. Freya coast defence radars, analogous in role and use to the British CD/CHL, detected the incoming bombers and contacted the local fighter base. The bombers were heavily mauled and the British turned to night raids, as would the Germans a year later.

A brief review may be made of the Chain status on the eve of the Battle of Britain. It had not seriously been tested by the Germans in the "Phoney War", though there had been several instructive events, in particular the Battle of France.

To defend France, in 1939 Watson Watt had been heavily involved in giving advice to the French to establish an early warning network on British lines[215], and the French were advised of the British radar "secret". In fact, a primitive French system, the David system, using the radar principle was already in operation[216]. This was a radar "tripwire" where the reflected pulses from the target were displayed as beats on a meter. Devoid of IFF, or any means of height or direction-finding, and never having been integrated into air defence or used to guide interception, it was of little value. As has been shown above, British equipment manufacturers were working to capacity for the UK Chain, and so very little could be given to France. Since only the shortest warning could be given by any radar near the Franco-German border, such a system would in any event have been of modest value. Some British Mobile Base (MB) radars were deployed, but were overwhelmed in days. Without early warning, a high proportion of Allied aircraft were lost on the ground due to German air strikes, or destroyed to avoid capture - around 200 Hurricanes were lost in this time, over half on the ground[217].

The "secret" of British radar was revealed to the Germans by the French after their armistice, although of course the Germans already had several systems in operation themselves. However, though this French action created ill-feeling at the time, incorrect assumptions were drawn by the Germans from that revelation. Noting that the Mobile Base radars captured at Dunkirk were crude compared to Freya, and that the Graf Zeppelin ELINT mission had found no radar, the Germans drew the flawed conclusion that the British system was one of tight, inflexible, ground control[218]. In apparent confirmation of that conclusion, the British operated standing patrols at Dunkirk where losses totalled another 109 modern fighters. This, as has been shown, was in fact because the TR9 HF radios did not have the range for interceptions to be controlled from England[219]. A Luftwaffe intelligence report of 16 July makes no mention of any early warning system employed by the British[220].

The British radar system was, however, under strain. The increasing demands for operators were illustrated above. In a desperate attempt to provide the required numbers, the training course length had been cut to three weeks on 17 June[221]. The result in terms of operator errors was so immediately obvious that Thompson, in charge of Yatesbury, refused to sign off course attendees as qualified[222]. O.R. confirmed the problem and the longer course was re-instated.

The commissioning and calibration of stations was also a major problem. 60 Group, RAF, called into being as late as February to undertake this role, serviced 21 CH and 16 CHL stations, soon to rise by a further 23 CHLs. As a result, the lengthy CH calibration process was behind plan. A previously unreferenced memorandum[223] shows that on 1 August, Ventnor, Poling and Pevensey – half the South Coast – could not give accurate bearings, while Ventnor, Poling and the critically-placed Dover could not give accurate height. An OR report also shows Pevensey, Poling and Rye cluttered with back echoes from behind the radars, rendering the screens difficult to read[224]. The result can be implied from subsequent, again unpublished, calibration information[225] – errors could amount to as much as 20 degrees, a difference of 17 miles at 50 miles range. The situation became so serious that Dowding chaired a conference on 8 August which effectively "sealed" CH radars from any further modification once calibration had been carried out[226].

An unexpected conclusion of the present research, stimulated by probing the sustainability line of development, is that the source of many calibration problems can be traced back to the minor component of the insulators on the CH aerial system. Though a clue is in the Official History[227], a further previously unreferenced file[228] sets out the events. An original specification for the insulators had been issued in November 1938, but amended in July 1939 to include cheaper materials and design changes. Accordingly only the original pattern insulators, 25% of the total, were supplied until the new insulators had been tested. These tests were expected to be straightforward and cost under £50, but a catalogue of errors followed – lack of test specifications and equipment, no purchase order for the tests, debate on whether a TRE witness needed to be present, and inability to recognise the insulators for test due to lack of Stores

Vocabulary reference numbers. Meanwhile, the original insulators were used. The tests revealed significant leakage to earth, but due to the confusion the results, dated April 1940, were forwarded only in November. Before that time, Wilkins had identified four cases, including Dunkirk, where leakage was a problem, and the manufacturers confirmed on 6 September that early batches had faulty glazing. The degenerative leakage so caused are likely to have caused many calibration and phasing difficulties and are illustrative of the need to focus on apparently minor components contributing to sustainability.

On a more elevated level, it is fortunate that further sources of information were available to the British. These were less likely to be strategic information from Enigma decrypts. Though the Luftwaffe was lax about security, G/Capt Winterbotham's memories of Dowding's receiving Enigma decrypts[229] appear invalidated by the fact that Churchill did not approve Dowding's having such data until October[230], and indeed the first timely flow of decrypts did not become available until some time into the Battle. Rather, the RAF had invested in SIGINT, a modest station being established at Waddington in 1934[231]. Further units followed at Montrose, Sutton Valence, Lydford and then a major site at Cheadle. After May 1940, "Home Defence Units" (actually VHF intercept stations, against Luftwaffe tactical communications) were established at 10 coastal sites[232]. Because of lax security, these often identified German targets and formations, and, when correlated with radar plots in Filter Rooms, this was of great value. A near-contemporary account by a Group Controller[233] gives SIGINT as significant a role as radar, and more so in a quoted major raid. This must be set against the fact that SIGINT is of limited use to guide an interception; but radar, with its deficiencies, was clearly not the only useful sensor in this Battle.

The problem with multiple sensors – in this case, CH, CHL, SIGINT, Observer Corps, radio D/F, some IFF - is their burden on C3I. The factors affecting the key C3I element in the Battle of Britain, the Bentley Priory Filter Room, and its capacity do not appear to have been previously remarked in detail. There were in fact seven such factors which need to be considered:

?? Significantly reduced processing time because raids were flown from France, as opposed to Germany, the plan assumption;

?? Mechanisation of CH station plotting, due to the Electrical Calculator, meant that plots could be communicated faster than the Filter Room could assimilate them (even given that the CHL stations passed their plots to the local CH, not the Filter Room, to keep down traffic);

?? IFF was neither in most RAF aircraft nor, even when installed, was it reliable – Filter Room had to resolve many more cases than planned;

?? Observer Corps and D/F stations had to report over-land and friendly fighter plots respectively, and all these reports had to be correlated;

?? SIGINT from HDUs and other intercept was flowing into the same location;

?? Lack of calibration of key radars fed added complexity and uncertainty into Filter Room decision taking;

?? Inexperience and short training of Filter Room staff and CH operators compounded the issue – the first trained officer filterers took up post on the eve of the Battle[234], and the two-week trained (sometimes untrained) radar operators had had no time to make up their skills. Flint also notes that experienced Observer Corps Operations Room plotters were transferred to the Filter Room as being at least partly trained[235].

Most of these factors fall directly into lines of development issues. To them should be added the complication of shifting German tactics in the Battle. After losses in the early phases of the Battle, Goering instructed his fighters to fly in defensive patterns around the bombers. The effect of this was to build up significant formations numbering into the hundreds covering a volume of airspace several miles in breadth, depth and height. These produced a radar plot difficult to interpret, and one for which operators had never trained, the expectation having been for much smaller formations approaching from Germany.

An excellent account is provided by Peter Flint[236] of the differing roles and styles of the two main plotting rooms of Bentley Priory – the Filter Room and the Operations Room – and of the differing decisions taken in each. His account contrasts the experiences of one WAAF from each, Joan Clarke, née Crawford, in the Operations Room and

Margaret Taylor, née Doll, in the Filter Room. Both rooms had large outline map tables of the East and South of England, but the similarity ends at that point. The Operations Room, shown in Fig. 50, was generally quiet, with the WAAF "croupiers" pushing small markers adorned with details of raids or defenders to positions identified by a Filter Room "teller". The various Controllers for fighters, AA, and air raid warning made their decisions and gave telephone instructions to Groups to dispose forces accordingly. The picture is familiar from films.

The Filter Room, by contrast, is very rarely considered. The room, shown in Fig. 51, is described as noisy and high pressure, in the attempt to decide upon the correct interpretation of raw data from radar, Observer Corps, CRDF and Sigint, and how best to correlate the disparate information to decide upon the picture for the "teller" to communicate to the Operations Room. Sections of the Filter Room map are illustrated at Figs. 52 and 53. Painted on the map are "range curves", centred on the radars, for 1940 radar is more accurate at range than bearing, and potential overlaps are resolved by range measurements from each radar ("range cutting") to give an accurate position. This is then correlated with Observer Corps, CRDF and Sigint data, and the agreed position "told" to the Operations Room. The major challenge was the lack of IFF on many friendly aircraft, which meant that every unidentified aircraft had to be cross checked with Bomber, Coastal, and Training Commands and the Navy's Fleet Air Arm. Given that several hundred aircraft would be in the sky at one time, the noise and pressure of the Filter Room may easily be imagined.

From early August, therefore, before the major raids, Larnder was concerned about potential system overload[237]. Early warning – the radar chain's essential function – was, he warned, not compatible with attempting mass short range ground controlled interceptions. A second issue arose simultaneously. Keith Park, commanding 11 Group and in the heat of the battle, became extremely concerned that the height and number of attacking aircraft were being wrongly assessed[238], so that too few fighters were despatched or were poorly positioned. An O.R. inquiry showed that the problem was inadequate training – the operators had developed their own, often inaccurate, rules of thumb[239]. This, while serious, was an operational, tactical, issue. By contrast, the collapse of the complete system through overload would have been a strategic disaster.

To counter this, a “macroscopic” system of raid plotting was established[240], whereby the raid was plotted as soon as possible with an assessment of numbers as “100+” , and tracked as best it might be (one suspects from SIGINT and D/F as much as radar).

The defenders were aided by the failure of the Germans to press home their attacks on the radar stations. Martini, the Luftwaffe Director of Signals, had persuaded Goering to attack the Chain following German intercepts during the Battle, which had identified some form of controlled interception taking place[241]. That was hardly practicable without radar, and hence Martini’s proposals for interdiction. On 12 August, 16 Me110s of Erpro 210 attacked Pevensey, Rye, Dunkirk (Kent) and Dover[242]. The attacks showed that radar stations could resist assault, the masts in particular being blast resistant. Ventnor, hit by 15 Ju88s in a separate raid, was more seriously damaged. By various expedients, most of the stations were off the air for minutes rather than days – Dover, for example, just 30 minutes and Rye 3 hours. An instructive and previously unreferenced source of information on the attacked radars is the reports of the RAF Inspector-General, Ludlow-Hewitt, who visited them immediately afterwards, and again at the end of August. He comments particularly about the lack of foresight in not creating adequate revetments and traverses; in not providing alternative shelters at Poling and Rye, where trenches could not be maintained due to the marshy ground; and on the exposed position of the critical ground/air mobile R/T stations which had moved onto the coastal radar sites to lengthen radio range, for their operators had to remain at their posts in their vehicle while the station was being heavily bombed around them[243]. Fortunately, Goering, unconvinced either of the criticality of British radar or the results of the attacks, called off further major raids. Only two more were flown – against Ventnor on the 16th and Poling a day later – but these did in fact disable both radars[244]. Ventnor restarted with mobile radar on the 23rd, Poling, evacuated due to unexploded bombs, was on the air again two days later, also with a mobile. On the 25th, Park advised his staff that future information from both would be materially unreliable[245]. In point of fact, as has been shown from the unreferenced calibration data, radar data from them was already suspect; interestingly, Ludlow-Hewitt reported that the operators thought that the mobile at Poling was better than the permanent station..

However, at that point Goering was changing his tactics, to focus first on airfields and then later on London. In so doing, he almost severed the Achilles tendon of the Chain, for that vulnerability was at the level of the Sector Control Rooms, based on the airfields – not in terms of the rooms, protected by earth revetments, but of their power and communications cabling, which had been insufficiently dug in. The result was that several were knocked out, and the Emergency Control Rooms established in local business premises were inadequate in both communications and equipment[246]. It has not been previously commented that, had filtering been decentralised as Joubert wanted, the likelihood is that this same damage would have caused more material disruption to the air defence system and disastrously downgraded its capabilities.

A game of electronic bluff and counterbluff was also in progress. On 19 August, Fighter Command had built up enough VHF sets to re-equip 11 and 12 Groups, and began to do so. However, the HF equipment was kept operating with false messages to deceive the German intercept service[247]. On the German side, Martini had moved from demanding bombing to setting up jammers, this being frequency-modulated continuous wave (FMCW) signals on the CH frequency. However, from the earliest times, the British had foreseen this possibility, and countermeasures – essentially, extra receiver circuitry and the use of red phosphor long afterglow CR tubes - proved adequate to defeat this[248]. Additionally the total British system included CHL radars and SIGINT, and neither were vulnerable to FMCW jamming on the CH wavelength. Nevertheless, jamming placed another burden on the imperfectly trained CH operators and Filter Room staff. That training did make a difference is shown by the response time of the stations in countering jamming – Bawdsey, Dover, Dunkirk and Canewdon were affected for only minutes, Great Bromley, Rye and Pevensey for much longer[249]. However, all met the challenge, and on 11 November the Germans ceased the effort.

German tactics and the strain on the Filter Room were proving an increasing problem. By mid-September, as the German assault was switched to cities, especially London, Dowding despatched the O.R. team to investigate[250]. Raids were now en masse, with many German fighters climbing to considerable heights and taking time to do this, so that their plots complicated the Filter Room maps. The Observer Corps often could not confirm their presence, because either of bright sunlight, or cloud below them. Park was then obliged to fly standing patrols, or to use VHF equipped Spitfires to shadow this German top cover[251]. In this September phase of the Battle, several raids were flown at 30,000 ft, and revealed a further problem with CH – at this height the gaps between the power projected by them (the "lobes") was considerable, and aircraft in those gaps were not detectable.

At this point, the entire question of where filtering was to be carried out was raised once more by the Air Staff. In this instance, the proximate cause was the inquiry by a Committee under MRAF Sir John Salmond into the organisation of defence against the night bomber. Formed on 14 September, that Committee produced its report eleven days later[252]. Dowding was much surprised to read, as the second of its recommendations, that filtering was to be decentralised to Groups, this being more a daytime than a night interception issue. He objected most powerfully[253], and a meeting was held on 1 October chaired by the CAS, Newall, and including Salmond, Joubert and Dowding. Dowding was forced to concede Group filtering, although he gained a delay until IFF was fully installed[254]. As has been shown, the difference in workload had IFF been widely fitted and working would have been substantial. The conflict between himself and Joubert was now open. Dowding wrote to Churchill a letter of complaint[255] which included a direct personal attack on Joubert, stating that in Joubert's three years as head of Fighting Area, ADGB (1934-6), Joubert had done nothing whatever in the field of distinguishing friend from foe. Churchill in turn wrote to Sinclair, querying the decentralisation proposal[256]. Joubert drafted the response, to the effect that if the Germans repeated their attacks in 1941, the system would collapse[257]. Still unconvinced, Churchill queried if the move really would save time[258]. Again Joubert drafted the reply, that an extra process would be eliminated, but in this case the Air Staff were unconvinced and that statement was removed, leaving only an assertion of saving between 30 seconds and "several minutes"[259] It is uncertain whether Churchill was convinced.

By this stage the O.R. report commissioned by Dowding in September on the capacity of the system was nearing completion. That report showed clearly[260] that 7 filterers would be needed for 11 Group alone, but that Stanmore had only 5 to cover 11, 12 and 13 Groups. Additionally, the report warned, the output from the Chain was likely to be doubled, given mechanisation of their output and more stations. Plainly, the Bentley Priory Filter Room was increasingly inadequate for its task.

It may appear that Dowding was at fault, but timing in war is crucial. Following the decision to decentralise, taken by the Air Staff on 1 November and implemented after Dowding's departure in mid-November, a target completion date of 1 February 1941 was set. In the event, completion was eventually achieved only by September 1941, GPO lines and equipment being key delay factors[261]. Realistically, if the decision to decentralise had been taken in March 1940, then it appears on this evidence likely that:

?? Filter Rooms would have been co-located with Operations Rooms, and at sector level would have been on airfields, and so subject to attack in the Summer of 1940 as described above;

?? Telephone lines would probably have delayed the move, as would the lack of trained filterers;

?? Confusion would have been the probable result, with an incomplete move in progress during the Battle itself. Given that the system as actually operated was close to collapse during the Battle - as shown above – and given the critical place of the Filter Room in the system, the likelihood is that collapse would have occurred with the decentralised system.

This does not imply that Dowding was correct to reject decentralisation in October. By that stage, he was undoubtedly tired, for in addition to overall direction of the battle, he was accustomed to drive to airfields in the evening for night-fighter tests. At least as important, but rarely remarked, the departure of Tizard in June 1940 had deprived Dowding of a trusted and well-balanced colleague. In 1939, Tizard had inclined to the view that radar might be separate from Fighter Command, and he was perhaps the only person who could have so persuaded Dowding. After June 1940, deprived of Tizard, exhausted, and under attack from Joubert, a junior whom he did not respect, Dowding was not thinking forward into 1941 – he was trying to fight the night Blitz – and personalised his rejoinder when the O.R. report on RDF capacity might have given an acceptable exit. Decentralised filter rooms in fact already existed for 9 Group, at Preston, for 10 Group, at Box, and for 14 Group at Kirkwall, and by November 1940 the question of decentralising filtering was simply one of when, not whether.

As this thesis is concerned with the acquisition of radar, and therefore at this point with its performance in the Battle of Britain, this Chapter has not rehearsed some of the most critical features of that Battle – in particular, the debates about the RAF's lack of pilots and aircraft, and about whether the "Big Wing" tactics of the north-easterly 12 Group could or should have been adopted by Keith Park's south-easterly based 11 Group. That analysis has already been made by John Ray in his Ph D[262] and subsequent books[263]. There are, however, two aspects of those debates upon which this thesis has cast extra light. First, in the case of the debate between Dowding, the Air Council and Churchill over whether more fighters should be sent to France, a definitive graph showing the rate of wastage of Hurricanes was powerfully used by Dowding. That chart was in fact prepared by the radar scientists of his OR Group, and in Dowding's words "did the trick"[264]. Likewise, during the "Big Wing" controversy – whether large groups of many squadrons of fighters should be assembled to meet the massed raids of September 1940 – technical factors were in Dowding's mind. Since the change back to VHF had started only on 18 August, and was not complete, it would not have been possible to control such "Big Wings" from their home bases since their TR9 H/F transceivers had only a 40 mile range. This basic point does not appear to have been realised in most studies of the controversy[265].

The radar system itself had, however, passed the test of battle without collapse and with considerable credit. Serviceability remained high at 97% [266], and this from 54 stations on 1 July growing to 76 within 90 days, although it must be remembered that this meant only that the radar was operating, not that its readings were at all accurate – that was a matter of calibration. The Chain "never failed to detect a major raid"[267], and contemporaries saw it as a key success factor, from Park[268], who actually fought the battle, to Dowding who directed it[269], to Group Controllers in its midst[270]. So also did the Germans as its opponent, from Galland as an operational leader[271] to Werner Kreipe as Chief Operations Officer of Luftflotte III[272] "radar at least doubled the efficacy of (the British) fighting force". The key point illustrated in this section is that, more than radar as an equipment – for the key South Coast stations were not performing effectively – it was the overall air defence system which was crucial, pivoted around the Filter Room, held together by the human element, refined by Operational Research and made effective by training and exercises. That system fought a battle which was not the one for which it was created, and fought it effectively.

IV.6. Summary and Conclusions.

Chapters III and IV have traced the acquisition of the radar-based air defence system to fight the day battle. Judged by the test of the Battle of Britain, and by radar's contribution to that test, this was a successful acquisition. As has also been shown, it was not an acquisition without faults.

At the outset, this thesis proposed a series of questions derived from its foundation in the UK MoD acquisition model. It is now appropriate to revisit these in the context of a successful acquisition, before analysing in Chapters V and VI the less successful acquisition of radar for the night battle.

The first of those questions was whether the MoD model, and specifically its lines of development component, is validated or vitiated by the facts of radar acquisition in the 1930s.

In general, the model appears validated. In structural terms, after 1936 there was a clear Equipment Capability Customer, Dowding; there was a clear equipment supplier, Freeman; and an independent champion of the total solution, Tizard. Dowding and Tizard in particular enjoyed a high trust, high respect relationship, and Freeman was seen as an exceptionally competent manager able to relate easily to suppliers at all levels. The equipment developer and programme manager, today's IPTL, Watson Watt, managed first the research (under Dowding as AMRD) and then the development (under Freeman as AMDP) with outward success until 1939.

Certain unusual features to the Dowding/Tizard relationship should be borne in mind for re-examination after reviewing the less successful "night radar" acquisition described in Chapters V and VI, to identify if they are critical to success. The first such feature was the fact that their relationship survived changes of role and was unusually long-lived. Tizard survived in his advisory role for six years, perhaps because of its unpaid nature, but also because of his ability – he had fought off the Churchill challenge in committee in 1936. Dowding changed roles, from AMSR to C-in-C Fighter Command, but also served in the latter role for an extended period because of a chance air accident to Courtney, his replacement. A second feature was mutual experiences; Tizard was a scientist who was a decorated pilot; Dowding was an airman who had participated in early wireless experiments. There was understanding of each other's problems. Third, in personality terms, Tizard was a humble listener, always explicit in never usurping others' responsibilities; Dowding, aloof and territorially sensitive, was analytical, relating well to Tizard's logic and advice. A particular feature of Dowding was that he never took radar for granted, a factor which clearly grated on Watson Watt. Dowding, who was responsible for Britain's defence whether radar worked or not, was continually testing, exercising and working on alternatives, such as the Observer Corps and radio D/F. The wisdom of this view was validated when radar did not live up to Watson Watt's promises, for example when it proved unworkable inland of the coast and the Observer Corps took over.

If we move to examine lines of development, then at the level of Doctrine and Concepts the advent of radar heralded a revolution. Before radar, deterrence through strategic bombing had been the primary doctrine; with radar, air defence became practicable. This wholesale shift was not necessarily welcome to an RAF schooled in the "Trenchard Doctrine" of bombing. Structurally, this contributed first to the dismantling of the ADGB structure which combined bombers and fighters, then to increasing investment in air defence acquisitions. Conceptually, Tizard's CSSAD ranged over the full field of defensive capabilities, including guns, barrage balloons, missiles and fighters. Underpinning the whole was the participants' shared experience of WW1 and its air defence system; that of 1940 was recognisably similar, but massively upgraded for the speed of attackers and defenders and hence optimised for rapidity of response. Tizard appreciated this from the start; hence his move to seek the Biggin Hill interception trials late in1935, as soon as radar had been proven workable.

Equipment was overtly the most novel line of development. Here perhaps the most important features for success were that the original proposal stretched, but did not over-stretch, existing technology; that it was subject to proof-of-concept test (the Daventry experiment); and that essential features – bearing and height finding – were demonstrated within months. When original ideas did not work well, as the keyed resonant wire for IFF, or the Optical Converter for information handling, the scientists rapidly developed alternatives – the IFF transponder and the Electrical Calculator. There were problems, such as avoidable delay in deriving specifications for commercial manufacture, where security, lack of skilled specifiers, and a desire for "design refinements" all played a part. By contrast, equipment designed in conjunction with the manufacturer – the Electrical Calculator with the GPO – caused far less trouble, as did equipment incorporating manufacturers' standard items, such as Pye's ex-TV IF amplifier for CHL. A major supply chain risk could have arisen where components came from future enemies. The pre-war UK radio industry was an assembler rather than a manufacturer, and was fortunate that, for example, Austria continued to supply parts after the Anschluss. A final lesson from the Equipment line of development concerns the scientists' desire continually to refine their equipment. A fluid design is a problem to manufacture, and this was compounded in the case of radar by the series of emergency and crash programmes to which the chain was subject (the original Chain; Advanced Chain Home; the Intermediate Chain; finally, the 1939/40 addition of CHL, itself the subject of two crash programmes). The result caused not merely manufacturing problems, but also significant training, sustainability and integration issues.

In terms of Infrastructure, primary issues were those of site selection and of the erection of masts and aerial feeder. On site selection, the radar scientists faced problems which persist today – chosen sites presented environmental issues, and there were protestors. The answers of the 1930s are equally familiar today – alternative sites, long negotiations, and public enquiries. The situation was easier only in two regards – the "D" notice was then respected, with resulting minimal publicity, and the approach of war facilitated compulsory acquisition powers being used. Of the construction of site buildings, little was novel, and set against the scale of the parallel airfield construction programme, radar was modest indeed. Aerials and their feeders were, however, a different matter. Watson Watt should not totally be blamed for not predicting the problem. Building tall aerials had not been a problem to Joe Airey, his redoubtable first assistant[273]. The prime contractors for the early masts, Harland and Wolff and C.F. Elwell, produced unexpected failures from previously efficient firms[274]. Attempts to speed the process by use of Merryweather's, the fire escape ladder firm, fared no better[275]. In the event, the slow processes of Air Ministry "Works and Bricks" bore some fruit, in that their massively engineered towers bore the extra weight of CHL aerials. However, this does not excuse their not predicting a major shortfall in the wood available to make the receiver masts, delaying radar acquisition by many months[276]. These aerial towers were far from unique. Other manufacturers such as Marconi's built aerial towers, and other organisations, such as the BBC, the GPO and the Admiralty project managed such installations. It was not necessary for Watson Watt to delay radar merely to duplicate expertise in this field. It is reasonable also to query why copper feeder manufacture was not contracted out earlier. Far from Watson Watt himself having to take a hand personally, as in fact happened, civilians were used to manufacture feeder after No. 2 Installation Unit was formed, and security was not compromised.

Sustainability - maintenance and spares – we have seen to be a factor in Watson Watt's eclipse. Originally, the Bawdsey scientists provided support to the chain. This was both ineffective use of their time, and a delay in establishing a proper structure. Additionally, given that even in 1935 Orfordness the scientists were cursing the inflexible Air Ministry "Stores Vocab", it is astonishing that a proper structure of spares, ordering, tools and testgear was not established on the move to Bawdsey at the latest. In the event, it took until February 1940 when 60 Group, RAF, was created out of the

Leighton Buzzard Base Maintenance HQ that such a structure began to be properly resourced. By that stage, the calamity caused by maintenance and spares issues at Drone Hill and elsewhere had become only too visible. The multiplying of equipments in a host of different Marks compounded the problem. Joubert's action in gaining approval to the recruitment of civilian radio and TV engineers was inspired, but blunted by the unreadiness of Yatesbury Training School in midwinter 1940 and the recruits' consequent glimpse of service realities. Radar was, of course, not the only equipment in the system - IFF, TR9 "Pipsqueak", VHF, Optical and Electrical Calculators, radio D/F and a host of telephone equipment had to be serviced. Two quotations give a flavour of the position on the ground. In January 1940, Hanbury Brown visited RAF Leuchars to speak to the Signals Officer after efforts of the greatest urgency to produce IFF:

> "Sorry", he said looking at me irritably over a mountain of papers on his desk,"I haven't got the time right now to look at your radar. I am too busy doing tests on carrier pigeons. Perhaps you would… show your radar to the Flight Sergeant…Oh, before you go – can you tell me if the boxes which keep on arriving here are to do with your radar? They are marked "SECRET" and so we have to lock them up and we are running out of cupboards with locks". He unlocked several cupboards and there were row upon row of radar transponders (IFF)." [277].

and Lang, a Group Controller, on the unsung telephone engineers:

> "Very little mention has been made of the heroic work of the G.P.O. Telephone Services, who, despite incessant bombing by day and by night, continued to repair cables and telephone exchanges while under fire. Their courageous and unceasing execution of their duties was an inspiration to the world. Without their unflinching heroism, essential telephonic communication could not have been maintained during a very critical phase of the battle" [278]

The human resources lines of development – people, training, and organisation – proved areas of great challenge, but proved also to be the strong point of the system.

In people terms, there were four critical groups – operators, plotters and filterers, maintainers, and scientists. In the scientific area, the issue was one of recruiting good people at Civil Service rates of pay into secret roles with no prospects of publishing work and apparently limited prospects of promotion. Both Watson Watt and Rowe failed to persuade the Treasury to be flexible. Watson Watt perhaps did not help the case by being President of the scientists' union, the IPCS, and a national negotiator with the Treasury, and by protracted argument over his own salary. His utilisation of his staff on such work as making aerial feeder, and most of all his bungling of the move to Dundee, caused further delay to radar. In the event, the scientific recruitment problem was solved only by war and the bringing in of the Cavendish scientists in 1939, but at the cost of the resentment of the "pioneers". The result of the lack of scientists was that the few available had to be concentrated on Chain Home to the exclusion of other work, such as radar for the night battle and for bombing.

For operators, the salvation was the decision to employ women in this role, and, in a move suggested by the Treasury, specifically WAAF. Women proved excellent operators (as one officer said, "They watched the screen"[279]) and resolute when the stations were attacked, as at Ventnor, Poling and Rye. Again, the grading of the role was a problem - trained operators were anxious to move up to such jobs as barrage balloon operator! Civilians had been suggested for this role, and indeed civilians were recruited, at Joubert's suggestion, to maintain the system. Most eventually joined the RAF, for improved terms. In the case of filterers, grading again loomed large. Originally assessed as corporal level because of the performance of two outstanding individuals at Bawdsey, the increasingly critical role in the Filter Room showed the need for officer-level staff. The fight to gain this grading lasted until the eve of battle, leaving time for only one group to be trained.

Closely linked to people was the question of training. Radar, akin to radio, nonetheless required specialist training even for maintainers, while operators, filterers, and plotters were novel. The early establishment of the Bawdsey School under the well-qualified Hart were extremely positive moves. The challenge was to keep pace with the increasing demands for trained staff on the multiplying models and marks of equipment. Only just enough staff were available to operate the equipment just well enough to suffice – refinements such as accurate counting or height-finding were, as shown above, not present. Fortunately, the Electrical Calculator simplified the training for CH, and the CHL equipment had no height finding capability to train for. Even so, the drastic measures of 1940, reducing the training to just two weeks and even feeding untrained staff into stations, were put in place until proven so counter-productive that they were dropped. A specific factor which aided the training programme was the inventiveness of the Bawdsey training staff; working with scientists, they developed the first, cam-driven, radar simulator[280], a boon because neither live targets nor student access to CH could be guaranteed – the scientists were still using the CH.

In terms of organisation, the significant transfer of air defence research from the Army's ADEE to the RAF through the medium of Tizard's CSSAD was noted above. The subsequent establishment of Orfordness and then Bawdsey were distinguished organisationally only by involving DSIR staff prior to the scientists' transfer to the Air Ministry. With further growth, and production responsibilities, the establishment of the DCD role in parallel to the DSR was logical. The appointment of Watson Watt appeared realistic at the time given his experience and the lack of alternatives. (The appointment of Rowe to head Bawdsey, by contrast, was contested but was outstandingly successful.) Again, the decisions Watson Watt took on appointment, such as establishing No. 2 Installation Unit, were perfectly sound.

When, in November 1939, Joubert took up his role to co-ordinate radar, events had already proven that Watson Watt's role had expanded beyond any one person's capacity. Tizard and Joubert agreed that the chain, with all its support activities might form a separate command. Dowding did not agree, so Joubert took over only maintenance and commissioning from Watson Watt. This left production; both the Ministry of Supply (for the War Office) and the Admiralty wished to go their own way, given the problems over CHL. The Admiralty operated almost autonomously, but the RAF and the war Office continued to operate joint procurement under the Air Ministry, now reinforced by Sir George Lee as DCD and by G/Capt. Leedham in the new post of Director of Communication Equipment Production. Watson Watt was sidelined to the advisory role of Scientific Advisor of Telecommunications.

Within the chain, the position of the filtering (centralised or decentralised) became a major dispute between Dowding and Joubert, as described in detail above. Dowding was undoubtedly correct to retain centralised filtering at the time, but as saturation of the system grew after mid-September, Dowding would have been well-advised to use the opportunity of his own O.R. study to move towards decentralisation.

The organisational transfer of the scientists to Beaverbrook's Ministry of Aircraft Production (MAP) as MAP Research Establishment (MAPRE) in May 1940 had limited effects on the 1940 air defence system which, in the main, was already beyond the research stage. Beaverbrook's insistence on cancelling all long term research, however, almost destroyed Britain's future defences through stopping centimetric research. W. B. Lewis, a Cavendish man, persuaded Rowe to conceal this work[281] and its success led to Britain's unassailable lead in radar after 1942. This major subject is, however, beyond the scope of the present thesis.

Communication and information handling were at the root of the success of the air defence system from its earliest days. Telephone landlines were a subject about which Dowding was obsessive, perhaps strangely to a modern reader. To this writer, responsible for telecommunications in a 1970s multinational, months of waiting for new lines has considerable resonance. The Biggin Hill experiments identified the need for reliable long range ground/air and air/air communications, and development of, first, the HF TR9 and subsequently the VHF TR1133 followed. Difficulties in hastening manufacture, and losses in the battle of France, caused VHF's withdrawal for the early Battle, but it was reinstated later in the light of many cases of poor R/T communication[282] and became a wartime standard. In the radar chain, the need to derive information quickly from the tube face led to, first, Bainbridge-Bell's Optical Converter, and when that proved unreliable, to Roberts' and Marchant's Electrical Calculator. The whole fed to the Filter Room at Stanmore which, in the absence of IFF, was the pivot of the entire system. Since 1938, O.R. at Fighter Command focussed almost entirely on communications and information; together with regular exercises, this ensured the system worked effectively in the heat of war.

It was in Integration (interoperability) across all these lines of development that the UK air defence system excelled. From 1935, Watson Watt conceived of such a system[283]; as stated above, his ability to visualise the "big picture" is not in doubt. Once the early equipment worked, Tizard moved quickly on to improve tactics and communications for air interception in the Biggin Hill experiments. The deficiencies of early radar were rapidly identified and compensated for - inland identification by the Observer Corps, identification friend or foe by IFF and filter rooms, and fighter location and control by "Pipsqueak" are examples. Operational Research identified deficiencies in process and communications. Dowding's insistence on regular Air Exercises from 1939 onwards tested and re-tested the entire system, just as the move to a 24 hour watch in the same period showed up shortcomings in equipment and the servicing organisation which were remedied.

The MoD acquisition model, and in particular lines of development, are, therefore, validated by the facts of the 1930s acquisition of radar. Where lines of development were neglected, the system was delayed or failed. Where they were respected, it was on time and worked. It is not anachronistic to apply that present-day model to a 1930s acquisition, since the model was based on what worked rather than upon theories unknowable in 1935. As has been illustrated, such experience was codified, for example in the Manning Plan process of the interwar RAF. Both the GPO and the BBC were used to large-scale electronic projects. This thesis has illustrated the application of their staff's skills to radar, such as Dixon specifying transmitters and receivers, and it was Sir George Lee as the retired GPO Chief Engineer who took over as DCD from Watson Watt. Large scale acquisition was not, however, a feature of 1930s science – such "big science" was a late war feature, exemplified by the nuclear Manhattan Project. Interwar management of scientists was a matter of small group management of high-IQ individuals, with Watson Watt at Slough and Bawdsey as an example. This writer makes the observation from experience in MoD and Xerox Corporation that that scientific structures tend to focus on knowledge-led groups and so to be reductionist, while major acquisitions tend to be broad-ranging and span many fields of endeavour. A generally accepted yardstick in industry, the HAY-MSL job grading system[284], typifies scientists as high-qualification, problem-solving individuals with a narrow field of expertise. By contrast, acquisition specialists are typified as lesser-qualified, results-oriented individuals spanning great widths of organisational skills. Individuals spanning both capabilities are rare – Rowe appears to have been one, while Watson Watt visibly failed. To Watson Watt, however, is owed the seminal paper which conceived radar as a technology to deliver an air defence capability, and which illustrated the position of CH, IFF and ground control within an overall system; Rowe is not known to have displayed that conceptual span.

The second significant question is whether application of the MoD acquisition model affords new insights, whether for the use of the model itself or to inform further historical research.

Any model is a methodology for organising facts in a structure to a specific end. In the case of the MoD model, the results are not recondite. It is simply the case that the total information processed is too complex to assimilate without such a framework. While some insights may appear trite, they are only so because the model's structure gives clarity to their identification. Practical contrast is afforded by one recent history covering similar ground – Bragg[285], where the lack of an analytical structure leads to a rich assembly of facts without a conclusion.

The insights from the 1930s experience for application to the refinement of the MoD model are twofold – the impact of personality, and the impact of success.

The impact of personality arose when individuals had the experience or training to predispose them to respect lines of development, so that their acquisition was more effective. Serving officers such as Dowding had the experience of a structured RAF planning process and of tours of duty in charge of training. Critically, they knew that it would take time to train, staff, and organise, and that it was unwise to rely on all parties being enthusiastic, skilled and in place in that time. Tizard had war experience as a pilot, then large organisation experience at DSIR, and training/education experience at Imperial. In today's terms, they understood that their management task was to manage the lines of development to deliver a capability, rather than merely to procure hardware.

Watson Watt would today be regarded as having "vision", the ability to conceive of the entire system to achieve a given capability, and he could also conceive of the radar hardware's place in the system to deliver that capability; his failing was in lack of ability to manage the delivery of that vision. It is reasonable to point out that he had no background in managing lines of development in major organisations – his experience had been in a research station of under 50 people; and that training in the skills of complex project management was nowhere to be found in the world of the 1930s. Those individuals who possessed such skills, an example being Sir George Lee, Chief Engineer of the Post Office, had learned them by practical experience.

The impact of success has not previously been remarked. Acquisitions of highly adaptable technology, typified here by radar, lead to customer requirements "creep", the multiplication of equipments, and personality contention. All are subjects for further study but may briefly be described:

?? **Requirements "creep".** The successful demonstration of a technology leads to increasing demand for refinements to cover deficiencies or improve performance. Computer systems today are prone to such "creep". In turn, this leads to:

?? **Multiplication of equipments,** as one system, Chain Home radar, led on to CHL and to IFF. When multiple systems are introduced in foreshortened timeframes, so that operators and maintainers are neither recruited nor trained, there are few if any spares, and information/ communications networks are not readied to receive them, problems ensue. In this case, information choking the Filter Room almost brought the entire system down, while lack of spares almost caused its early demise. One consequence is that the few staff often try their best to make the system work by "string and sealing wax" solutions, the difficulty being that these are prone to failure under the stress of battle and also complicate the introduction of a permanent solution. An example in WW2 radar was the over-rapid introduction of different Marks of airborne radar from September 1940 to June 1941, described in Chapter VI below; the complications caused the Air Ministry to hold back the introduction of new aerials, which would have cured a known fault and better equipped the RAF to fight off the Blitz.

- **"Dysfunctional diffusion",** the over-rapid application of a novel idea into new areas. In the present case, the War Office's Coast Defence radar proved to fill a gap in Chain Home's capabilities so that it could locate low flying aircraft. Equally, it filled a Naval demand for protecting Fleet anchorages against U-boats as well as low-flying aircraft. These demands coincided and competed in urgency, the Army demanding coast defence radar, the Navy CHL and CD(U), and the RAF CHL to supplement Chain Home. The result was chaos, further deepened by buccaneering actions such as those of Cockroft. In turn, neglect of lines of development problems such as staffing and maintenance created operational issues of communication of results and of unserviceability.
- **Desirable requirements "creep".** When technologies are new, scientists have a natural desire to add refinements as quickly as possible. The result can play havoc in particular with sustainability. In the case of radar, such modifications necessitated taking the station off the air for a week for re-calibration, or accepting inaccurate plots. Again, the area has not been well-researched.
- **Personality contention**. "Success has many fathers, defeat is an orphan" - when problems occur with a successful system, many come to "help", but often without the necessary knowledge, leading to simplistic or damaging solutions. In radar, Joubert, away from radar for two years, returned at a senior level in 1939; because he had missed key experience on IFF and filter rooms, and because he saw a role for himself, his intervention had mixed results.

In terms of insights for historical research, there would appear to be five – radar's readiness for war; its usefulness in war; the pivotal role of the Filter Room; the importance of operational research; and vulnerability of communications. Taking these in order:

- Reference is often made to Britain being unready for war. In the case of the radar-based air defence system, Britain was ready (just, and thanks to the delay of the "Phoney War") to meet the threat it expected, but did not fight the war for which the system had been acquired. CH had been built to focus on East Coast defence against flights of bombers trackable for 100+ miles over the North Sea. The Battle of Britain was fought with that same system against a South Coast assault of massed bombers escorted by fighters, trackable for only 20 miles over the Channel. However, unlike the Maginot line, radar was not outflanked. The system worked (just) as a result of the human resources staffing it, and constant exercises.

?? CH radar information was less reliable in the Battle of Britain than is generally accepted. Surviving documents show that the South Coast radars were deficient in calibration and phasing, so that their plots could be in error by 20 degrees. This study has identified that one contributory problem was likely to have been the apparently trivial case of defective aerial insulators, exacerbated by confusion over lack of Stores Vocabulary reference numbers. Heights were also known to be often wrong, and counting of raiders frequently so. The total system in fact relied on SIGINT (the Y service), the Observer Corps, and sunny weather, all crucially collated and resolved in the Filter Room, to work.

?? Bentley Priory Filter Room was key. Given the absence of IFF and with radar's known inaccuracies, this room was pivotal. Precisely for that reason, it became a major dispute between Dowding (for centralisation) and Joubert (for decentralisation). Given the few trained staff and the need, if filtering was decentralised, to build new rooms and re-lay complex communications wiring, Dowding was right to refuse a change initially. He would have been wrong for 1941, as Stanmore had shown itself limited in capacity and overloaded in the latter stages of the Battle. Joubert was right to re-open the issue in September, but by then Dowding was exhausted and saw the problem in personality terms.

?? Operational Research was as important as hardware. The scientists such as Rowe thought so at the time, but – perhaps because O.R. is not fashionable, and is not "visual" in leaving photographs or hardware – it is rarely mentioned in histories, Kirby[286] and Zimmerman[287] being honourable exceptions. Continual exercises, observed by scientists, refined the system to cope with hardware and training shortcomings.

?? Vulnerability of communications. Again, rarely mentioned in histories of the Battle is the damage caused to Operations Rooms located on airfields, in particular by the severing of power and communications cables. Haste in construction had meant that these links had not been buried deeply enough, and not duplicated. Without these links, the Operations Rooms could not function, and the proposal to decentralise filtering and reporting would have been disastrous.

There are more minor and specific insights, such as the bungling of the physical relocation to Dundee which almost stopped research for six months, the failure to recruit scientists in 1936-9 which again cost months of delay, and the diffusion of effort into unproductive areas which compounded that problem.

It is relevant now to move on to contrast a less successful acquisition, that of radar for the night battle (the Blitz), and compare the conclusions there with those now drawn.

IV.7.

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176. J.F. Coales and J.D.S. Rawlinson, op. cit, ibid.

177. IWM/HTT 79, MS letter Rowe to Tizard 24.11.39.

178. M. Bragg, op. cit, p.170.

179. TNA/PRO AVIA 7/410.

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182. TNA/PRO AIR 20/2267.

183. Derek Wood, op. cit, p.60.

184. Ibid, p.62.

185. Ibid, p.82, quoting H.C.T. Dowding *The Battle of Britain*, Supplement to the London Gazette, 11 September 1946.

186. TNA/PRO AVIA 7/438.

187. TNA/PRO AVIA 7/161.

188. TNA/PRO AIR 20/1484.

189. TNA/PRO AIR 20/1484; TNA/PRO AVIA 7/737.

190. .TNA/PRO AVIA 7/397.
191. TNA/PRO AVIA 7/183.
192. IWM/HTT 226.
193. D. Zimmerman, op. cit., pp.186-7.
194. Ibid, pp. 190-3.
195. TNA/PRO AIR 2/3143.
196. TNA/PRO AIR 2/3143.
197. TNA/PRO AIR 2/3461.
198. TNA/PRO AIR 10/5485 pp. 40-2.
199. M. Bragg, op. cit., p.181.
200. Ibid.
201. TNA/PRO AIR 2/5056.
202. TNA/PRO AIR 16/277.
203. TNA/PRO AIR 2/5056.
204. TNA/PRO AIR 2/5056.
205. TNA/PRO AVIA 7/161.
206. M. Bragg, op. cit., pp. 204-5.
207. M. Bragg, op. cit., pp. 201-2.
208. D. Zimmerman, op. cit, p.231.
209. Sir Robert Watson-Watt, op. cit., pp. 245-6.
210. TNA/PRO AVIA 46/58.
211. TNA/PRO AVIA 7/106.
212. E.G. Bowen, op. cit, Chapter 9.
213. TNA/PRO AIR 41/12 p.112.
214. D Pritchard, op. cit, p.101.
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217. D. Zimmerman op. cit., p.195.
218. Air Ministry, *Rise and Fall of the German Air Force,* London: HMSO, 1948, p. 80; TNA/PRO AIR 10/5485 p.47.
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220. D. Wood and D. Dempster op. cit, pp. 3-5.

221. TNA/PRO AVIA 7/410; TNA/PRO AIR 41/12 p.116.

222. TNA/PRO AVIA 7/410.

223. TNA/PRO AIR 20/2268.

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232. F.H.Hinsley and others, op. cit., Vol. I, p.180.

233. TNA/PRO AIR 25/197.

234. TNA/PRO AIR 10/5485 pp. 40-2.

235. Peter Flint, op. cit,

236. Ibid; TNA/PRO AIR 10/5485 pp. 37-42.

237. D. Zimmerman op. cit., p.201.

238. TNA/PRO AVIA 7/212.

239. TNA/PRO AVIA 7/212.

240. TNA/PRO AVIA 7/1007.

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242. TNA/PRO AIR 41/12 p118; R. Hough and D. Richards, *The Battle of Britain*, London: Hodder & Stoughton, 1989, pp. 141-3.

243. TNA/PRO AIR 33/4.

244. TNA/PRO AIR 41/12, pp.118-9.

245. TNA/PRO AIR 25/197
246. TNA/PRO AIR 16/1067; AIR 10/5485, pp. 47-8.
247. M. Bragg, op. cit., p. 220.
248. M. Bragg, op. cit., p. 225; TNA/PRO AIR 41/12 p. 123.
249. TNA/PRO AIR 2/7348.
250. TNA/PRO AVIA 7/178.
251. TNA/PRO AIR 10/5485 p. 51.
252. D. Zimmerman op. cit., pp.209, 212.
253. TNA/PRO AIR 16/387.
254. TNA/PRO AIR 8/577.
255. TNA/PRO AIR 16/277.
256. TNA/PRO AIR 19/476, Churchill 12.10.40.
257. TNA/PRO AIR 19/476, Joubert 18.10.40.
258. TNA/PRO AIR 19/476, Churchill 27.10.40.
259. TNA/PRO AIR 19/476 Joubert 30.10.40, 9.11.40.
260. TNA/PRO AVIA 7/1007.
261. M. Bragg op. cit, p. 243.
262. J. Ray, unpublished Ph D thesis, 1991, at the University of Kent Library, Canterbury.
263. J Ray, *The Battle of Britain: New Perspectives,* London: Arms and Armour, 1994, and *The Night Blitz,* London: Arms and Armour, 1996.
264. Maurice Kirby, op. cit, pp. 77-9.
265. Peter Flint, op. cit, pp. 150-1, is the only one to have done so.
266. D. Zimmerman op. cit., p.199.
267. TNA/PRO AIR 41/12 p.125.
268. TNA/PRO AVIA 7/212.
269. H.C.T. Dowding, *The Battle of Britain,* Supplement to The London Gazette, 11 September, 1946.
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271. See Title Page of Thesis, quoted by E.G. Bowen, op. cit., p.28.
272. W. Kreipe, 'The Battle of Britain' in W. Richardson and S. Freidin, *The Fatal Decisions,* London: Michael Joseph, 1956, pp 10ff.

273. Sir Robert Watson-Watt, op. cit, pp. 135 – 7.

274. See Chapter III pp. 156 – 7.

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276. Ibid, p61.

277. Hanbury Brown, op. cit., pp. 48-9.

278. TNA/PRO AIR 25/197.

279. F. Roberts, oral interview with the author, November, 2006; the author had heard the comment in conversation previously, at the RAF Radar Reunion, York, 2004, suggesting that the phrase was more widely known.

280. TNA/PRO AVIA 15/250.

281. Sir Bernard Lovell and D.G. Hurst, 'Wilfrid Bennett Lewis', *Biographical Memoirs of Fellows of the Royal Society,* Vol. 34, 1988, pp. 467-76.

282. TNA/PRO AIR 10/5485 p. 49.

283. R. Watson Watt, Memorandum of 9 September 1935 to CSSAD, reproduced as Appendix E of S.S. Swords, op. cit, pp. 285-92.

284. See www.haygroup.com. HAY-MSL is a proprietary point-scored job evaluation system based on the education necessary to perform a job, its management breadth, width, problem solving and responsibility for assets.

285. M. Bragg, op. cit.

286. Maurice Kirby, op. cit.

287. D. Zimmerman, op. cit.

IV.8.

FIGURES.

Fig 29. Ventnor Chain Home station. Apart from the fact that Ventnor was positioned above high cliffs, this picture of Ventnor is reasonably representative of the South Coast Chain Home stations. Ventnor was to be the most heavily bombed station in the battle of Britain. ("The Second Step – National Defence" by John Finch, Knowler Edmonds Collection).

269

PHYSICS

May Spot Airplanes With Television Receivers

"ENTIRELY possible" is the scientific verdict of radio engineers at the National Bureau of Standards to British dispatches citing the use of television receivers as "spotters" of airplanes.

While Army officials would not confirm reports that similar methods are being worked out for the military uses of the United States, it was admitted that secret research is underway to test other ways of spotting airplanes than by the present sound detection methods.

Since television broadcasts have been in progress over London it has been noted that when airplanes are flying in the vicinity there are produced "ghost" images in the television receivers. These "ghosts" are caused by reflection of the television waves from the metal airplane surface. Thus the reflected waves arrive at the television receivers at a slightly different time than the ordinary waves. The result is a dual image of the scene being transmitted. The image of the plane itself is not received.

According to British reports the displacement of the "ghost" image has been correlated with the distance of the plane away from the television receivers. A system has been worked out whereby television receivers on England's eastern coast could thus serve as "spotters" for approaching enemy aircraft in time of war.

Whether the plan can be worked out in complete detail and serve a valuable military use is for the future to decide, but in principle the method is an almost exact counterpart of the system of determining airplane altitude by having the plane send down to the ground a beam of radio waves and then having the plane pick up the signals of the reflected waves. This method was announced by Dr. E. F. W. Alexanderson of the General Electric Company in 1928.

For the television case, in contrast, the waves go up, strike the plane, and are picked up by ground receivers. By multiple receivers and methods of triangulation it is believed the altitude of the plane and its approximate direction and distance could be worked out.

In another analogy the television spotting system for planes can be called "upside-down" geophysical prospecting. In geology, metallic masses are located by reflected radio waves.

Science News Letter, April 23, 1938

Fig 30. Many nations had developed a form of radar in the late 1930s, and there was open speculation about the prospect of radio and television detection of aircraft. No nation, however, wished to confirm such rumours – all believed their innovation unique. (Imperial War Museum, London: Tizard papers HTT 57).

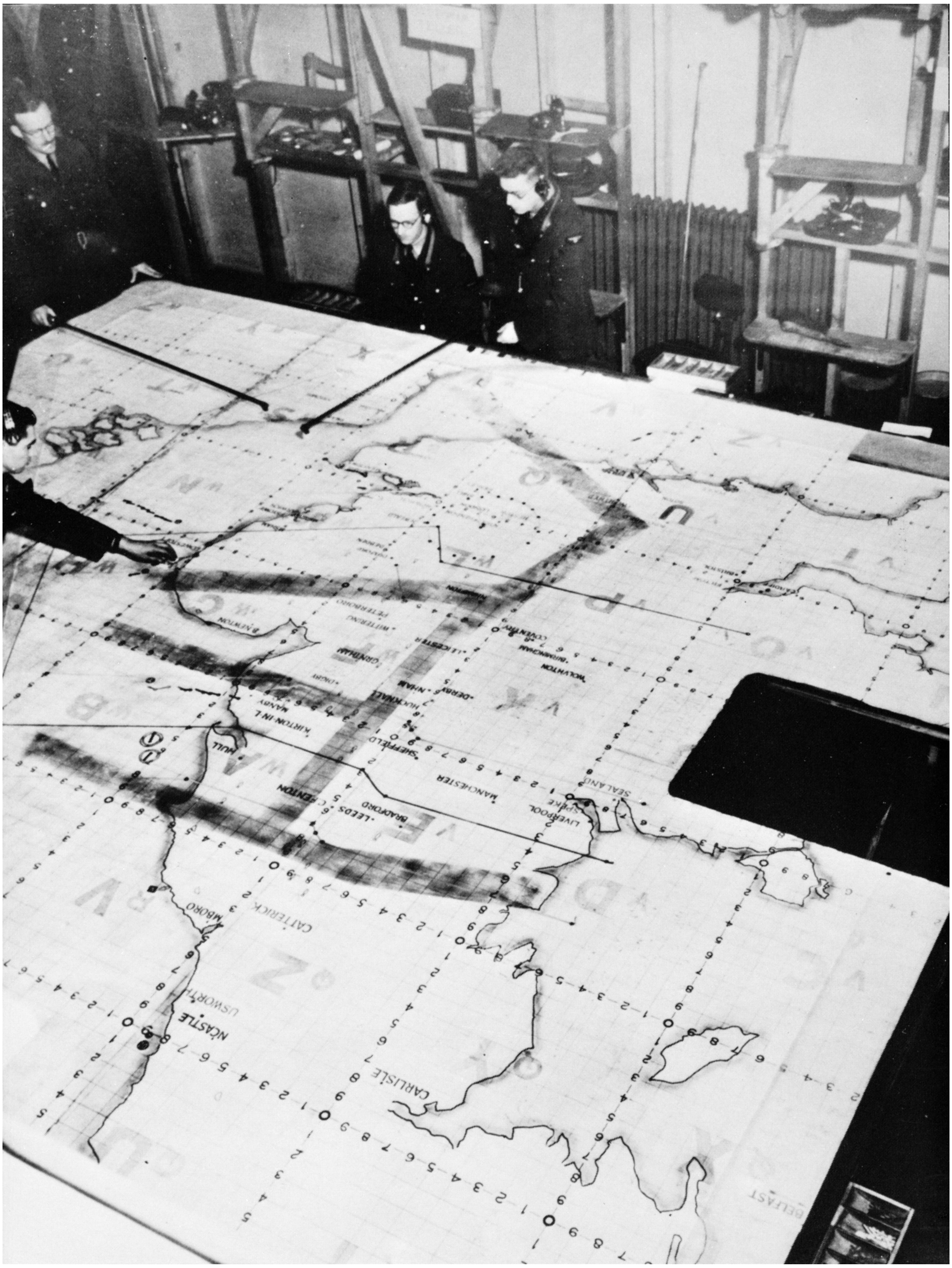

Fig 31. The Operations Room at Fighter Command HQ, Bentley Priory, Stanmore. This is the earlier "Ops Room", converted from the original ballroom, and superseded by the purpose-built underground Operations Room ("The Hole") only in March 1940. (Peter Flint, op. cit, Fig. 14/ Crown Copyright).

Fig 32. The earlier Operations Room, platform level, with the lower level map of Fig 31 at the lower right. The improvisation from the house's ballroom is clearly visible. (Peter Flint, op. cit, Fig. 15/ Crown Copyright).

Fig 33. The three Bawdsey secretaries whose success as "guinea pig" radar operators led to the recruitment of WAAF for this role. They are, from the left, Miss H. Booker, Miss N. Boyce and Miss M. Girdlestone. (Imperial War Museum, London, IWM E(MOS) 1426, 1427).

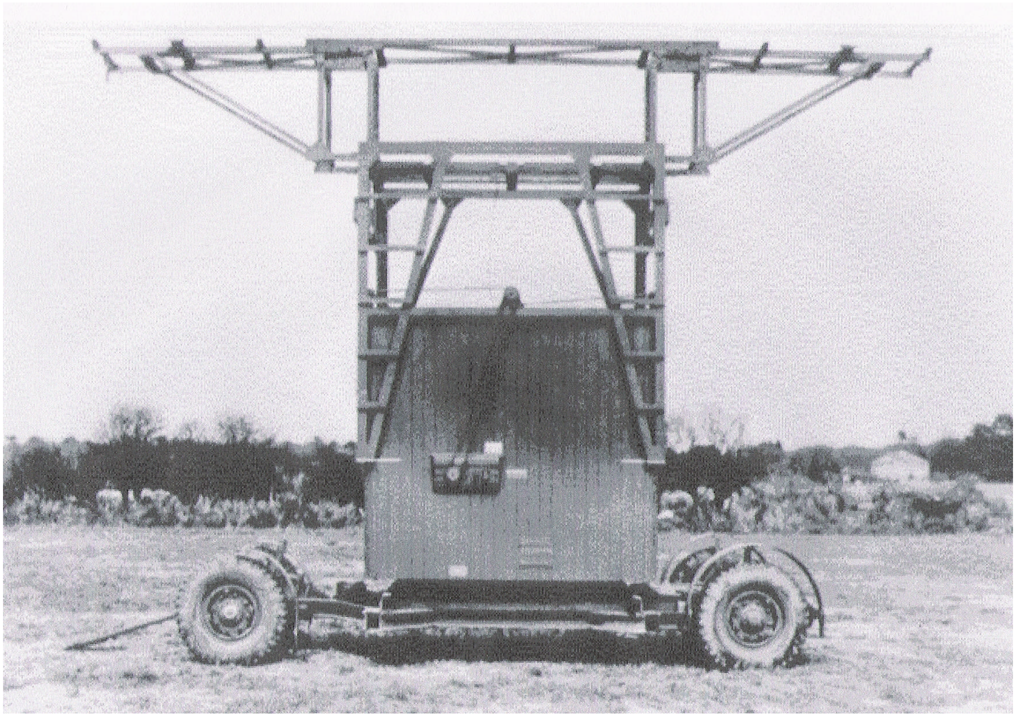

Fig 34. The Army's anti-aircraft radar, GL Mk. I. The one illustrated is fitted with the "Bedford attachment" for finding elevation. (Penley Archive B/1).

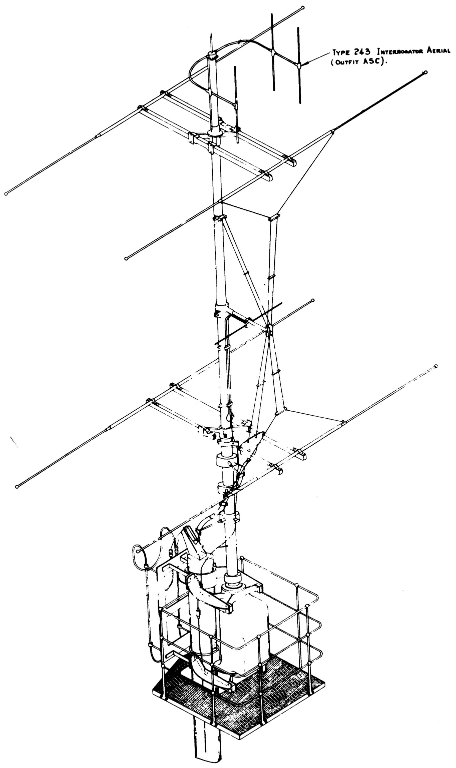

Fig 35. The Navy's Type 79 masthead radar aerial. Each of the dipoles is 12 feet long, making the installation unsuitable for small vessels. (F.A. Kingsley (Ed.), *The Development of Radar Equipments for the Royal Navy 1935-45*, London: Macmillan, 1995, p.137/Defence Research Agency).

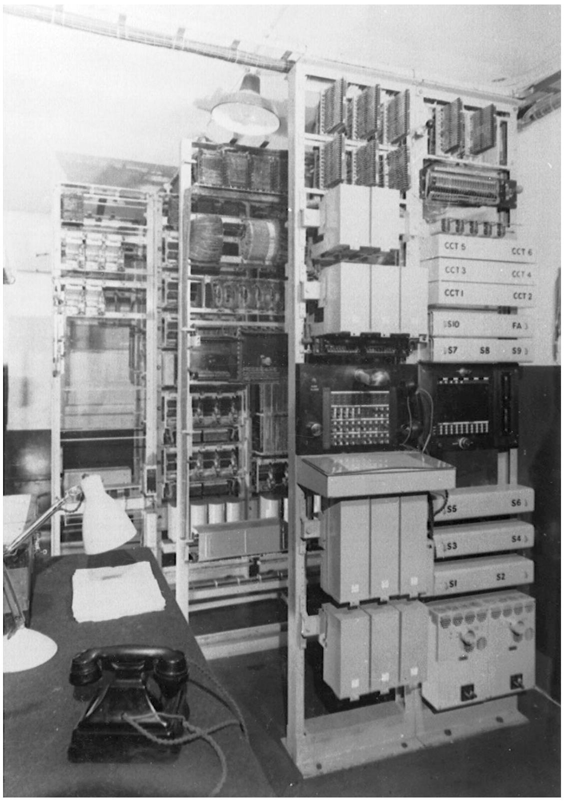

Fig 36. Electrical Calculator Type Q, used for rapid derivation of heights and fitted to Chain Home stations on the eve of the Battle of Britain. (Colin Latham and Anne Stobbs, *Radar: A Wartime Miracle*, Stroud: Sutton, 1996, p.22).

Fig 37. Typical Chain Home receiver room, housed in a wooden hut on the surface, during the Battle of Britain. This is Ventnor, the station illustrated in Fig 29. (IWM C1868)

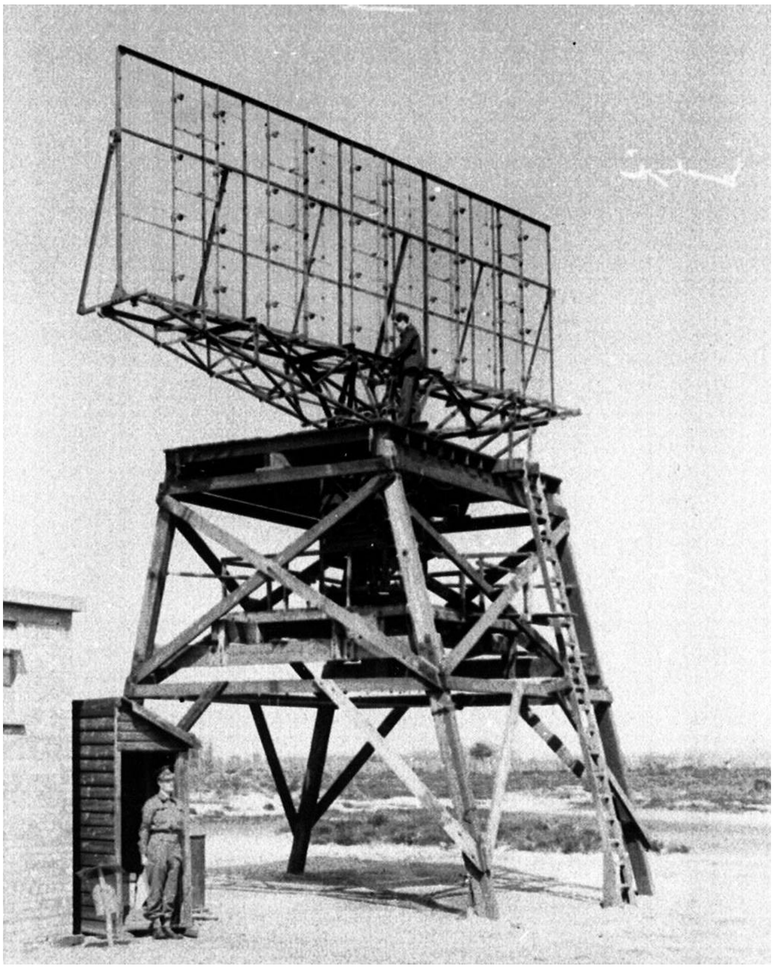

Fig 38. Chain Home Low (CHL) mounted on 20-foot gantry. (The National Archives/ Public Record Office (TNA/PRO) AIR 16/935).

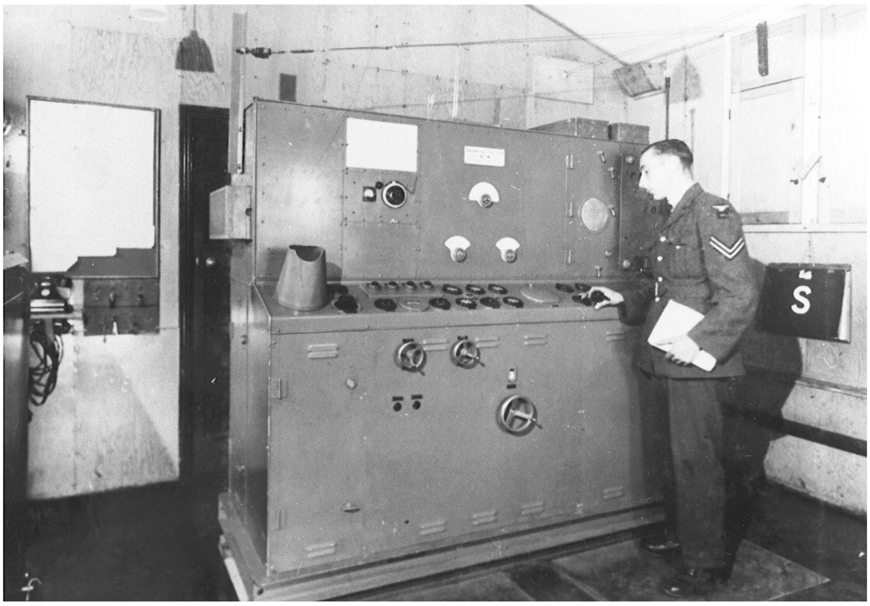

Fig 39. Chain Home Low transmitter. (IWM CH 15196).

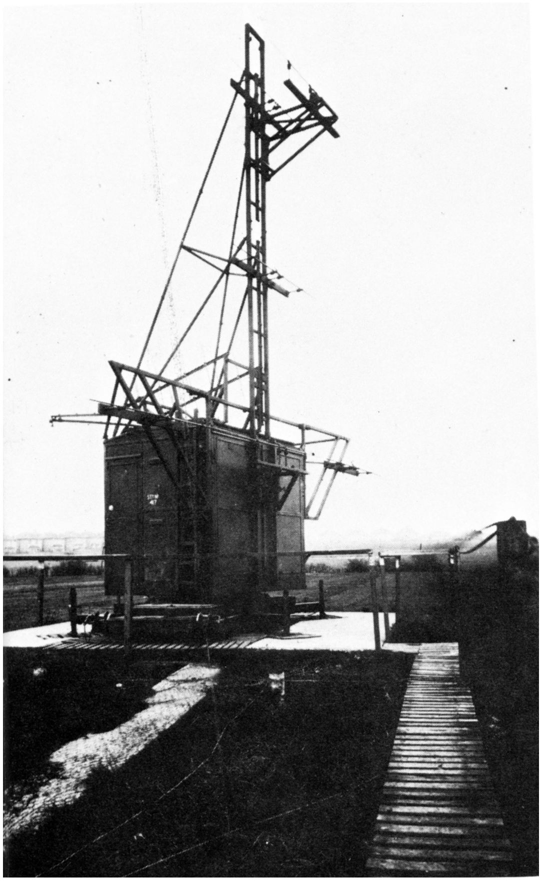

Fig 40. Army GL II AA radar transmitter. (Penley Archive, B/3).

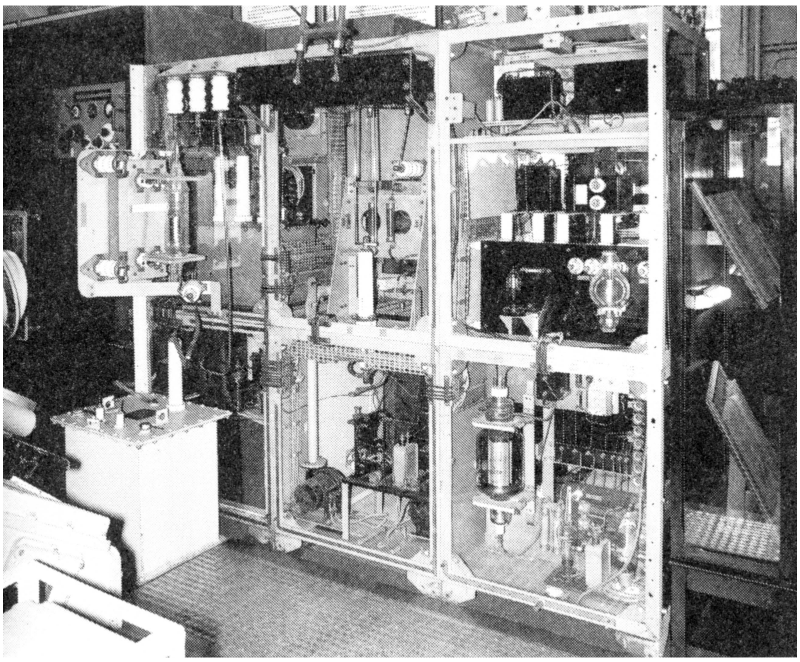

Fig 41. Navy Type 79 radar, production engineered version. (F.A. Kingsley, op. cit, p. 143/ Defence Research Agency)

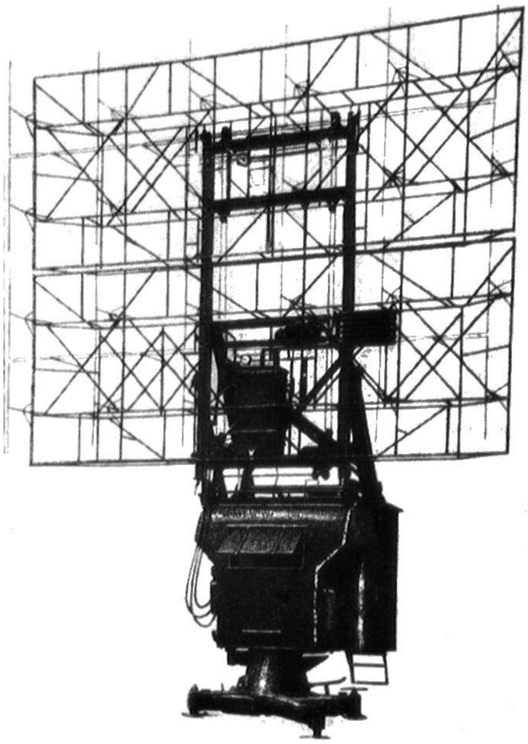

Fig 42. German “Freya” radar, copied from its Instruction Manual. This metric wavelength radar originated as a Kriegsmarine gunnery radar, but was adapted to early warning in a remarkable parallel to the story of the development of Chain Home Low.(Winbolt Collection).

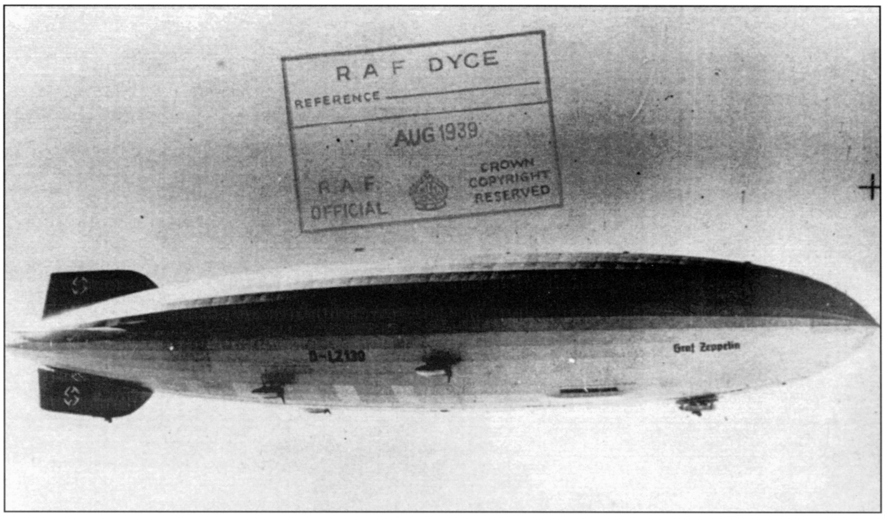

Fig 43. The Graf Zeppelin photographed from RAF Dyce, Scotland – the station stamp is clearly legible – while on its August 1939 ELINT mission against the British Chain Home radars. For reasons which are still debated, it detected nothing. (Colin Latham and Anne Stobbs, *Pioneers of Radar*, Stroud: Sutton, 1999, p.52/ RAF Museum, Hendon).

Fig 44 A “binder” – an airman turning by hand the aerial of Chain Home Low, following the indications on the meter in front of him. (Penley Archive, B/38).

Fig 45. A WAAF Chain Home operator, Denise Miley. Her left hand is by the goniometer control and her right is ready to select direction- or height-finding. (IWM CH 15332).

Fig 46. The original Filter Room at Fighter Command HQ, Bentley Priory, adapted from a room next to the ballroom which had been modified into the Operations Room. On the left, a Scientific Observer (colloquially, a "Scob") from the OR team is taking notes. (Peter Flint, op. cit, Fig. 21).

Fig 47. The purpose-built underground Filter Room in "The Hole". Contrast the busy nature of the room with the Operations Room, illustrated in Fig. 50 below. (Peter Flint, op.cit, Fig. 25).

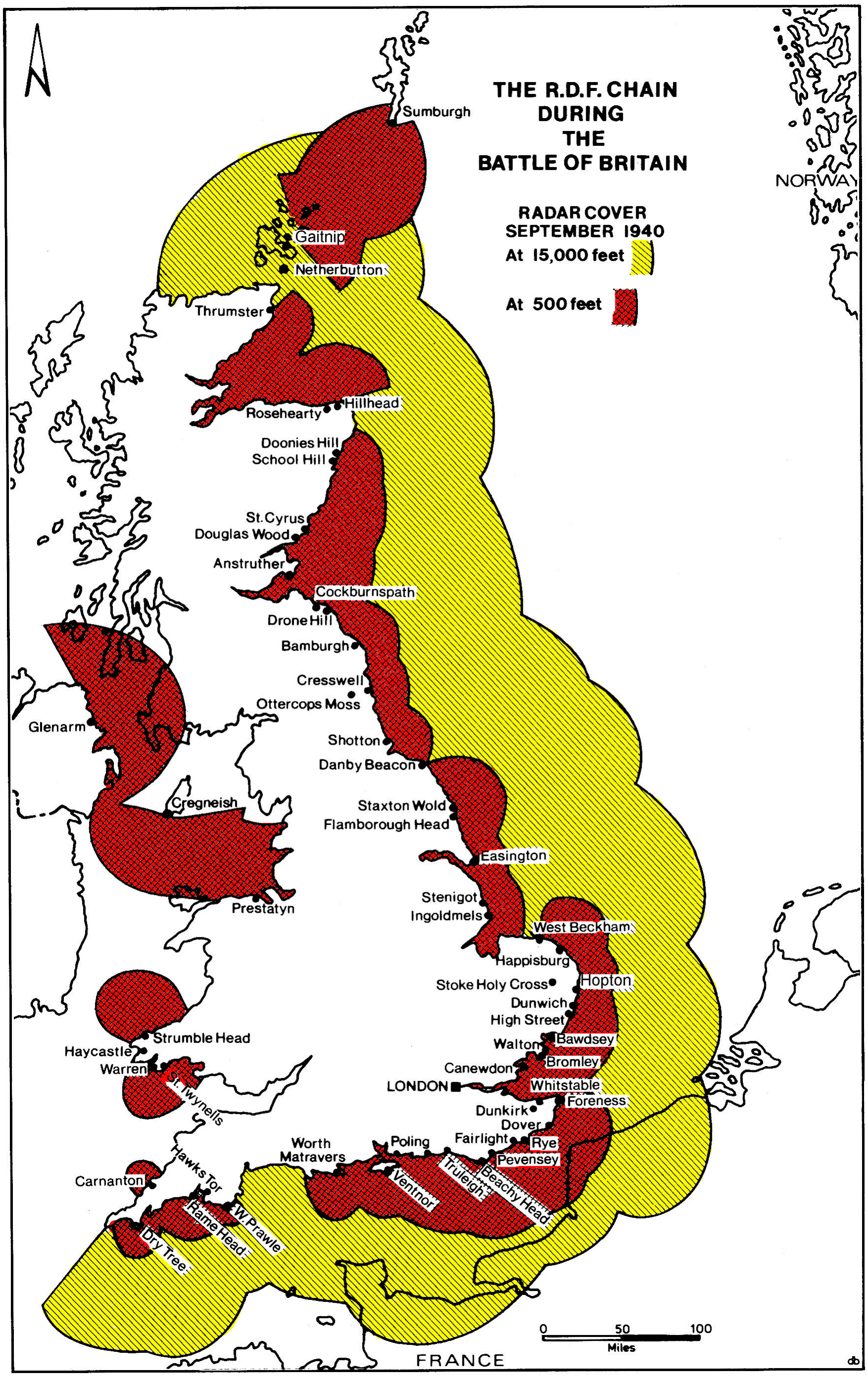

Fig 48. Radar coverage by Chain Home (15,000 ft.) and by Chain Home Low (500 ft.) during the Battle of Britain period. The **East** Coast, where attacks from Germany were expected, was well-covered; the **South** Coast stations would in fact be critical. (Derek Wood with Derek Dempster, *The Narrow Margin*, London: Tri-Service Press, 1990, p.270).

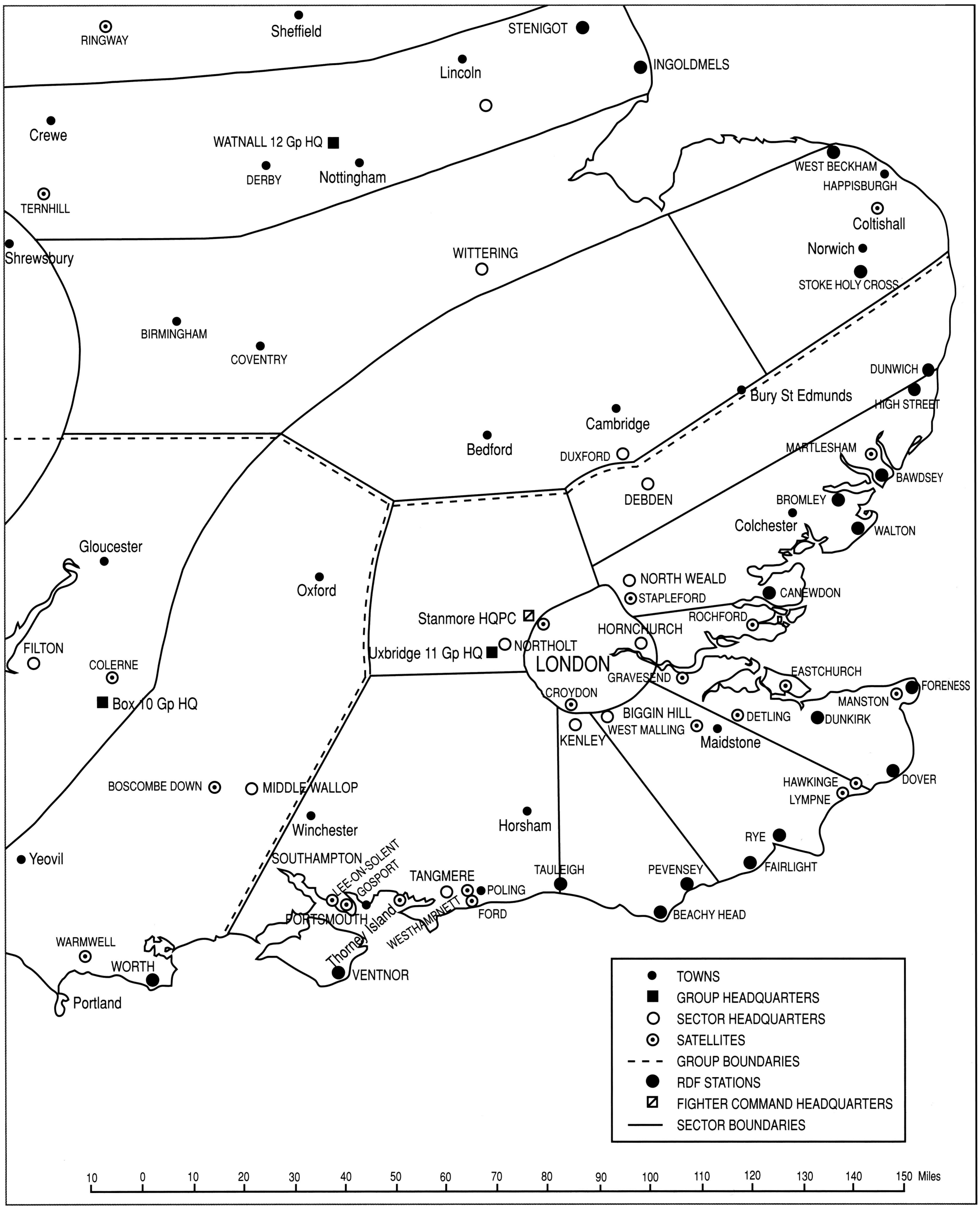

Fig 49. The area of the Battle of Britain in greater detail. (Roy Conyers Nesbit, *The Battle of Britain*, Stroud: Sutton, 2000, p.150).

Fig 50. The underground Operations Room. (Peter Flint, op. cit, Fig. 16).

Fig 51. The underground Filter Room. The WAAF centre right is “telling” the plots to the Operations Room WAAFs illustrated in Fig 50 above. (F/O Felicity Ashbee, WAAF).

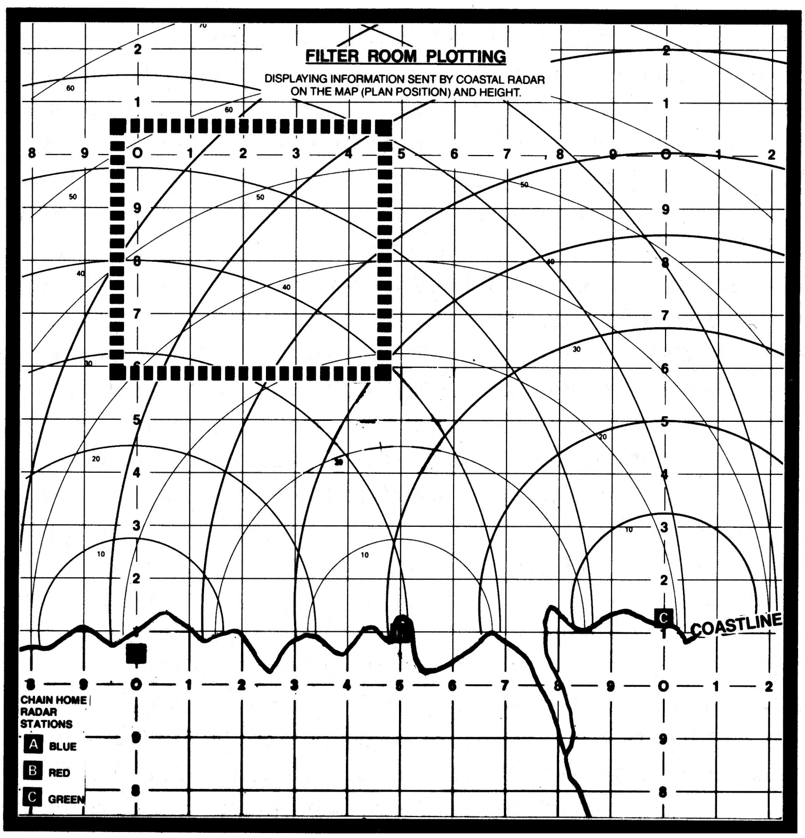

Fig 52. The Filter Room map is marked with the ranges from a series of coastal radars, overlaid on a standard grid. (Peter Flint, op. cit, p. 14).

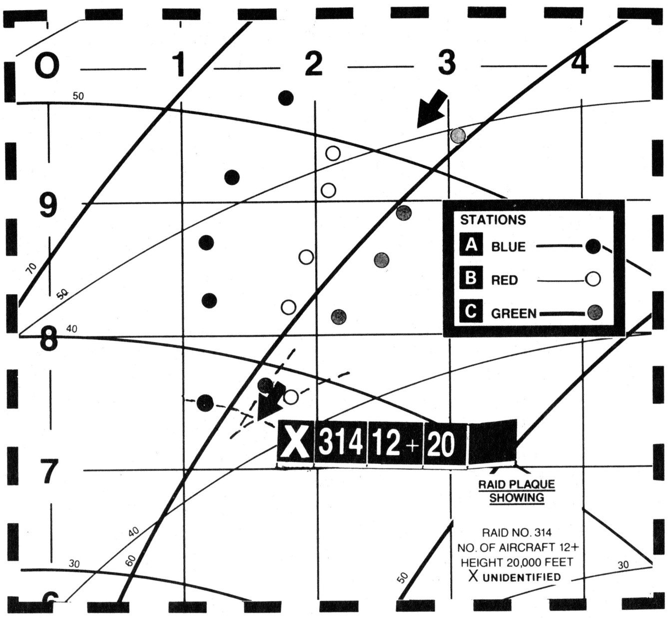

Fig 53. An example of filtering – 3 tracks plotted by 3 different radars are resolved by plotting ranges (where the radars are more accurate than bearing) and taking a mean position to be the actual, a single group of unidentified aircraft, (an “X plot”). (Peter Flint, op. cit, p. 15).

V

ACQUIRING RADAR FOR THE NIGHT BATTLE

THE FIRST 1,000 DAYS: 1936-1938

V.1. Introduction.

In the air, as on the ground or at sea, an enemy's withdrawal by day may not signify complete strategic victory - it may merely presage a night battle. So it was in 1940, as the Luftwaffe gradually changed the emphasis of its attacks from daytime to the night "Blitz". Night attacks had begun as early as June 1940, and the German progressive shift towards a night phase of assault was facilitated by their pre-war development of accurate radio-navigational aids. In this second, "Blitz", phase, an effective British night interception radar defence arrived too late to prevent significant damage to cities and war industries, although a hastily-contrived and partly-successful British radio counter-measures (RCM) campaign against German radio-navigational aids limited the devastation to some degree. Nonetheless, 43,000 people were killed and material damage done to war industries, so that by this yardstick, the acquisition of a radar-based air defence system for the night battle was a relative failure. On a second measure, success in air combat, German figures[1] show 1,733 Luftwaffe aircraft shot down during the day Battle of Britain, against British claims of 2,692; but for the first two months of the Blitz, from some 12,000 German sorties, only 8 aircraft were lost to British night-fighters, as against 54 lost to AA. On this criterion also, the acquisition was less than a success. Chapters V and VI analyse this less successful radar acquisition as a contrast to Chapters III and IV, the successful acquisition of radar for the day battle, in order to develop balance in the conclusions of this thesis.

It should immediately be noted that, although personal memoirs related to Chain Home are few, there is a rich seam of published reminiscence related to airborne radar. Of the pioneers, Bowen[2], the head of the team, Hanbury Brown[3], Lovell[4] and Wood[5] have published memoirs, albeit all were written at least 50 years after the events they describe. The service users of the system, the night fighter pilots and their radar operators – Chisholm[6], Cunningham[7] and Rawnsley[8] as examples – also contributed memoirs, or were the subject of biographies, published from the 1950s to the present day. Full use is made of this material, but it is here balanced by contemporary documents, by research carried out by Lovell for the Royal Society's Biographical Memoirs of Lewis[9] and Hanbury Brown[10], by the previously untilled 1945 memoir of Touch[11] (Bowen's original deputy), by the flying diary[12] of, and an oral interview[13] with, the only living pioneer, Keith Wood, and by the original daybook of 219 Squadron[14]. It is a contention of this thesis that the emphasis of the pioneers' memoirs, which focus primarily upon radar, has inadvertently distorted the history of the acquisition of a night interception capability. It will be shown below that airborne radar was *not* seen as the prime means of providing such a capability until mid-1939, and both documentary and archaeological evidence will be adduced to illustrate this fact.

V.2. Acquiring a radar-based night air defence system in the 1930s.

Chapter III described the characteristics of the early-warning radar Chain Home, the hardware basis of the 1930s acquisition of a radar based air defence system for the day battle. In considering radar and the move towards a night Blitz, then the first point of importance is that, of itself, darkness does not affect radar. It does, however, dramatically reduce the visual range of human beings, and, as was also described in Chapter III, because of the imperfections of Chain Home, the reality was that day interception capability had actually been achieved by Chain Home's guiding fighters only to within a 5-mile visual range of the enemy. At this point the defenders used their own eyes to guide themselves the rest of the way, to identify friend from foe, and to attack using the RAF's normal daylight tactics. However, by night the visual range for seeing a target was normally between 200 and 2,000 feet, depending on the weather, cloud and moon conditions[15]. The radar guidance needed therefore demanded more precision than Chain Home could provide. The eventual radar-based solution to achieve this precision included two radar components – the first, an accurate and dedicated Ground Control Interception (GCI) radar, which brought the fighter close enough to the target for its crew to activate the second radar, their own on-board Air Interception (AI) radar, and this in turn guided them to within visual range of the bomber.

However, for most of the period before 1941, radar was simply one among several night air defence possibilities. A primary strand in considering the acquisition of night interception capability in its proper context is therefore to track the alternatives sourced to achieve that same result. Most were unsuccessful, and because memoirs and retained files do not normally concentrate upon failure, this thesis has for the first time identified several un- or rarely-referenced systems. These are briefly described below, so that their characteristics may be borne in mind as this analysis proceeds.

The doctrine and concepts of the interwar RAF concerning night attacks are clearly apparent in the 1930s RAF Manual of Air Fighting[16], which identified the appropriate strategy as interdiction bombing of the enemy's airfields. If this did not suffice, then searchlights surrounding likely British targets would be employed, to "light up the sky" and illuminate the attackers so that normal day fighter tactics could be applied.

Such a use of searchlights originated in the First World War, where it had proven successful against large, slow, Zeppelin dirigibles. It may be observed that continuing a concept of "light up the sky and use day fighter tactics" would be reassuringly familiar to the RAF, and would lay no great burden upon those developing tactics and training pilots. The daytime defence system being built around Chain Home would also probably also suffice for fighter guidance at night if clear, moonlight weather could be guaranteed. However, both the Tizard Committee and Fighter Command identified that in normal conditions, searchlights were only effective on one-third of nights. On cloudy nights, the searchlight beam was diffused into a milky pool. As will be described, the Tizard Committee did not regard airborne radar in 1935 as other than a remote possibility, and instead pursued the concept of "lighting up the sky" through a scheme called "Silhouette".

Under "Silhouette", which is described in detail and in context for the first time in this thesis, a grid of powerful upward-facing diffuse-beam floodlights would illuminate the cloud base, such that high-flying fighters could look down, see their bomber targets as silhouettes against the illuminated clouds, as in Fig. 54, and dive to the attack. Cloud conditions for Silhouette was considered favourable on one-third of nights, so that, with searchlights alone already effective on another, cloudless, third, then two-thirds of nights now enjoyed some defensive aid, the remainder being deemed unfit for bombing.

This thesis will illustrate that significant resources were devoted to testing Silhouette, which was eventually discarded only in April, 1940. Silhouette's requirement for radar, and indeed almost all lines of development except infrastructure, would have been modest – essentially only Chain Home, as for day interception. By contrast, airborne radar development proceeded for some time with minimal resources on a "B" priority[17]. This pursuit of a deceptively simple capability solution as an alternative to radar will form one theme within this thesis.

A second strand of the present analysis focuses upon the different concepts of airborne radar developed after 1936. The eventual concept of airborne radar adopted in World War II positioned both the transmitter and the receiver inside the fighter. This was known as RDF2 (later, AIH), by comparison with radar totally based on the ground, which was termed RDF1. However, an intermediate possibility existed, which comprised a ground-based transmitter and an airborne receiver. This was variously termed RDF1.5, RDF1A, or later, AIL. Bowen's memoirs[18] imply that the RDF 1.5 system was dropped before 1937, but this thesis has for the first time identified that it continued to be developed until mid-1940, implying, at the least, a diversion of scientific effort and added complication in lines of development.

The tactical means of achieving night interception, which clearly also affect lines of development, are also examined here for the first time. When, during 1938, the first doubts began to surface about Silhouette's effectiveness, and about the nation's ability to construct its infrastructure in time for any likely conflict, and when simultaneously it appeared that airborne radar might be practicable, air interception radar was not primarily seen as facilitating an interception where the defender's guns would be used to shoot down an attacker. Instead, and from 1935-1940, the preferred method of attack was for the defender to sow an aerial minefield in the path of the bombers[19]. A later alternative, pursued during 1938-40, was for defending aircraft at high level to "bomb the bomber", using bombs detonated barometrically, by radio or by photocell[20]. Again, guidance by Chain Home would have sufficed for such purposes. The delay caused in lines of development by these alternative concepts of how airborne radar was to be employed forms a third element in the present analysis.

It was in fact only after July 1939, when AI radar in a crude form had been demonstrated, that the concept of night interception and combat by fighters using radar began to be considered in a structured form. By November of that year, this had led to the realisation of the need for two parallel hardware developments[21] – not only major refinement of the AI airborne radar, but also development of accurate ground control radar, GCI.

In July 1939, airborne radar was undeniably crude, but developing AI at all in the 1930s had been a challenge far greater than that of developing CH. There had been few limits on CH's size, weight or power consumption, or on the dimensions of its aerials, beyond running out of wood for their towers. In an aircraft, there were strict constraints on all four. To meet those constraints, AI had to operate on a short wavelength, for which no suitable aircraft transmitter valves existed. Suitable aircraft power supplies had also to be devised. The aircraft environment was extremely hostile to radar equipment because of vibration, noise, cold, and at altitude, thin air which encouraged high voltage arcing inside the radar. A data display had also to be developed showing its user the relative positions of target and fighter dynamically and in an instantly assimilable format. This had to be achieved despite the RAF's having no suitable night fighter until 1940, nor any concept of whether AI would be operated by the pilot or by an observer.

A particular challenge to the scientists was the RAF's demand for AI to have a minimum range of 300 feet or less[22]. The reasons for this demand were twofold – not only the need for short range so as accurately to aim and fire a lethal broadside into the target, but also – and preferably before opening fire – the need positively to identify friend from foe. Electronic IFF was neither reliable nor widely installed before late

1940, and even then did not operate on the airborne radar's frequency. This minimum range demand, and the lack of IFF, massively complicated the development and testing process for AI. One consequence was the production of four separate Marks and variants of AI - Marks I, II, III, IIIA, IIIB, and IV[23] - within twelve months. Each Mark and variant required, but was not furnished with, its own lines of development, and the complications and frustrations arising will be examined as a fourth strand within the present thesis.

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On the ground, meanwhile, attempting control of night interception by Chain Home (CH) radar alone proved impossible. There were three major vitiating factors. First, as the detailed description of CH in Chapter III identified, for each incoming bomber the CH operator needed to take three readings – range, bearing, and height. If that were possible in 30 seconds, a 240 mph bomber would in that same period have travelled a further 2 miles, beyond the limit of visibility for such a target at night. However, the controller would have needed to do more – he would have had to have added in the fighter's position from CRDF ("Pipsqueak") or to have taken three more CH readings. In either case, it is apparent that real-time fighter control was impossible, given the total time delay alone. Second, a Chain Home reading taken was accurate only to 5 miles, and as was identified in Chapter III, not at all accurate for height. It was not possible for a pilot with a human's limited night visual range to overcome this inaccuracy. Finally, Chain Home did not operate inland, where many interceptions would take place. As explained, these inadequacies were acceptable by day, where a 5 mile visual range was possible, but at night, the RAF demand was to guide the fighter to within 300 feet to identify its target.

The Chain Home pioneers complicated the issue by persisting in trying to make Chain Home interception work as late as October, 1940[24]. However, it had by then increasingly been accepted that there was need for radar equipment which would both give inland coverage and also would present target and bomber together on a display easy for the ground controller to assimilate. The solution was found by developing, over a parallel timeframe to AI Marks II-IV[25], the Chain Home Low (CHL) radar to present its results, not as "blips" on a line representing range, but instead in the form of a map with the operator at the centre and fighter and target shown as dots, swept by a radial trace corresponding to the rotation of the aerial[26]. This data display was known as a Plan Position Indicator (PPI, illustrated in Figure 55) and the radar itself was renamed Ground Control Interception radar (GCI). Because the fighter appeared on the same GCI PPI display as the attacker, the fighter no longer needed to be located by CRDF and "Pipsqueak" – its VHF radio could now be connected to the controller at all times. However, extra urgency was imposed upon the supply of reliable IFF, for without it the fighter and bomber traces could not be distinguished. GCI was of equal importance to AI radar for the night air defence system, but its development and acquisition have not previously been given equal importance. It is here considered as an important fifth strand in this analysis.

The confusion in experimenting with, and progressing, all these equipments simultaneously created a major series of problems for both Service leaders and scientists, particularly in the twelve months after the outbreak of war. Equally, the compression into these twelve months of most of the associated lines of development – in particular, the selection, training and organisation of pilots, radar observers and maintainers; sustainability, in terms of production engineering, test gear and procedures; interoperability; C3I; and development and manufacture of the hardware – might be expected to lead to delays and effectiveness in the acquisition, and these will be fully explored. Problems of bungled relocations, grossly inadequate facilities and personality clashes compounded the situation yet further[27].

A final, contrasting, element is provided by the fact that, before the war, the Germans had developed accurate radio-navigational beams to aid their night bombers. Once these were suspected, radio counter-measures, to detect, identify and neutralise these in order to destroy the accuracy of the night attack, became a significant component of the British night air defence system. Previous accounts have treated the topic separately, as an intelligence success[28]. In this thesis it is considered as a component of the total defence system, and its lines of development described.

In summary, there are five strands in the present analysis:

1. pursuit of an alternative to AI radar in giving night interception capability, the Silhouette scheme:
2. pursuit of an alternative radar technique, RDF 1.5, to the RDF 2 AI eventually adopted;
3. delay caused by alternative concepts to the use of radar to achieve an actual interception to destroy the enemy, these alternatives being to sow aerial minefields or to "bomb the bomber";
4. multiplication of the Marks and varieties of RDF 2 AI radar itself, and
5. the delay caused by not realising that ground control, GCI, radar was an essential counterpart to AI airborne radar in achieving the capability needed, and its consequent hasty development.

V.3. Night defence: Silhouette, radar, radio-navigation and radio counter-measures.

As has been indicated, there was a plethora of equipment relevant to the search for night interception capability in the 1930s, ranging from the Silhouette lighting system, through AI airborne radar of different techniques and Marks, to the German radio-navigational beam systems and the British radio counter-measures (RCM) to them. Before considering the part each of these devices played in the British acquisition of a radar-based night air defence system, a brief non-technical description may be helpful in illustrating each one.

The lowest-technology technique, the Silhouette scheme for cloud-base illumination, pursued for four years as the primary option for night defence, forms a convenient starting point. This consisted of a ground-based grid of powerful wide-beam (140 degree) electrical floodlights, shining upwards onto the lower surface of the cloud-base (Fig. 56). Viewed from above, the illuminated cloud-base gave the impression of a ground-glass screen across which the silhouettes of bombers moved slowly (Fig. 57). Despite extensive search, no original plans of a Silhouette site have so far been located, but surprisingly one survives, despite 67 years of disuse, at North Fambridge in Essex[29] (Fig. 58) and a single sketch by an Army subaltern (Fig. 59) has been identified in

National Archives files[30] to illustrate the general layout of the 50 Essex sites constructed. Each one consisted of a 50 ft wide dodecagonal concrete base, on which a ring of sheet steel buildings was erected. These carried on their roofs two concentric arcs of 3Kw. floodlight bulbs, backed by aluminium reflectors and together forming a complete circle. The lights were controlled from a central switching "kiosk", and for those locations not served by the electricity grid, a hut for the 300Kw. generator required was positioned close by. Archaeological survey for the Essex Sites and Monuments Record has identified the precise location of ten of the 50 original sites [31], one having pleasantly been found a new role as a rose garden on Harwich's Marine Parade

It must be emphasised that this "Silhouette" system was not a fantasy to be summarily dismissed. Silhouette was almost identical to a German concept of 1943 called "*Leichentuch*" ("shroud") or "*Mattscheibe*" ("ground glass screen"), whereby British bombers were silhouetted against the prevalent industrial haze layer which was then illuminated by searchlights and parachute flares (Fig. 60). They were then attacked with some success[32] by day fighters under loose ground control (the *Wilde Sau*/Wild Boar system), exactly as would have been the case under Silhouette.

Moving next to consider the form of radar installations, two alternative concepts were progressed simultaneously. The first, called both RDF1.5 and RDF1A, consisted of a ground-based transmitter with the aircraft carrying only a receiver. Fig. 61 illustrates a view in elevation, and Fig. 62 in azimuth. The advantages of this technique appeared to be twofold. First, there was a weight and power saving in the fighter which did not have to carry the heavy and power-hungry transmitter; indeed, in 1935 no suitable valves existed to make such a transmitter. Second, the system offered a significant maximum range, perhaps 20 miles, for the ground transmitter could be more powerful, and a small minimum range. This was important because, as described below, metric-wavelength AI radar was restricted in range to the aircraft's height above the ground, usually 2-3 miles, and Chain Home was not more accurate than 5 miles. However, in practice the complexity of the receiver circuitry needed for RDF 1.5 proved beyond 1930s technique, and it was found also that in practice ground returns so confused the signal received by the fighter that a realistic minimum range was 2,000 – 3,000 ft. Development was therefore halted, but only in mid-1940.

In terms of RDF2, the fully-airborne radar, the wavelength used was restricted to 1.5 metres (200MHz) by the size of aerials an aircraft could carry. The necessarily basic aerials then fitted projected the transmitter's power in front of the aircraft in a balloon shape illustrated in elevation in Fig. 63 and in azimuth in Fig. 64. Every object within the limits indicated returned an echo to the aircraft receiver aerials, but it will be observed that the earth itself is one such object. This "ground return" is so great as to swamp echoes from any greater distance. Hence in Fig. 63 the fighter F can "see" the bomber B1, but the bomber B2 will be swallowed up in the ground return, being slightly further away than the earth. The maximum range of this metric radar is therefore equal to its height above the ground, so that if the fighter F is flying at, say, 10,000 ft., it will "see" bomber B1 at 1.5 miles range (7,920 ft.) but not bomber B2 at 2 miles range (10,560 ft) because B2 will be subsumed in the ground return.

It is important to note that it became possible in 1940 to generate high power at centimetric wavelengths, using the strapped cavity magnetron valve[33]. Centimetric waves, "microwaves", are possible to "beam" using a reflector dish resembling today's satellite dish, and of a size capable of being mounted in a fighter (Fig. 65a). This produced a narrow beam of power as shown in Fig. 65b, which could be directed only in front of the fighter and hence produced no ground returns. In this case both bombers B1 and B2 are visible to fighter F. The relative priority to be given to developing microwave radar, as opposed to making metric radar work, would become significant in 1939/40 and would split Bowen's team apart.

In the data display eventually adopted in 1939-40, two cathode ray tubes were mounted side by side, one to display the relative azimuth position of the bomber to the fighter, and one the relative elevation. The fighter transmitted its radar pulses over the volume as shown earlier in Figures 63 and 64. On the fighter were two sets of receiver aerials, one on either side of the aircraft, so arranged as to receive the returning echo in overlapping "lobes" shown in Fig. 66; and a second set arranged above and below the wings to receive the returned echo in the lobes shown in Fig. 67. These sets of aerials were connected by a motor-driven switch to the receiver, and each set of aerials in turn produced a trace on the respective cathode ray tube. In Fig. 68, the azimuth tube shows a trace with a longer "blip" to the right, indicating that the target is to starboard; and the elevation tube has a longer "blip" above the axis, showing that the target is above the fighter. The distance of the "blips" along each axis indicates range, and at the end of each axis the "Christmas tree" (the term was used in 1940) shows the ground returns at the limit of range.

The airborne radars had to be accompanied by suitable ground radar to achieve effective guidance of the fighter. This Ground Control Interception (GCI) radar had to present an instantly assimilable real-time display of the relative positions of both fighter and bomber[34]. This was a major challenge to 1930s technique, for both were moving in three dimensions at 200-300 m.p.h. The solution adopted, the Plan Position Indicator (PPI), achieved this by displaying the area scanned by the rotating aerial of the radar as a map with the radar at its centre, as illustrated in Fig. 69. Today's air traffic radars have similar, though much more sophisticated, displays. In 1940, both fighter and bomber appeared only as "smudges" rather than pinpoints on the tube display. Eventually, when IFF became available and reliable, the friendly fighter's IFF ("Canary") distinguished its trace by a "crown of thorns" effect as shown. Displaying height was more complex, and a GCI height/range display is shown at Fig. 70.

Examining now the technology available to the attackers, the Germans had learned the need for navigational accuracy from WW1 and from their Spanish Civil War experience. Accordingly the Luftwaffe employed four major radio-navigational devices, each of which would be countered by British RCM (radio counter-measures).

The first was a series of radio "beacons" similar to civil air traffic radio beacons today, and by taking a bearing on two or more such beacons a German bomber could locate its position. To frustrate this, the British picked up the German beacon transmissions in the UK, and re-broadcast them from British transmitters called "masking beacons" or

“Meacons”[35]. The Luftwaffe aircraft equipment could no longer gain accurate bearings on the German beacons because of the stronger British signal on the same frequency.

In the second system, “Knickebein”, the Germans developed a high power version of their Lorenz radio beam system for blind landing[36]. In that system, two overlapping “lobes” of power were transmitted, one modulated by Morse “dots” and the other with Morse “dashes”; this is illustrated in Fig. 71. When flying down the centre of the lobes, a steady note was heard in the pilot’s headphones as the dots and dashes merged. Using Knickebein, the bomber followed the steady-signal beam for its course, and an intersecting beam was transmitted from another station, crossing with the steady-signal beam over the target. The only aircraft equipment needed was a more sensitive version of the normal blind landing receiver. The first British counter was to jam the beam with random noise. Later, the British confused the beam signal with spurious dots and dashes, leading to claims that they “bent the beams”. The British had code-named Knickebein as “Headache”, and the jamming transmitters were consequently code-named “Aspirins”.

The third German radio-navigation aid, X-Verfahren (often wrongly called X-Geraet, which is the name of the aircraft equipment) was code-named “Wotan I” by the Germans and “Ruffian” by the British[37]. In this case the pilot also followed an approach beam, but under the X-Verfahren system the aircrew activated a cockpit clock, controlling an electromechanical computer, on signals from intersecting beams. This computer then controlled the release of the bomb. The British jammers to counter “Ruffian” were known as “Bromides”.

Finally, the Germans employed a completely automatic system known as Y-Verfahren (Y-Geraet, or “Wotan II”), which controlled both course and release of the bomb[38]. In this case, the bomber had to transmit a signal so that its range from the controlling German station could be determined. This was a weakness, for the British could also receive that same aircraft transmission and re-radiate it more powerfully on the same frequency, thus “unlocking” the automatic bomb system. London’s unused Alexandra Palace TV transmitter was used for this purpose, and code-named “Domino”.

The thesis now examines the acquisition of a night defence capability during the first 1,000 days of development, until December 1938. At the end of each calendar year, a summary "red/amber/green" table is used to illustrate progress towards the system eventually adopted, on each of the lines of development for the its five main components. These are AI and GCI radars; IFF; VHF ground/air communications; and radio counter-measures (RCM) against German navigational aids.

V.4. Night defence before 1936.

As described in Chapter III, the earliest significant night raider of the First World War was the Zeppelin dirigible[39]. Typically 800 feet long and moving at 80 m.p.h. in still air, the Zeppelin took some 24 hours to arrive from its base in Germany. During that time, most were located by radio direction finding on their transmissions, at naval D/F stations such as those at Cleethorpes or Stockton-on-Tees[40.] Because of their great size and slow speed, Zeppelins could be illuminated and held by searchlights for many minutes.

However, searchlights in the First World War faced the same meteorological challenges as those in the 1930s – though useful on clear nights, their beam was diffused by cloud into a milky pool. Accordingly, on 23 September 1915, F.W. Lanchester proposed to the Aeroplane Subcommittee of the Naval Board of Invention and Research[41] the concept of illuminating the cloud-base over a large belt of country stretching from Lincolnshire to the Channel, "to form a veritable carpet of light against which hostile aircraft may be located in silhouette from aeroplanes flying at high altitude"[42] (Fig. 72). Tests at the National Physical Laboratory were encouraging, and an estimate of £1 million was derived for 1,000 lighting towers, each with a 20Kw. generator, as the infrastructure for this "carpet". However, full-scale trials at Upavon in July 1917 proved unsuccessful; and Zeppelin raids had by this stage given way to the Gotha bomber.

To counter the Gotha raids, attention focussed upon the creation of a comprehensive system of aircraft detection involving ships at sea, lightships, sound locators and inland observers, linked by the trunk telephone system to a central control room. From here, searchlights, guns and the despatch of fighters were directed, as was their control through a ground radio transmitter. This system was described in detail in Chapter III and in the contemporary accounts of its creator, Ashmore[43], and of an AA and searchlight commander, Rawlinson[44]. It sufficed to defeat the modest threat posed by German night bombers in the closing months of the war.

During the interwar years, the doctrine of the RAF regarding night attacks was that these could best be countered by the bombing of enemy airfields or by fighter intruder raids over them[45]. In the event of their defending home territory, pilots were warned that "the chances of encountering aircraft in the dark are small" and that their best chance was by "efficient co-operation between pilots…searchlights and anti-aircraft guns"[46]. The pilots were also advised to approach very closely, and that the visual range for identifying friend or foe was rarely greater than 100 yards[47]. It has only rarely been commented that training in night flying was not common, the intent for each selected squadron being to "produce nine fully qualified night flying pilots …every year"[48]. Full qualification was defined as "a period of five hours night flying", including "at least 12 landings"[49]. Such a level might qualify a pilot to land without crashing, but did not permit much training in, for example, night navigation, far less night fighting tactics. As late as 1940 there were only 84 "qualified" night fighter pilots, and the continuing impact of this line of development on the acquisition of different components of a night defence system should be borne in mind over the following narrative. Allowing for a national distribution of these pilots, for the duration of an average patrol against the length of winter night hours, and for leave, sickness, training, casualties and unserviceable aircraft, it is no surprise that each sector was able to field only one flight of three aircraft at any given time during such a night[50]. There is clearly a limit to the damage that so modest a force might inflict, even with the best of scientific aids.

However, the annual Air Exercises up to 1933 produced successful results for night defence, with interception levels over 60%. Such reassurance was misleading, since for peacetime safety reasons the attacking bombers kept their navigational lights on, and hence were visible several miles away[51].

The tocsin on night attack was sounded in 1934 by Lindemann. Concerned primarily about night defence because he thought the RAF could deal with the day threat, he saw night defence as "more important than a cure for cancer"[52]. He was not alone in perceiving the threat; Watson Watt's second radar memorandum of 27th February 1935 is quite explicit in referring to the night bomber[53], a fact overlooked by researchers[54]. From its first meeting, the Tizard Committee discussed night defences; its first instruction at that meeting was to discover hard evidence on searchlight detection at high altitude[55]. At its first "site visit", to the Air Defence of Great Britain HQ on 21st February, it was advised that "night attack was to be expected at least as frequently as by day". Fighters, it was emphasised, would only be effective "if contact is made with the enemy in the lighted zones"[56], but Brooke-Popham, C-in-C of ADGB, felt that searchlights, as recommended in the Manual of Air Tactics, would be of low value given the increasing performance of bombers[57]. By April, the Committee was already noting the ability of searchlights to illuminate the cloud-base[58] and, in parallel with its visit to Orfordness and encouragement of radar[59], had begun to consider "means for the visual detection of aircraft at night in the absence of searchlights"[60].

It may be that these moves were given added stimulus by the advent of Lindemann to the Committee. Before he joined, he wrote to Tizard on June 11 a letter whose eight pages are almost entirely about the night bomber. The best defences, he considered, were aerial minefields and infra-red detection[61]. A previously unreferenced critique by Rowe[62] comments that "Lindemann always talks of night bombers as though countering them is the only problem". It is rarely observed that the debate between Tizard and Lindemann takes the form of two men talking past each other rather than arguing with each other – Lindemann focussed upon first countering the night, cloud, and bad weather threat (some 75-80% of UK experience) while Tizard chose to start with a defence effective on clear, fine, days (the remaining 20-25%) and build upon that foundation.

By July the Committee, now including Lindemann, agreed to a visual detection conference being held under A.V. Hill, one clear focus being the night detection of one aircraft from another[63]. Some input was provided to the Conference, held on 1

October, by the 1935 Air Exercises; aircraft illuminated by searchlight were visible for 3 miles, and the interception rate had fallen to 42% even with navigation lights on. The Conference considered a private report by F/Lt. Atcherley that searchlights had been shown to illuminate a layer of cloud, mist or dust against which aircraft could be detected in silhouette[64]. AVM Joubert considered that if wide-angle searchlights could achieve this, it would be preferable to fitting searchlights in aircraft, and it was agreed that experiments be carried out. Rowe wrote to Hill after the Conference suggesting the idea of electrically driven helicopters with downward floodlights positioned just above the clouds[65], and referred to Lanchester's experiments. A second meeting resolved that RAE Farnborough should carry out tests.

During the Christmas holiday, Rowe produced a comprehensive "Appreciation of the Present Position"[66]. He lamented the lack of information on searchlight capabilities, summarised the intent to progress "Silhouette", and assessed air-to-air visibility as "one of the most important of air defence problems. Failure to solve it will leave a serious gap in the defences". He noted also that "it has been suggested that some form of RDF locating device might be fitted in fighter aircraft, but the problems have not yet been explored". Methods of destruction of bombers ranged from AA to aerial minefields and "bomb the bomber" proposals, fighter interception being only one among these. The relevance of these numerous proposals to acquisition is that each required different tactics and different forms of radar, which in turn would necessitate distinct lines of development. His eventual recommendations were for Chain Home, Silhouette, searchlights and aerial minefields to be given A* priority, while the development of radar for fighters was to be given the lower A rating, to move up to A* only when staff were available or when Chain Home was completed.

Night Air Defence Lines of Development Position at 31.12.1935.

Night air defence was eventually achieved by the combination of five elements. Four of these were dedicated to achieving night interception capability – Airborne Interception (AI) radar in the aircraft; the precision Ground Control Interception (GCI) radar to guide the fighter; Identification Friend or Foe (IFF) to distinguish bomber and fighter;

and VHF R/T to act as the guiding link. (H/F R/T would be proven inadequate since the "Pipsqueak" contactor cut off the intercom for 15 seconds in every minute and so made it impossible for the radar operator to guide the pilot). The fifth, no less important, comprised the radio counter-measures (RCM) designed to interfere with the enemy bomber's capability to navigate and bomb accurately. As in the case of the elements of the day air defence system, each had its own lines of development, and these will be assessed in a "red/amber/green" format at appropriate milestone dates.

The conclusion of 1935 forms an appropriate baseline. As distinct from the rapidly-developing day defence position outlined in Chapter III, the question of acquiring radar to achieve a night interception capability had only just been raised. Priority was being given to the alternative technique of Silhouette, and to searchlights when the weather was favourable, in line with the doctrinal and conceptual position of the RAF for illuminated night fighting. As the contemplated methods of destruction of attackers included aerial minefields and "bombing the bomber", it was possible to regard Chain Home, still under development but with a national chain approved in principle, as all the possible solution required. No work was therefore in progress on the lines of development for the main components of the system eventually to be used.

31.12.1935	AI	GCI	IFF	VHF	RCM
Doctrine & concepts					
Equipment					
Infrastructure					
Sustainability					
Personnel					
Organisation					
Training					
C3I					
Interoperability					

Table 7. Radar-based night interception capability: summary position at 31.12.1935.

V.5. 1936.

During 1936, Silhouette advanced from the laboratory to field experiments at Farnborough. In the spring, airborne radar acquired its first, part-time, researcher Dr.

E.G. “Taffy” Bowen, who concentrated on the RDF 1.5 technique. However, the failure of radar in the September Air Exercises – a failure relieved only partly by a successful demonstration of Bowen’s experimental equipment, then being tested in the towers of Bawdsey Manor - caused the small team he had acquired to be diverted back to Chain Home radar for a time. By December, RDF 1.5 in a basic form had been air-tested, but little other advance had been made, and Silhouette together with searchlights remained the primary proposed method of night air defence.

On 14th February, the Visual Detection Subcommittee of CSSAD held its first meeting[67], chaired by Hill; there had then been little progress on Silhouette, and by the 16th CSSAD meeting on the 26th [68], air-to-air searchlight tests had also “given somewhat disappointing results”. At the same meeting, Watson Watt gave a detailed explanation of his airborne radar proposals, showing that considerable thought had been given to the RDF2 technique. The operating wavelength was seen as between 0.5 and 4 metres (75-600 MHz.), with a minimum range of “well under 150 yards” and a maximum of 5Km. Curiously, the power output was assumed to be 1 watt. Experiments in the Bawdsey Manor towers were estimated to begin in April and last for two months, followed by six month’s airborne test work before fitting in a fighter. Tizard “regarded the work as of great importance”.

The Silhouette measurements began to become available in mid-March[69], and Hill pressed his case to Tizard in a letter of 25th March[70], seeing Silhouette as being as useful on cloudy nights as searchlights were on clear nights. His argument was partly resource-based; a zone 200 miles by ten would require, he estimated, around 60 MW of power, “about the power of 1 cruiser”. Hill saw air-to-air searchlights as “quite useless”, as he likewise viewed sound locators and undirected gunnery or searchlights. The 19th CSSAD on 29th May[71] supported his recommendation for a larger, 10 square mile, experiment, based on the RAE results so far.

At this point, the Lindemann disruption of the CSSAD took place, and, as was noted in Chapter III, Tizard had to withstand the assault of Churchill, supported by Lindemann and helped by Watson Watt, at a time when his own support was weakened, for Swinton was new in post and Freeman, his Air Staff member, weakened by a personal scandal. The powerful letter of support which Hill then penned to Tizard must therefore have given Tizard great comfort. The letter[72] is specific in pointing out that the trials of Silhouette were being delayed by "foolish experiments with bombs tied to parachutes", and Hill openly declared his intent to use his media (Daily Mail) and party-political (Labour) connections in support of Tizard.

Hill's own Subcommittee met on 3rd July[73] to begin to set up the 10 square mile trial; Dowding was made aware of this on 7th July in general terms, with more detail being supplied in a note of 13th August by Rowe[74]. That note identifies that the test area was now only 4 square miles, and the necessary power would be provided by 36 searchlight generators. More detailed planning took place on 16th September at a meeting chaired by DCAS[75].

While these plans were proceeding smoothly, radar was performing disastrously in the September Air Exercises. These have been fully described in Chapter III; in the present context, the points of significance are:

- ?? That the reputation of radar was in some small part saved by the fact that Bowen, who had been given the task of developing airborne radar as a part-time role, had constructed a 30Kw transmitter in one of Bawdsey's two towers and a receiver in the other, his intent being to trial the RDF 1.5 technique on the ground[76]. This worked perfectly and was demonstrated to Dowding following the failure of the main equipment[77].
- ?? Tizard, at this point, had staked his reputation on a system which appeared to have failed, and had very publicly done so when fighting off Churchill's attack at the ADRC. His letter of rebuke to Watson Watt[78] is by the conventions of the 1930s both pungent and acidic. In such circumstances, both bringing Watson Watt in on a tight rein and also lending support to a low-technology solution, Silhouette, must have seemed attractive.

Bowen, in his memoirs[79], considered that it was Tizard who first saw the need for night defence, and this may be so, although Lindemann's obsession with the subject before Tizard's Committee was even formed certainly would have ensured the subject was not overlooked. Bowen describes how he had angled for the task of developing airborne radar, an open topic of speculation among the Orfordness scientists during late 1935-6, as the alternative of driving round the country to find suitable Chain Home radar station sites did not appeal to him; it would become Wilkins' role. His first move had been to discuss the physical constraints with local aircraft engineers, and to assess these as 8 cubic feet volume, 200 lbs weight, and power consumption of 500watts[80]. He had then proceeded to interview as many people in the Air Ministry and Fighter Command as he could, but had discovered no ideas on night tactics at all, and not even a consistent idea of what a night fighter should be (e.g. a single-seat or 2-person fighter)[81]. Nevertheless, progress had not been slow; as an example, by July Tizard had asked, in the context of the Biggin Hill experiments, what range would be needed for a fighter AI[82]. For a receiver, Bowen experimented with an EMI TV receiver chassis on a 6.7 metre wavelength[83]. He believed that the chassis had been obtained from EMI laboratories "by the back door". Curiously, he states that it was to be his only AI receiver for two years, although Touch disputes this[84]. Using it, Bowen concentrated on the AI receiver and display, and devised his EMI-based unit with a total weight of 20 lbs[85].

The radar history of the remainder of 1936 is one of Watson Watt being brought under tighter control and being gradually forced to concentrate on Chain Home. The shock caused by the Air Exercise fiasco is revealed by a summary note of the "State of Investigations – September 1936"[86], which accepts that there may be value in sound locators and even in the 200 ft. sound mirror. The Silhouette trials, about to begin, are presented positively, being seen as obviating the need for aerial minefields, for using Silhouette, fighters could attack directly using day fighting tactics. The option of "bombing the bombers" is also seen as viable, with significant space devoted to it. Airborne radar is simply noted as having had a trial on 6.8 metres, valves for shorter wavelengths being unobtainable.

At the October meeting of CSSAD[87] – the first meeting of the re-formed Committee, with Appleton replacing Lindemann – much time was spent reviewing radar, as might be expected. Hill was away in the USA, but Rowe reported positively on Silhouette, and Tizard added that it had extra value in "confusing attacking bombers" by obscuring ground features. The Air Staff were to be asked if aerial mining merited any further effort, but “bombing the bombers” was encouraged. After the meeting, Tizard wrote a summary note of progress[88], referring to airborne radar as “promising”, but devoting much praise and space to Silhouette. Within a fortnight the next CSSAD received the RAE report that Silhouette had “very favourably impressed” the experimenters[89]; every effort was to be made to continue the tests, and the Air Staff were to be advised of them.

A third CSSAD of the month (31st October)[90] focussed almost totally upon Bawdsey, and is relevant in two regards. First, the recommendation is made that airborne work should focus on the RDF 1.5 technique, and secondly, there is discussion of the use of a “radio searchlight”, a beam transmitter operating on 4 metres (75 MHz) with mechanical turning of the beam. The concept had been suggested by Bowen as the “radio lighthouse” in 1935[91], but not developed due to lack of staff. It would, after many vicissitudes, become the Ground Control Interception (GCI) equipment. Lee, the GPO’s Chief Engineer, offered “short wave beam turntables” to Bawdsey on 3rd November[92] to aid the development.

It may be that the recommendations on RDF 1.5 and on the “radio searchlight” were stimulated by the visible progress of Bowen at this time. He had managed to secure some staff[93] (Fig. 73) for his project – Gerald Touch, a Clarendon Ph. D. who would specialise in receivers; Perc Hibberd, in transmitters; Sidney Jefferson, and, later, Keith Wood[94]. The Bawdsey tower transmitter was built up to a 40 Kw output and its pulse width reduced to 3-4 microseconds, giving a 40-50 mile range on target aircraft. RDF 1.5 airborne tests were then arranged in a Heyford aircraft from Martlesham, the power being provided by a collection of accumulators and dry batteries which were carried on to the aircraft for each flight[95]. Despite this crudity, a range of 8-10 miles was achieved.

However, an interim report on the Farnborough Silhouette experiment became available at this time[96], and was generally very encouraging. The CSSAD now began to discuss the involvement of commercial contractors[97], GEC being specifically mentioned, and also the extension of the trials to an even larger area. The idea of searchlights on-board aircraft was discounted by DCAS, and the greater collection of meteorological data to identify the extent to which Silhouette and searchlights could be used was "likely to be of supreme importance for home defence".

Hill prepared his own note on the Farnborough trials[98]. This document is extremely enthusiastic, anticipating that with more powerful lamps and a greater concentration of lights over a larger area, 3-4 miles visual range could be achieved by the fighter pilot, which would "revolutionise detection and therefore defence". He proposed a 200 (20x10) square mile test area "to the S.E. of London" for further trials, and his comments specifically include the facts that neither "complicated apparatus in the aircraft" nor "special training of the pilots" was needed. Extensive RAF tests were proposed "as soon as possible". This note was discussed by CSSAD on 18th November[99], where Wimperis agreed to contact GEC, though the large-scale trial would have to await Air Staff review.

During this time, the pressure on Watson Watt continued to mount. A detailed paper of every recommendation CSSAD had made on radar[100] was put to him for a progress report on each one, and these were reviewed by Appleton and Wimperis on 25th November[101]. On radio searchlights ("beam technique") Watson Watt stated that the difficulties were great and he preferred to proceed with Chain Home. His view on airborne radar was that, given the success of the RDF 1.5 flights in the Heyford, he would continue with the work, and interestingly, in view of Bowen's comments, EMI was to be asked to produce more TV chassis to help.

The final Farnborough report on the four square mile experiment became available in early December; Figure 74 reproduces from the poor quality original of that report a picture of one of the flood-lighting units. The CSSAD meeting of 21st December[102] concentrated upon radar, and particularly upon discussion of a detailed note provided by Rowe on the present position. The CSSAD was obliged to defer the January Air Exercises (intended to remedy the poor showing of those in September) and now determined to focus its energies on Chain Home. In line with that decision, "no further work" was to be done at Bawdsey on radio searchlights, although "getting it developed at some commercial firm" was discussed. A lengthy discussion on airborne radar identified its main use as interception above cloud at night, and so it was decided that it had to be balanced against other methods of achieving this (clearly, Silhouette). The need for "perhaps 100 yards" minimum range was emphasised, as was the fact that the Heyford test was "far removed from a practical system". The conclusion was that "it seems probable that the difficulties confronting successful RDF 2 operations are so great that their solution will engage the whole time of some of the best available Bawdsey staff, perhaps for years" and that the diversion of effort had to be fully justified. Ground tests on minimum range were proposed, with no further flying work to be done until these were successful, and RDF 2 as a project was to be balanced against Silhouette, aircraft-mounted searchlights, and infra-red detection. AI was assigned a B priority, against A or A* for Chain Home[103]. By contrast, preparations for the 200 square mile test of Silhouette forged ahead with a meeting the following day[104].

The Night Air Defence Lines of Development Position at 31.12.1936

By the end of 1936, one possible AI technique, RDF 1.5, had proven successful in a very basic test, and the idea of "radio searchlights" which would lead to GCI had at least been tabled and debated. Nonetheless, and directly as a result of the September Air Exercise debacle, work was to be entirely focussed on Chain Home in radar and on Silhouette and searchlights for night detection. On the bulk of the lines of development there was, therefore, no progress, considerably to the disgust of Bowen who would have wished for a rapid introduction of RDF 1.5 to the RAF, essentially to develop tactics[105]. As will be shown below, exactly this lack of tactics for night interception would prove a major problem in 1939-40. The team at Farnborough who would develop VHF ground control R/T was being gathered to start on this challenge, albeit for interception in general rather than specifically for night combat. IFF had been conceived, but was still at the stage of reliance on Watson Watt's untested keyed resonant wires. The need for radio counter-measures had not reached even the stage of being conceived.

This position would, of course have been perceived differently by the Tizard Committee, who were placing their reliance on Silhouette. That alternative concept appeared to be performing well in its small-scale trials at Farnborough, and would necessitate neither equipment in the aircraft nor any tactical training of the crews.

31.12.1936	AI	GCI	IFF	VHF	RCM
Doctrine and concepts					
Equipment					
Infrastructure					
Sustainability					
Personnel					
Organisation					
Training					
C3I					
Interoperability					

Table 8. Radar-based night interception capability: summary position, 31.12.1936.

V.6. 1937.

During 1937, CSSAD sought and eventually obtained £400,000 from the Treasury to establish a test area of 50 Silhouette sites in a 200 square mile sector of Essex. The scale of this expenditure – equivalent to 40 times the amount given for the experimental phase of radar, and equivalent to £60 million in 2007 – supports the contention that Silhouette was seen as the major component in night defence, and not as some eccentric scheme. Airborne radar, with much more modest resources and a lower priority, made significant strides as both aircraft and suitable transmitter valves became available. A totally airborne system was first successfully flight-tested in March, and trials of the Air to Surface vessel (ASV) configuration were crowned with success in September with the location, from the air, of the British Fleet on exercises. However, for Air Interception (AI), the RDF 1.5 technique, with the transmitter on the ground, was still seen as the preferred solution.

The January meeting of the CSSAD[106] approved Bawdsey's research programme with AI radar on a B priority, and Rowe advised the Committee of the arrangements for the 200 square mile trial of Silhouette. The subject was discussed in greater detail four days later, at Hill's Visual Detection Subcommittee[107], where GEC were identified as the lighting designers and such design parameters as the beam divergence debated.

Concerns about lack of structure and progress were expressed by Rowe in a private letter to Tizard on 31 January. In that letter[108], where he writes of Silhouette on the same level as radar and the Biggin Hill experiments, Rowe points out that Dixon, recently seconded from the GPO to give structure to the process, felt extremely strongly about the lack of organisation, and Rowe emphasised that Watson Watt could not be made to stay at Bawdsey "either in heart or body" even though both Freeman and Wimperis thought he should not leave there until radar had been "solved". Typical of such unresolved complexities was the reference in a note by Dickins[109] that night defence would be thwarted simply because of the inadequate number of radio channels available per sector to guide fighter aircraft; there is no evidence that this had been considered even for fighters working with searchlights.

The request for so much money for Silhouette had certainly stimulated discussions between Dowding and Peirse (DCAS), such that Peirse, with Freeman, Air Member for R&D, attended the next CSSAD on 10 March[110] to brief themselves on Silhouette, and to debate concerns which had been expressed. These appear to have focussed first on cost benefit issues, in particular that the full national scheme would cost £13 million (£2 bn. in 2007 terms), with a London-only scheme costing £4m (today's £600m), and secondly on the fact that for modern monoplane fighters, keeping watch downwards was difficult owing to the wing position. During the discussion, there were emphasised the contentions that neither special training for the pilots nor special apparatus for the aircraft were needed, and it was observed that the expensive electrical generation plant might have peace-time applications in the electrification of farms. DCAS appeared convinced by the arguments, and undertook to gain an Air Staff decision soon.

The cost of Silhouette raised issues in other quarters; Lord Weir, acting for the ADRC, was asked to accelerate the scheme[111], but was convinced by GEC that it entailed "formidable equipment" including cooling fans, and that a 15-month timetable was "optimistic rather than conservative". Tizard, called upon for help, was "surprised that the actual lamp equipment is getting so elaborate" but undertook to see if it could be simplified.

Any chance of savings by use of parachute flares to provide part of the illumination was, however, quashed by a negative Farnborough report[112], and at April's ADRC Swinton, the Secretary of State for Air, tabled the formal request for £400,000. Silhouette, he explained, was expected to be effective on 111 nights per year, and the

200 square mile test area would require 50 sites, each of one acre, furnished with a 400 Kw. lighting unit, and projecting from a glass-roofed building a 160-degree divergent beam to illuminate 4 square miles of cloud. GEC would be the prime contractor and the cost of a full scheme might "be anything from £7,500,000 upwards"[113].

Possibly unsurprisingly, the ADRC did not immediately agree, a fact reported back to the CSSAD on May 19th [114]. The same meeting recorded that the Committee would "welcome a short report on the naval use of RDF", and that a searchlight in an aircraft could be useful "in conjunction with RDF 2, the searchlight being operated at short ranges where RDF 2 broke down". Both points are relevant to the work then being pursued by Bowen's group at Bawdsey.

That group had begun to make rapid strides, despite their minimal resources and low priority. A suitable transmitter valve, the American WE316A "doorknob", became available and, using it, Hibberd designed a 45 MHz transmitter to match the EMI TV chassis used as the receiver[115]. When test-flown in March, this configuration achieved ranges of 3-4 miles against ground targets[116], which made it the world's first airborne radar. The team set themselves to achieve higher powers at shorter wavelengths, which would increase the range and reduce aerial size. In particular, they were concerned to pursue echoes from ships, the ASV use of radar, of obvious interest to both the Royal Navy and to the RAF's Coastal Command. Bowen had also indented for an aircraft to help in the tests, and was surprised to receive two[117]; both were Ansons, a vice-free aircraft standard in Coastal Command, and so equipped for flights out to sea, which at this date most RAF aircraft were not.

For night air defence, the approval process for Silhouette continued, the Defence Policy Requirements Committee[118] proving reluctant to agree at its June meeting, and asking if there were cheaper alternatives. The CSSAD in reply generated supportive notes[119], and in its mid-year position paper continued to press the scheme[120]. RDF 2 was accorded a very brief mention, in the context of searchlight aircraft, and more space was devoted to the constraint posed by lack of sufficient radio channels to guide intercepting fighters.

By 5th July, CSSAD again debated Silhouette[121], having been put on notice that the cost of the complete scheme, at £12.5 million, was a likely objection. London, it was observed, could be defended for £2 million, and the Committee "recorded their views that the large scale Silhouette trial was highly desirable". As a minor item, work on the radio searchlight, the proto-GCI, was continuing, though Watson Watt was "somewhat pessimistic".

One of the infrequent meetings of the RAF's Air Fighting Committee took place a fortnight later, chaired by Sholto Douglas and attended by Dowding and his staff, and is relevant for the user views expressed. In a brief comment on night fighting, the RAF's doctrinal position was set out by the Chairman in a stark fashion[122]:

> "The Chairman …remarked that nothing of any consequence had been done in that connection since the Great War. The opinion was expressed that the subject was comparatively straightforward i.e. the target would be lit up by searchlights so that the fighter could keep his sights on, or it would not illuminated (*sic*) and the fighter would not be able to see it clearly".

The subject was referred to the Air Fighting Development Establishment, but not on a high priority; Blenheims would be required for the trials but were needed for other work first.

Tizard was no doubt pleased to report to July 26th's CSSAD that the Treasury had approved the Silhouette trial[123]. At Bawdsey, however, radar developments were moving on apace. Hibberd had successfully produced a stable and more powerful transmitter on 1.25 metres, using two WE316As in push-pull, and Touch had developed a sensitive superheterodyne receiver using American "acorn" valves at radio frequency and the EMI chassis as a 45 MHz intermediate frequency amplifier[124]. A technical point is relevant here. Hibberd's transmitter configuration was a self-modulated "squegging" oscillator, which obviated the need for a separate modulator and thus saved weight. The penalty was that the transmitter pulse was ill-formed and trailed on into the time when the receiver should have been "listening"; a consequence was poor minimum range performance[125], a factor not relevant for the distances involved in ASV work but deemed essential by the RAF for AI. This point became important in 1939/40, as will be seen in Chapter VI.

Clear echoes were obtained on the first flight, on 17 August[126], and a minor modification to 1.5 metres (200 MHz) followed to improve sensitivity. Within three weeks the team used the opportunity of a Navy exercise to locate units of the fleet by radar[127], and because during their observation aircraft took off from the carrier HMS Courageous and were seen on the display trace in the Anson (Fig. 75), AI radar may be said to date from this 4th September flight. The achievement generated considerable excitement at Bawdsey, with an urgent letter being sent from Dr. Paris, the Deputy Superintendent (Watson Watt, interestingly in view of Rowe's earlier observations, was away) to Wimperis, giving full details[128]. It should immediately be noted that the only measurement at this point was of range; Fig 75 shows a typical trace, and there was no azimuth information. The AI configuration in use was later sketched by Touch, and Fig. 76 reproduces this sketch for the first time. Fig. 77 is the only known picture of an early pattern transmitter.

At the following CSSAD[129], Appleton, who had visited Bawdsey, pronounced himself "impressed", and the proposal was tabled to increase the staffing on the project. The connection with progress on the radio searchlight was noted, with the aim of raising the priority of this also. After the meeting, Tizard prepared for himself an aide-memoire[130] on which comments were made by Watson Watt. This note clearly identifies his support for RDF 2 as an ASV radar, but he considers the power inadequate for AI use and proposes that RDF 1.5 be used for this purpose, apparently in the belief that the airborne receiver could remain the same. Watson Watt added his agreement on the 20th [131], the eve of the next CSSAD.

That meeting[132] held a lengthy discussion on the inadequacy of the present ground/air communications in terms of both range and number of channels. This left little time for consideration of AI; Tizard pressed his view on RDF 1.5 and a further meeting was arranged for the following week. Tizard there[133] repeated that ASV was "very promising, but the low power of the transmitter reduced its utility for the location of aircraft". RDF 1.5 was put forward, and the Committee stated that "every effort should be made to develop the RDF1a *(i.e. RDF 1.5*) technique"; Watson Watt thought azimuth indication would be possible in about six months. The Committee noted also that "beam technique" (the radio searchlight) had been further developed, recommending the use of sound locator turntables as rotation gear, a suggestion which was taken up.

It is important to note here that Bowen's memoirs[134] imply that RDF 1.5 was dropped before March 1937 – "Watson Watt would have none of it" – but the entries in Wood's daily diary[135], and the CSSAD minutes[136], are quite clear that RDF 1.5 continued. It is also the case that the radio searchlight and beam technique continued to be developed, despite Bowen's implication that nothing was done. It may be that, since the Army cell at Bawdsey were handling this work, Bowen was unaware of the detail at this point, although he certainly knew of it from mid 1938 onwards[137].

1937 moved towards its close with an interesting letter from Dowding on 15th November, in which he clearly restates his views to Peirse that the Silhouette trials earlier in the year were "most unpromising"[138] and that future monoplane fighters would have a "very poor downward vision". He attached a letter from 11 Fighter Group which was even more disparaging. The Service user was, it seems, far less enamoured of Silhouette than CSSAD or the Air Ministry.

An unreferenced end-year report from Bowen survives[139], showing the research foci to be increasing transmitter power to increase maximum range; improving the data displays; optimising the system for ASV use, and examining its potential for contour mapping and navigation, a crude forerunner of the H2S blind navigation and bombing system.

Night Air Defence Lines of Development at 31.12.1937.

At the conclusion of 1937, airborne radar had been convincingly demonstrated in an ASV configuration, even though it was as yet only capable of determining range. For AI radar, the preferred technique remained RDF 1.5, even though aircraft returns had now been seen on a fully airborne radar. Constraints on ground control caused by inadequate R/T had at least been identified, and, as was described in Chapter III, VHF R/T was under development. IFF was still a concept dependent on Watson Watt's untested resonant keyed wires. Silhouette continued to be the preferred means of facilitating night interception, its advantages being seen as including no RAF requirement for either equipment or training. Although the main user was unimpressed, the Treasury had approved £400,000 for a major trial. Most lines of development for AI had therefore not been addressed, and within the RAF, there was still no clear concept of what a night-fighter aircraft would look like – one or two man crew, single or multiple engined – since clearly this would depend upon the night fighting aids adopted. A generous summary of the position is set out below.

31.12.1937	AI	GCI	IFF	VHF	RCM
Doctrine and concepts					
Equipment					
Infrastructure					
Sustainability					
Personnel					
Organisation					
Training					
C3I					
Interoperability					

Table 9. Radar-based night interception capability: summary position, 31.12.1937.

V.7. 1938.

During 1938, preparation of Silhouette's Essex trial area proceeded in a stately fashion. Cheaper reflectors were developed, the first GEC unit installed at Rayleigh, and the 50 sites necessary for the full test, illustrated in Fig. 78, were purchased. By December, the tender was published for providing the 49 lighting units, delivery to be by mid-1939. Airborne radar, by contrast, developed rapidly, for ASV use early in the year, and then subsequently for AI, stimulated by new Service interest and the Munich crisis. Higher powered transmitters were built, the aerial systems refined, data displays improved, and the infrastructural issue of inadequate aircraft power supply resolved. However, because of the earlier concentration on ASV, a number of hidden flaws for AI purposes had been unwittingly been incorporated in the system. Perhaps most importantly, during the year there was also a convergence between the CSSAD, the Air Ministry, and Fighter

Command, the end user, who proved at this point not to have thought that AI-guided interception was even possible. As a result, the practical issues of Identification Friend or Foe (IFF) and ground control began to be assigned a higher priority.

The constraints of inadequate ground/air communications occupied January's CSSAD[140], though they were advised that RAE Farnborough had the matter fully in hand. A month later[141], the Silhouette scheme was reported to be achieving a "considerable reduction in costs" through redesign of the metal reflectors. Airborne radar had now acquired an acceptable azimuth data display which it was hoped to test in an aircraft in May. Hill reported in March[142] that he was impressed with the cost savings of the new aluminium reflectors, but the prime topic of debate was the failure of Chain Home to guide even daylight interceptions on civilian airliners flying known routes. Tizard visited Bawdsey on 30 March to investigate[143], commenting that Canewdon was not working well and that no height indications were being provided at all – a serious matter for day interceptions, but a crucial matter for the night battle. One approach taken by Tizard was to advise Watson Watt to put more effort into the beam technique (radio lighthouse), and to visit MetroVick[144] to urge the production of more powerful transmitters for that purpose.

On 20 April, the Air Ministry responded[145] to Dowding's letter of 15 November 1937, which had been dismissive of Silhouette; their reply betrayed ignorance of the system, specifying only limited times of night during each month when it would be available. Calling it a "silly letter", Dowding advised his staff[146] that Silhouette appeared to be operable for only 4 hours a month, a "tiny part of the problem of intercepting raiders without searchlights".

It was increasingly apparent that Dowding regarded Silhouette as close to useless, even though positive reports on its progress were being made to CSSAD[147] and to ADRC[148] in April and May, and though Tizard was positive about its design on a visit to Farnborough on May 11th [149]. Accordingly, he and Hill arranged to meet Dowding on May 24th [150]. Tizard's record of this meeting[151] is previously unreferenced, and is important because the discussion focussed upon the lack of downward visibility from monoplane fighters, and Tizard realised for the first time that “Silhouette may possibly break down because of this”. Tizard and Hill evidently raised the question of twin-engined fighters, the observer being employed to scan the sky below; they discovered that “Dowding is rather against them”, preferring instead to fly single-engined fighters in formation so that the leader could perform this role. Tizard proposed to Dowding that the Blenheim be used as a fighter, and particularly for the test of Silhouette. The meeting clearly revealed a significant gulf between developers and users which the remainder of the year was used to bridge. The first evidence of this is to be found in a Fighter Command conference on 15 June[152], but it is appropriate first to summarise the developments in airborne radar at Bawdsey in the first half of 1938.

During that time, the Bawdsey airborne radar team had expanded by a further six including the highly capable Hanbury Brown (himself a pilot), and concentrated on ASV research[153]. Coastal Command, the potential user, was extremely interested, and ASV problems were more straightforward than AI as its ship targets were, by definition, only beneath the aircraft, at sea level, typically very large, and moved slowly. Additionally, no special tactics were required of the pilot, and Coastal Command was headed by Joubert, who had been involved with radar since its earliest days. Touch asserts[154] that six ASV sets were in fact ordered by Coastal Command, and that, though they were never delivered, this provided the stimulus for the researchers to concentrate on ASV.

There were two primary areas of work - developing a more powerful transmitter, and devising suitable aerial configurations. A more powerful transmitter valve, the WE 4304, became available from the USA, and a transmitter of 1-2 Kw. output was produced with a 12-15 mile range[155]. Working on this transmitter inspired one of the airborne team, Eastwood, into using the same 200 MHz frequencies when he moved across to Bawdsey’s War Office team[156] and worked on the practical use of the beam technique, Coast Defence (CD) radar. CD would be the origin of Chain Home Low (CHL) and thence of the GCI radar used for night fighter ground control. In the aircraft, many different aerials for ASV work were flight tested, earning the team’s long-suffering Anson the soubriquet of “The Flying Washing Line” (Fig. 79). Eventually, designs were refined into two types, for search and for homing[157]. Search aerials emitted the transmitter power in sideways lobes from the aircraft; homing aerials projected the power forwards. Azimuth bearing in terms of left/right direction could now be determined by use of switched overlapping beams. Fatally for AI, the team resolved upon the use of “horizontally-polarised” aerials to reduce the spurious screen traces known as “wave clutter”. This decision, perfectly logical for ASV, had unfortunate consequences, for it produced a “squint” when used for the shorter AI distances[158] so that signals from the left showed as being on the right, and those from the front as from behind. Vertical polarisation of the aerials solved this series of otherwise intractable problems[159] but, as will be seen in Chapter VII, the results of this decision persisted into 1941.

In May 1938, ASV detected the aircraft carrier Courageous with a side-search aerial array, and photographed the trace[160], illustrated in Fig. 80. Two months later, the system was satisfactorily demonstrated to a positive Joubert[161]; it would be another year before AI would be demonstrated to Dowding, who as will shortly be seen was in fact unaware of the potential of AI.

At his June conference[162], Dowding opened by outlining his concerns that searchlights alone would prove inadequate for night interception; he had, he said, witnessed them being defeated by an extremely thin layer of cloud in a test at Aldershot the previous autumn. Silhouette was discussed, and Dowding “stated that he did not believe in this “illuminated floor””, essentially because of the cost and the ease with which the bomber could avoid interception by simply flying into the cloud, at which point it became invisible. He speaks of the experiment as being “allowed by the Air Ministry” and “we (Fighter Command) would co-operate with that experiment when required”. The meeting proceeded to revisit the ideas of parachute flares and of airborne searchlight illumination, before deciding that their best hopes lay in looking for exhaust flames in the dark and in their own airfields having better gun defences. Following the conference, Dowding sent the minutes to Tizard, and it is instructive to quote part of Tizard’s reply in detail:

> "You are very pessimistic about the Silhouette scheme. I am not optimistic at all, but I think we had better wait until experiments are done"[163].

He went on to accept that modern fighters were "unsuitable for night searching" and to consider instead the question of airborne searchlights. In replying on 1st July, Dowding said:

> "I am sorry if I appear to have prejudged the issue about the Silhouette scheme. We will give it a fair trial when it comes along"[164]

Clearly stimulated by Tizard, Pye, Wimperis' successor as DSR, quickly sent Dowding further details of airborne searchlight research, which he "had been thinking of in relation to both RDF 2 and the Silhouette scheme"[165].

The stage was set for a major conference on Night Defence on 21st July[166], chaired by Sholto Douglas and attended by Tizard, Dowding, Freeman, their staffs and the entire CSSAD. This was the first joint meeting of scientists, the Air Ministry, and the user, Fighter Command, and apparently was a revelation to all parties. Prior to the meeting, Watson Watt and Pye circulated a previously unreferenced note[167] and questionnaire which would form its agenda. This note outlined the fact that, at night, Chain Home would provide early warning. Of the two airborne radar techniques, RDF 1.5 and RDF 2, RDF 1.5 could give a maximum range of 15 miles and a minimum of 1 mile, but neither azimuth nor altitude data, though these might be available in 2 and 6 months respectively. RDF 2 was "working in an Anson" with a maximum range of 2 miles and a minimum of 200 yards, perhaps reducible to 100. Again, azimuth and altitude data could be expected in 6-9 months. The Silhouette trial area would, the note continued, be ready by Autumn 1939. For the first time, the question of IFF was also discussed.

At the conference itself[168], Sholto Douglas opened by advising that Freeman had suggested the meeting. Lengthy debate followed on the likely numbers and tactics of potential night raiders, and Dowding advised that the defence would consist of two to three, or at the best four, ground controlled aircraft per sector. Tizard was not discouraged, arguing that it was necessary "only to intercept 30 out of 300 raiders" to achieve success. It was agreed that, inland, sound locators and the Observer Corps were of limited value at night. Dowding stated, for the first time, that "hitherto he had not considered it to be practicable to dispense entirely with illumination and rely on RDF carried in aircraft", but he was now prepared to think along this path – in which event, the minimum range should be 100 yards. He strongly wished to have an automated IFF, but Tizard warned that this might be difficult and that alternatives should be pursued.

Stimulated as it no doubt was by the threat of the Munich crisis, this conference undoubtedly focussed senior level attention of researcher, acquirer and user upon AI development for the first time. Ripples from it spread quickly; within a month, Touch at Bawdsey observed[169] that ASV experiments, hitherto the priority, received "little further work … for a year, as the need for an AI, to which little attention had been paid, was pressing". Bowen was invited to CSSAD personally on 22nd. September[170], and the Committee proposed to speed up the supply of high power VHF transmitting valves to help in his work. A long debate also took place on IFF, although hopes at this stage were still being placed on a tuned resonant aerial rather than dedicated IFF equipment.

Two obstacles to the development of night interception, revealed both by the CSSAD minutes and by Tizard's note of a visit to Biggin Hill on 21st November[171], were that the methods of interception were still seen as the use of "shadowing" aircraft, or of air-dropped mines, and that night attack practices were still performed with navigation lights kept on. Neither, of course, aided the process of devising the tactics needed for an AI equipped fighter to shoot down a bomber.

The clearest evidence of the growing integration of Service leaders and scientists was seen in the addition of Sholto Douglas, ACAS, to the Tizard Committee on 23rd November[172]. Night interception at this point became an agenda item, and the Committee expressed an urgent need for large-scale night exercises, for the trials of Silhouette, and for the development of the IFF transponder.

Some idea of the added impetus can be gained from the fact that six sets of airborne radar had been ordered in October by Watson Watt in his role of DCD, the transmitters from Metropolitan Vickers and the receivers from Cossor, the same manufacturers as for Chain Home[173]. This was despite the fact that AI had been tested only in September, and was in a highly fluid state. The orders were to prove disastrous through lack of specification, of briefing and of production control, all functions of the new pressures on the scientists. Cossor could only be given a verbal briefing, while Metro-Vick were given a two year old superseded transmitter as a model, for there were no blueprints or drawings. The results would be wretched. The Cossor receiver was far too heavy and insensitive, and MetroVick were visited by Watson Watt who insisted that they exactly copy the outdated model[174], with predictable results.

Bowen did however resolve one infrastructural problem, that of limited aircraft power supply. He visited Metro-Vick personally, unbolting the DC generator from the aircraft he was using[175] to take into the meeting. He asked that an AC generator be designed for the maximum power output possible within the same physical dimensions. This proved to be at 80 volt, 1600Hz which became a WW2 standard.

One final 1938 proposal for illuminating the night sky should be mentioned. This was the apparently fantastic recommendation to create an artificial aurora borealis. The proposal, put forward by Professor Bailey, was to stimulate such an aurora by radiating a 500 Kw. signal "by means of an aerial system consisting of 800 horizontal half-wave aerials …at an elevation of 50 metres". A half-wave aerial was some 100 metres long, from which the scale of this project may be visualised. A paper was prepared for, but not circulated to, the CSSAD[176]; the subject recurred in 1940, when it was identified by Rowe that the original calculations had been in error and that 100 MW would be required, but it illustrates the tenacity of the concept of "lighting up the sky". .

Night Air Defence Lines of Development Position at 31.12.1938.

By the end of 1938, progress had been made in bringing together the various parties involved in AI development and its potential application – the scientists, the Air Ministry, and Fighter Command, the end user. Silhouette continued to be developed, although, it can be assumed without great enthusiasm, despite the reports which continued to be made to the ADRC to justify their £400,000 investment. Bowen's group had the genesis of a workable, if experimental, system, and Watson Watt had even ordered sets commercially. The flaws in that order, and those arising from AI's ASV origins, were not at this point apparent. True IFF, as opposed to keyed resonant wires, was now actively being pursued, as also was VHF for fighter ground control, but no thought had been applied to staffing, training, organisation, or sustainability for any of the elements of the system. Most importantly, there had been no test of interoperability - whether CH could in fact guide a fighter close enough to an attacker for AI to take up the chase successfully.

31.12.1938	AI	GCI	IFF	VHF	RCM
Doctrine & concepts	red	red	yellow	red	red
Equipment	yellow	yellow	yellow	yellow	red
Infrastructure	red	red	red	red	red
Sustainability	red	red	red	red	red
Personnel	red	red	red	red	red
Organisation	red	red	red	red	red
Training	red	red	red	red	red
C3I	red	red	red	red	red
Interoperability	red	red	red	red	red

Table 10. Radar-based night interception capability: summary position, 31.12.1938.

V.8. Summary and Conclusions.

At the level of doctrine and concepts, it is difficult not to conclude that pre-existing doctrine and WW1 experience had a negative effect on night defence research. The primacy of strategic bombing assigned a secondary role to all defence, while experience with searchlights and Zeppelins led to tactics based on the assumption that searchlights would illuminate the night target sufficiently to allow day tactics to achieve a "kill". The Silhouette scheme would have seemed a natural extension of searchlights, and, it might be repeated, a similar scheme was successfully used in Germany later in the war. It involved no abstruse research for CSSAD and, for the RAF, no change of tactics, no fighter-borne high technology, and no pilot retraining. At the least, and even if Silhouette was seen only as a contingency (which is extremely unlikely, given its expense) it appears to have facilitated the limited scientific and service thought remaining focussed on "radar for day defence" problems. We might note, however, that it was the Air Ministry and the Air Staff who were supporting the idea; Dowding, as C-in-C Fighter Command and hence the “end user”, was rather more sceptical. The acquisition lesson is that pre-existing doctrine, and the presumption of an easy development and introduction to service of a solution based upon known technology and concepts, and requiring no training and no in-flight equipment, may divert the search for a radical alternative rather too soon.

In spite of this lack of higher-level interest, airborne radar developed quickly, even though it faced apparently insuperable technical challenges and worked under a low priority. Bowen’s small team had reached out beyond existing technology, as CH had not, and achieved three world firsts – the first airborne radar of any type, the first ASV, and the first AI. However, looking beyond the aura of these major achievements, the team’s pursuance of two distinct techniques, RDF 1.5 and RDF 2, and then within RDF 2 of two distinct applications, AI and ASV, undoubtedly diverted some thought away from the key and difficult practical question “how exactly would AI be used in an air-to-air interception”, as opposed to the more self-evident “how might ASV be applied to locate ships”. The “pressing” need for the scientists to switch attention between the two applications is very evident in Touch’s memorandum[177]. Clearly, these diversions drew attention from the lines of development necessary for AI to be brought into effective service. As examples, there was no thought given to such important considerations such as who would operate the AI (would it be the pilot, who was also occupied with flying and fighting the aircraft, or a separate operator, as for ASV – the answer in turn having major implications for the infrastructural question of which aircraft might be used), or to what training was required, or to how sustainability was to be achieved. Organisation and communications were at this time simply assumed to be the same as for the day battle.

A series of questions arise from this analysis. The RAF men quizzed by Bowen early in 1936 offered him no insights on tactics and use, and in any event Bowen’s major challenge at that stage was simply making the equipment work. Hanbury Brown’s memoirs[178] confirm that the scientists *did* think of its use - “One had to imagine oneself chasing some bomber in the dark…What precisely should the radar do? Where could it go in the aircraft and who would operate it? How should the data be displayed? These were all urgent questions and we put an awful lot of effort into answering them". Given this, there seems to have been no testing of whether the basic assumption – that CH could control a night interception until AI could acquire the target - would work. Such a test did not have to wait for war, for it could have been managed in the same way as the Biggin Hill experiments and mounted in 1937, as perhaps Tizard, who in the context of Biggin Hill asked about the implication for AI ranges, may have intended. Such a test might also have generated useful ideas for the eventual radar display needed both on the ground and in the air. The answer, of course, was that even at the end of 1938, AI was essentially seen as aiding the sowing of aerial minefields or of "bombing the bombers" – it was not primarily seen as a means of achieving a "kill" by air combat unaided by searchlights. The reaction of Dowding at the July 1938 conference, that he had never previously considered such a possibility, confirms this.

Hanbury Brown's memoirs also detail frustrations with lack of testgear, spares and tools[179]. No-one apparently made the connection that AI's acquisition by the RAF would have to take account of these issues on a much larger scale. As noted, the first AI hardware was ordered without specification or blueprints. It is difficult to accept that it was impossible to spare Dixon, the GPO engineer who specified the CH hardware, to do the same for AI. Most puzzling of all is why Bowen says repeatedly that he continued development for over two years using only one EMI receiver chassis. His memoirs state that at this time he had two Ansons, a Battle and a Magister in his radar flight[180], with this one chassis having to be passed around them for test flights. He could not, apparently, acquire another TV receiver chassis, even though he could fly to Metro-Vick and commission a new aircraft AC generator, an action authorised by Watson Watt only after the event. According to these memoirs, even Watson Watt could not produce another chassis[181], which is almost impossible to credit; Touch, the receiver designer and so more directly involved, disagrees with Bowen's recollection[182]. Even if strict security was an issue, acquiring a commercial EMI TV from a retail outlet on the pretext of domestic use would not seem an inconceivable stratagem. The memoirs of Shayler clearly state that at the Royal Navy's radar facility there were many TV chassis[183] employed for radar work.

Arguments are also advanced that the airborne radar team was too small and that, due to the ill-feeling between Bowen and Rowe, it was at odds with its management[184]. Undoubtedly there is some truth in these statements. However, even with its modest priority, at the end of 1938 the team stood at 10 people with a significant flight of aircraft, so that, though small, it was not trivial. Likewise, judging from the example of the aircraft AC generator, Bowen could rely upon Watson Watt retrospectively authorising significant orders when necessary, so that any management blockage was not absolute. It is also the case that, as will be shown in Chapter VI, Rowe could and did support Bowen powerfully on AI. The more significant problem for Bowen was that the plethora of alternatives ensured a low priority for AI even in the eyes of his fellow scientists in the CSSAD, and that this was the root cause of the delay and frustration he felt. While there is some force in Bowen's arguments, therefore, they are not completely persuasive.

At the conclusion of 1938, AI radar was still entirely experimental, and no conclusion can at this point be drawn on the question posed at the start of this chapter regarding the impact of the large number of short-lived Marks and variants on the acquisition process. Regarding the final strand in this analysis, GCI, it may be observed that Watson Watt did not appear to favour this "radio lighthouse" equipment, preferring instead to devote his energies to Chain Home, and assuming without test that Chain Home could suffice to guide a fighter to the point where its AI radar could take over. He made due apology for this in his memoirs[185], but the result would delay the introduction of radar-based night interception capability by a year.

Chapter VI now examines the next 1,000 days of the creation of Britain's night air defence system.

V.9.

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V.10.

FIGURES.

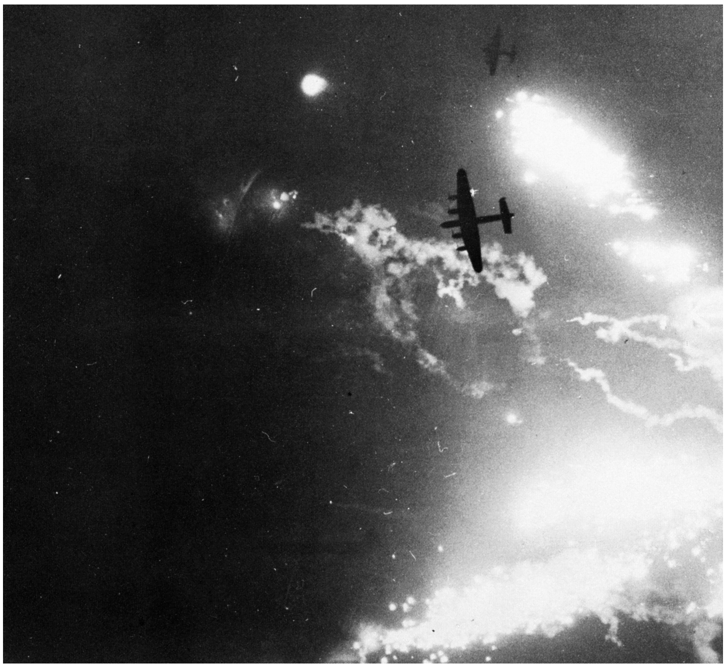
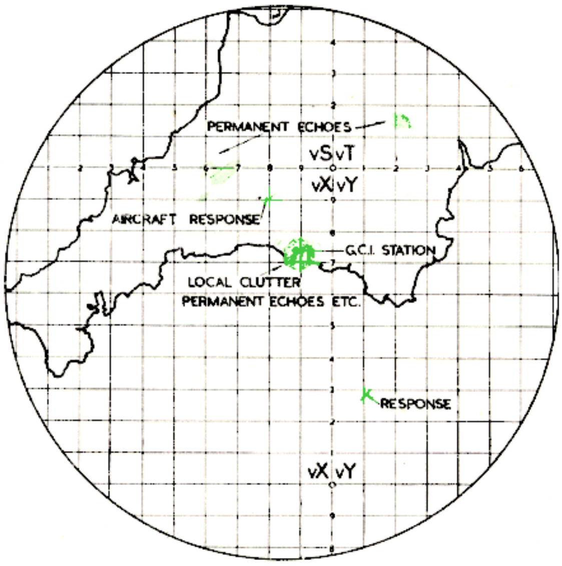


Fig 54. An RAF bomber outlined against an illuminated background, the light provided in this case by target indicators. (Alex Thorne, *Lancaster at War 4*, London: Ian Allen, 1990, p. 104/ Crown Copyright).



THE P.P.I. TUBE

Fig 55. A typical Plan Position Indicator (PPI) display. The map grid and coast outline would be drawn by chinagraph pencil on a transparent overlay above the display tube. (TNA/PRO AIR 10/5485 Diagram 17).

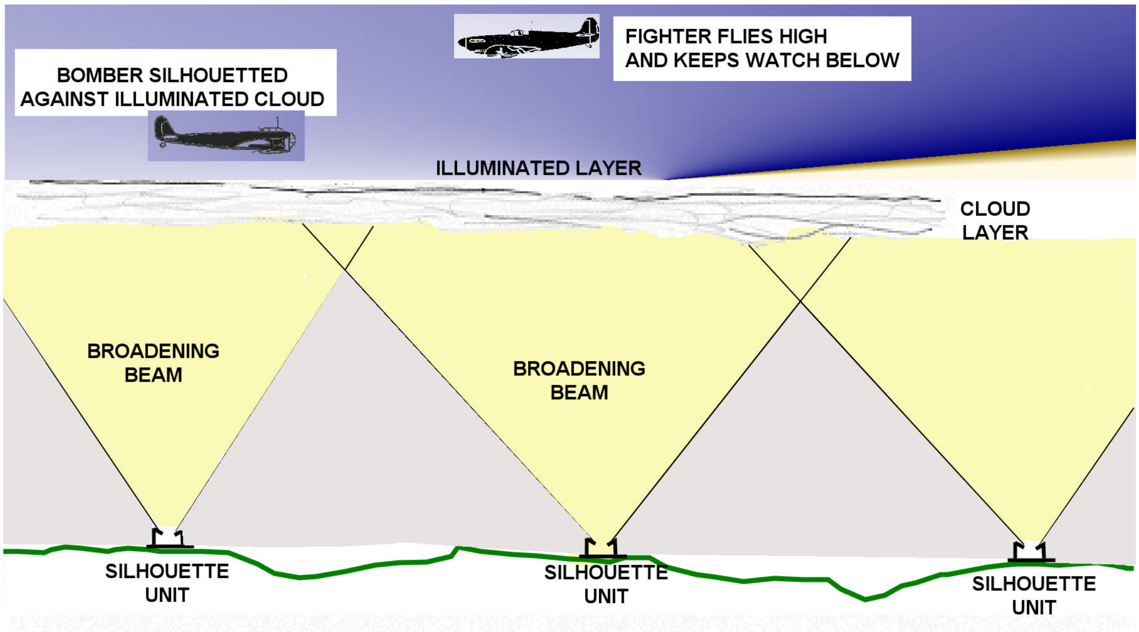


Fig 56. Elevation view of the “Silhouette” system as projected. (Author).

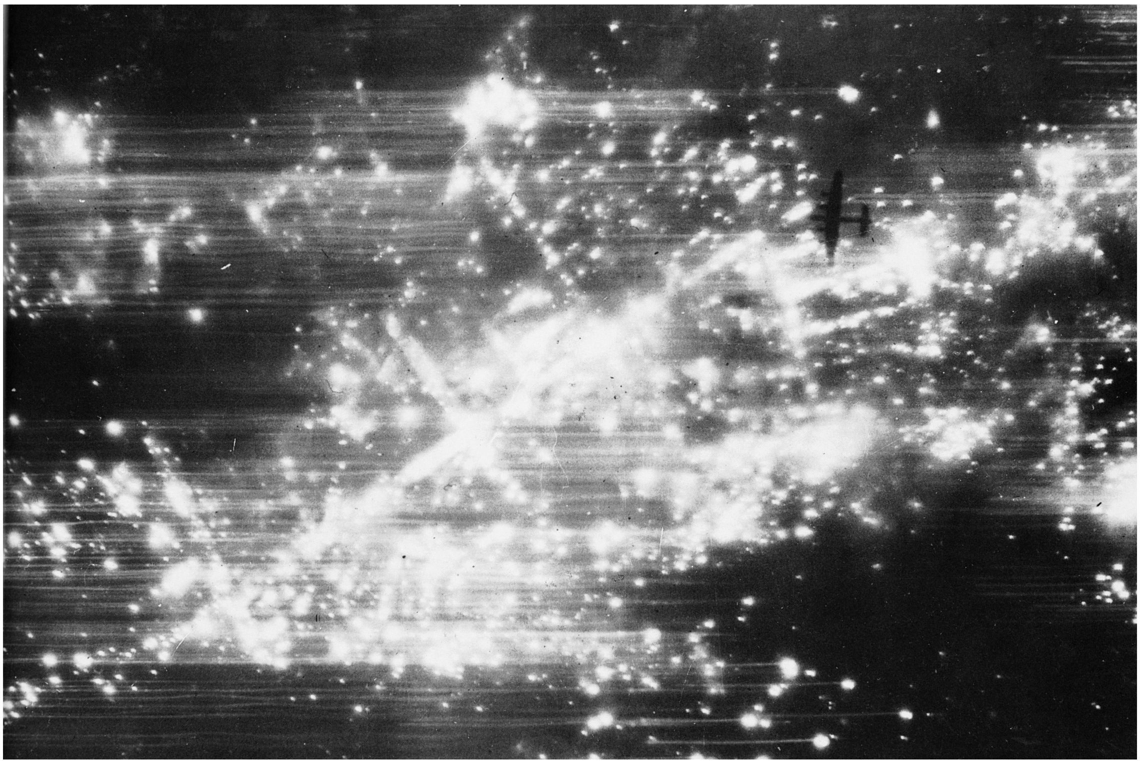


Fig 57. Hanover, 22 October 1943. A British bomber can be seen upper right silhouetted against the burning city. (Imperial War Museum (IWM) C 3898).

Fig. 58 a,b. North Fambridge Silhouette site (Essex County Council SMR, Ref. 20565).

Fig 58 c,d. North Fambridge Silhouette site, detail of buildings. (Ibid.).

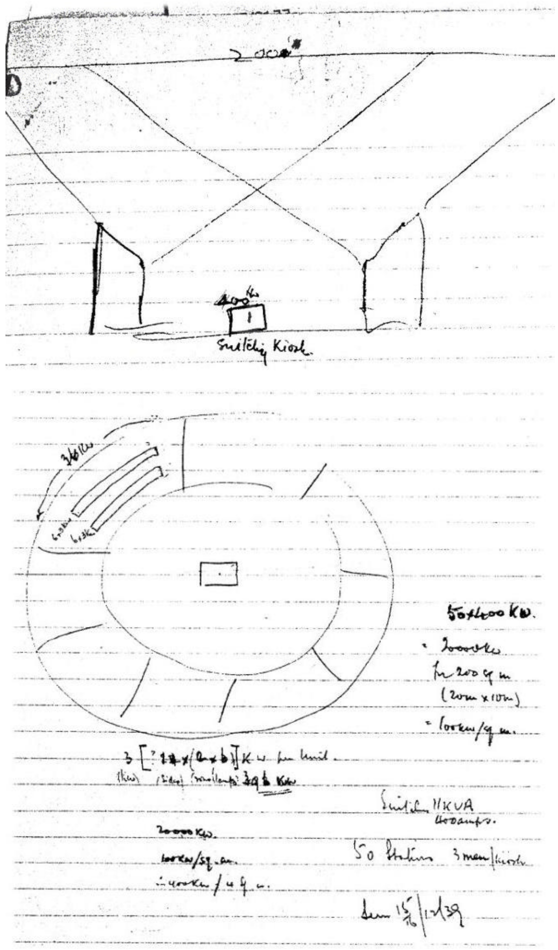


Fig 59. The only surviving, and previously unpublished, sketch of a Silhouette installation.(TNA/PRO AVIA 7/3177).

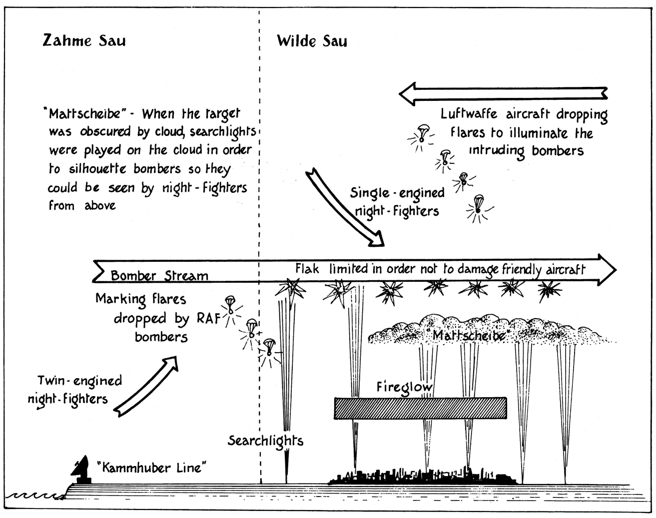


Fig 60. The German "Mattscheibe" concept, where loosely-controlled "Wilde Sau" fighters engaged British bombers silhouetted against searchlight-lit clouds – and the burning city. (Martin Streetly, London: Macdonald and Jane's, 1978, p. 219).

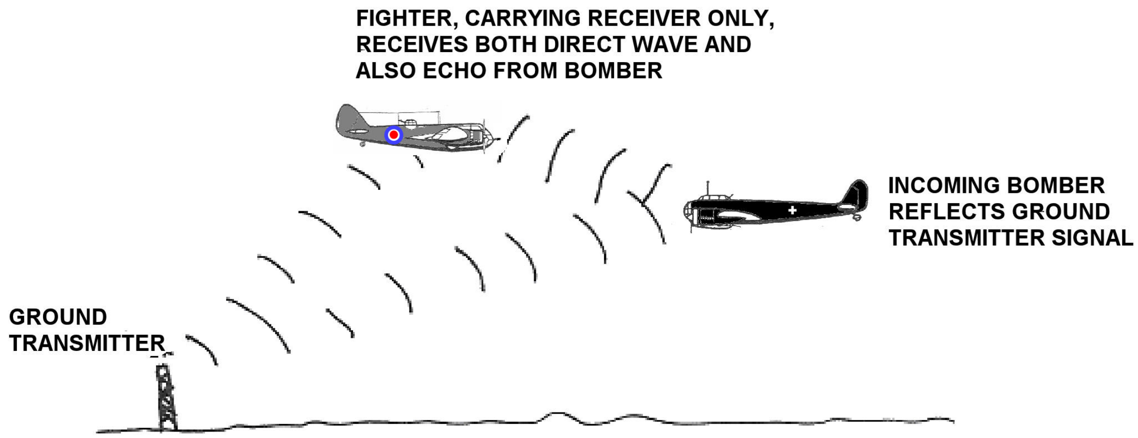


Fig 61. The RDF 1.5 concept in elevation view. The large, heavy and power-hungry transmitter remains on the ground and the receiver only is carried in the aircraft. (Author).

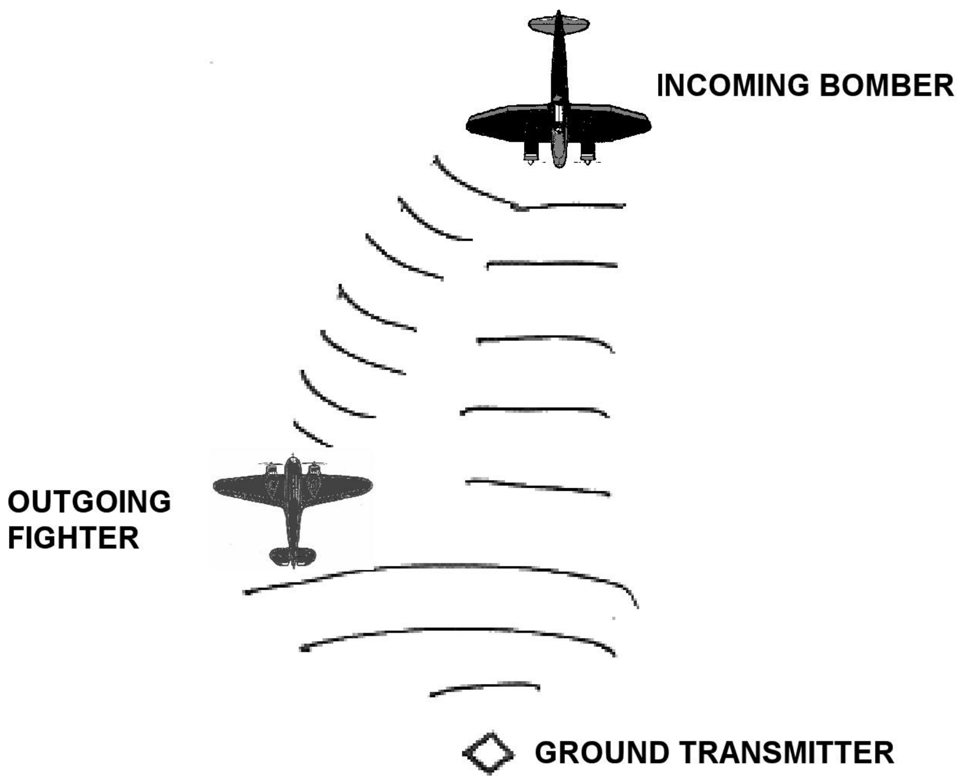


Fig 62. The RDF 1.5 concept in plan view. The problem here is the complexity of receiver circuitry required to process the geometry to give the pilot a clear indication of the position of the enemy; in 1940, bomber, fighter and radar would have had to have been in a straight line. (Author).

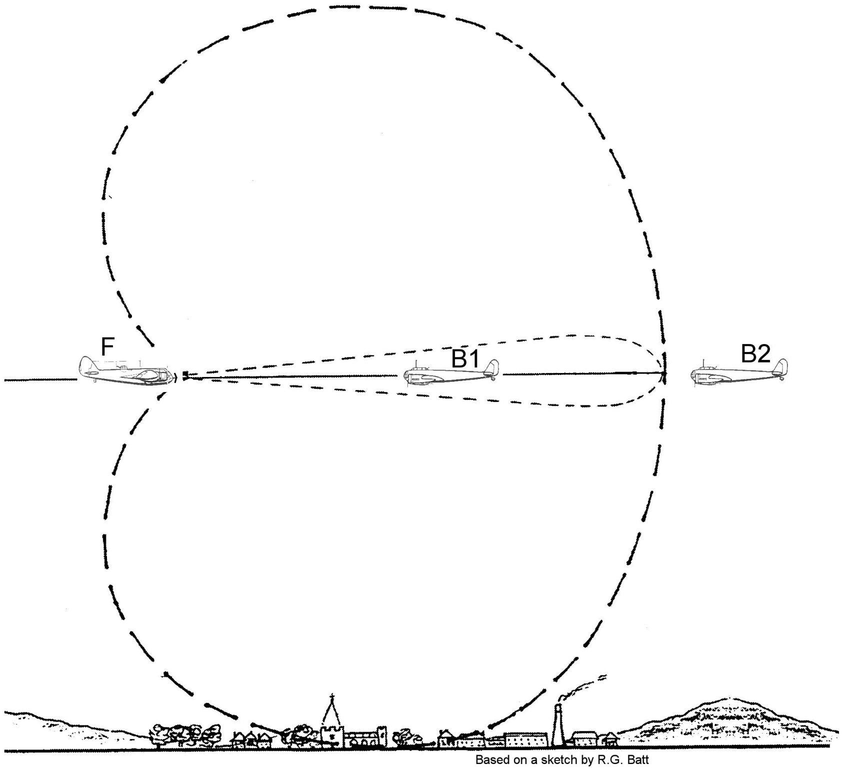


Fig 63. RDF 2, used in its air interception configuration, showing the transmitter power "lobe" in elevation view. It will be seen that the "lobe" touches the ground, which sends back so powerful an echo that no signal can be received from a greater range. Bomber B1 is therefore visible, but B2 is not. This "ground return" means that the maximum range of a metric-radar fighter is equal to its height above the ground, a significant problem. (Colin Latham and Anne Stobbs, op. cit, p. 29, modified by Author).

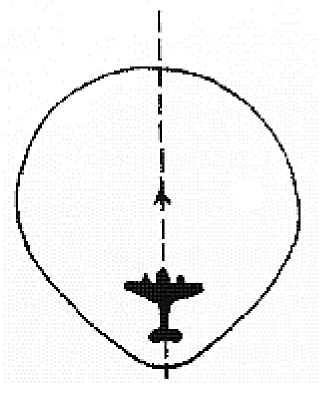


Fig 64. RDF 2 in AI configuration, showing the same power "lobe" but in plan view. In RDF 2, both transmitter and receiver are carried in the fighter, which then requires upgraded power supplies. All previous fighter supplies had been DC, but Bowen solved the power supply problem by ordering the 80 volt, 1600 Hz. alternator, which delivered more power for the same size, and which provided high frequency AC that could be transformed to voltages needed by the radar without heavy rotary convertors. (TNA/PRO AIR 10/5485).

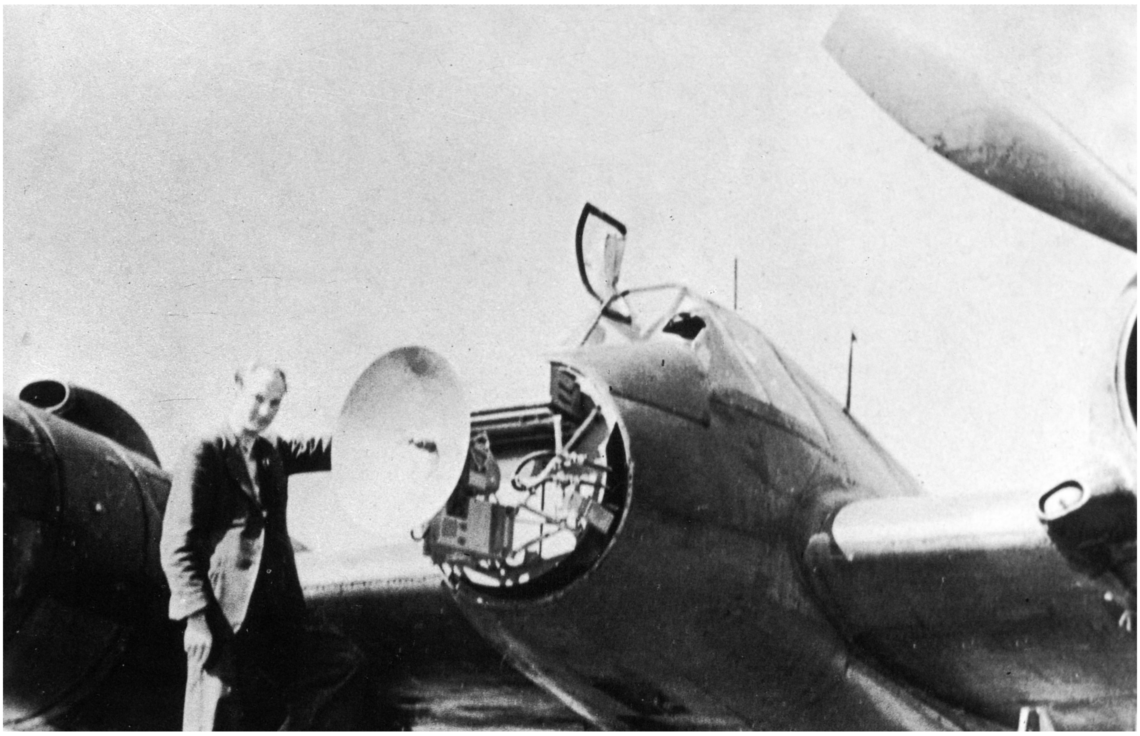
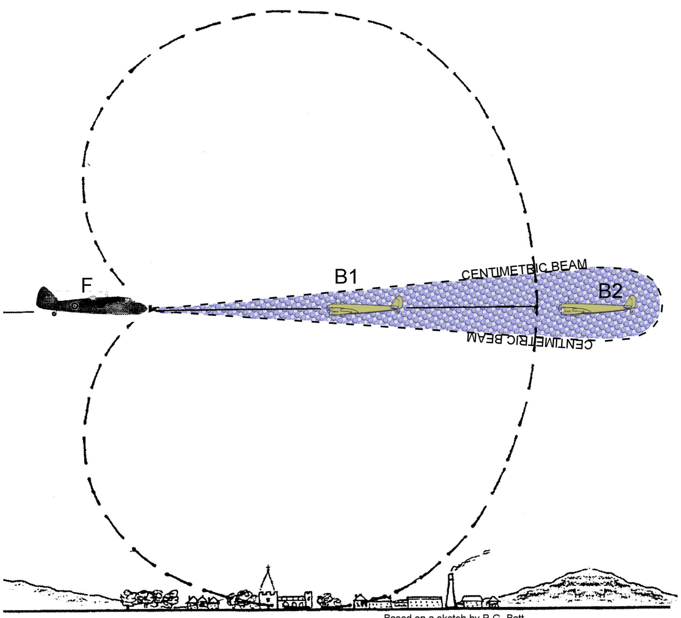


Fig 65 (a). Aerial dish for centimetric radar in the nose of a Beaufighter. The dish ensured that the transmitter’s power was concentrated into a beam projected in front of the aircraft and did not touch the ground, so that there were no “ground returns”. The range of centimetric radar was therefore not limited to its height, which was a problem with metric radars. (Robert Jackson, *Air War at Night*, Shrewsbury: Airlife, 2000, p 43). **Fig 65 (b)** illustrates the elevation view of the beam projected from the aerial of a typical World War 2 centimetric radar, compared to the beam shown in Fig. 63 for a metric radar. Both bombers B1 and B2 are visible to the centimetric radar. (Colin Latham and Anne Stobbs, op. cit, p.29, modified by Author).



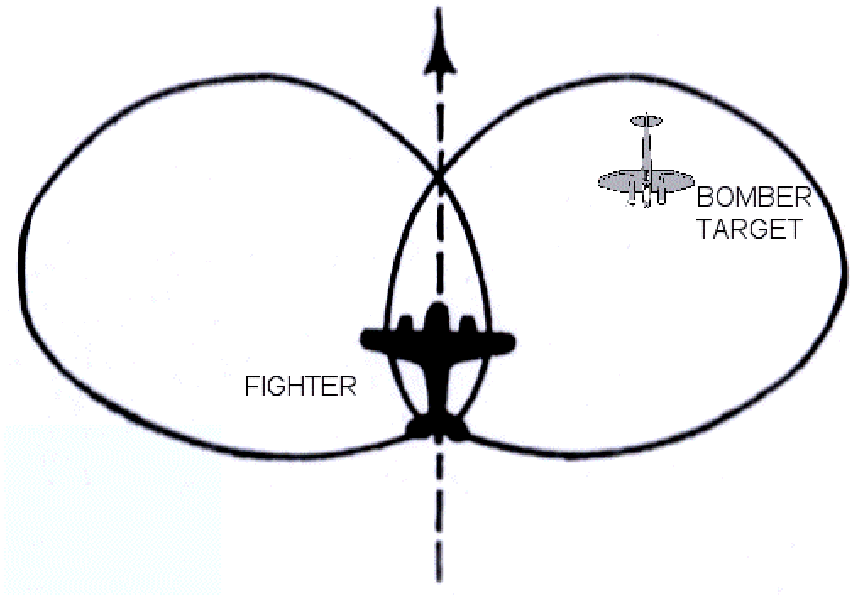


Fig 66. RDF 2 in AI configuration: receiver aerial "lobes", azimuth view. The lobes indicate the area of highest sensitivity to the echo of the transmitted pulse reflected from the target. In this case, the bomber is approaching on the starboard, and the display in Fig 68 below will show this by indicating a strong echo signal there. (TNA/PRO AIR 10/5485, modified by Author).

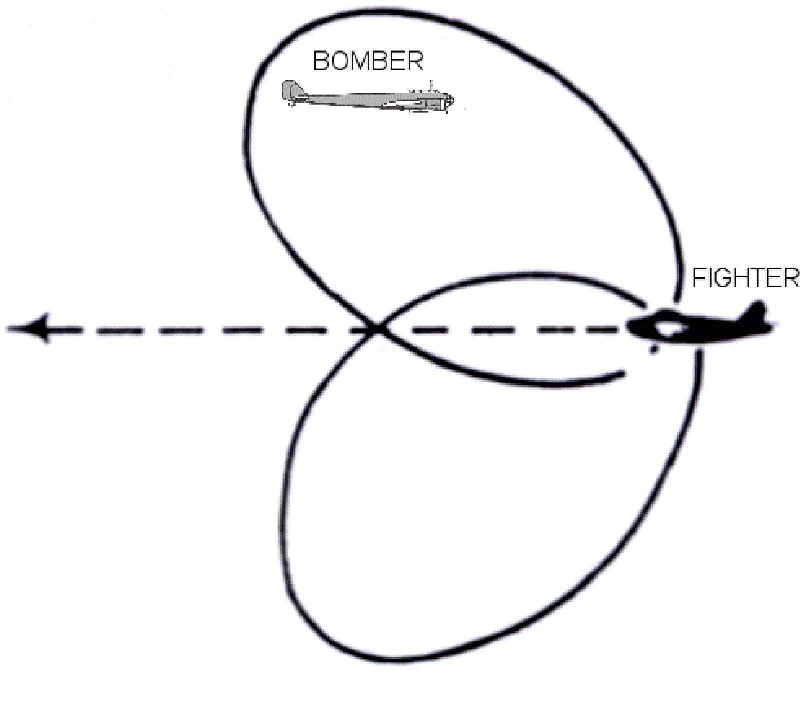


Fig 67. RDF 2 in AI configuration: receiver aerial "lobes", elevation view. The same principles apply as in the description for Fig. 66 above. In this case, the bomber is above the fighter, the returned echo will be stronger in that lobe, and the display in Fig. 68 below will indicate this. (TNA/PRO AIR 10/5485, modified by Author).

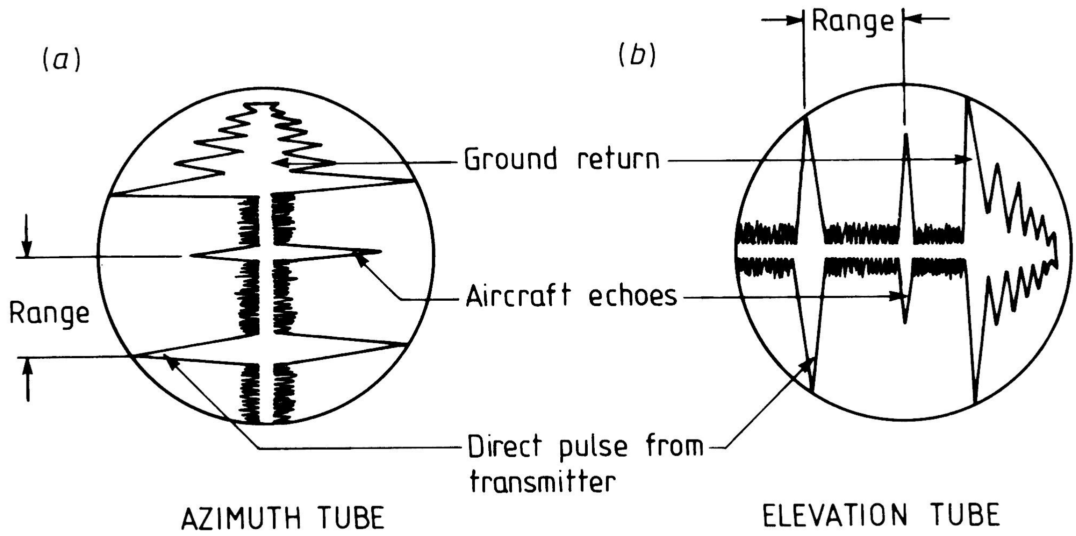


Fig 68. RDF 2 in AI configuration – the two-tube display. In Fig 68(a) the left-hand tube displays azimuth. In this case the "blip" is longer on the right than the left, so the target is to starboard. In Fig 68(b), the right-hand tube displays elevation. Here, the "blip" is longer above the base line than below it, so the target is above the fighter. The range is indicated by the distance of the "blip" from the direct pulse fed from the transmitter into the receiver. The "ground return", the echo received from the earth, is so large that it swamps any return from any greater distance, and so the fighter's height above the ground is the maximum range of this radar. The ground return was usually called the "Christmas Tree" after its distinctive shape. (E.G. Bowen, *Radar Days*, Bristol: Adam Hilger, 1987, Figure 4.2).

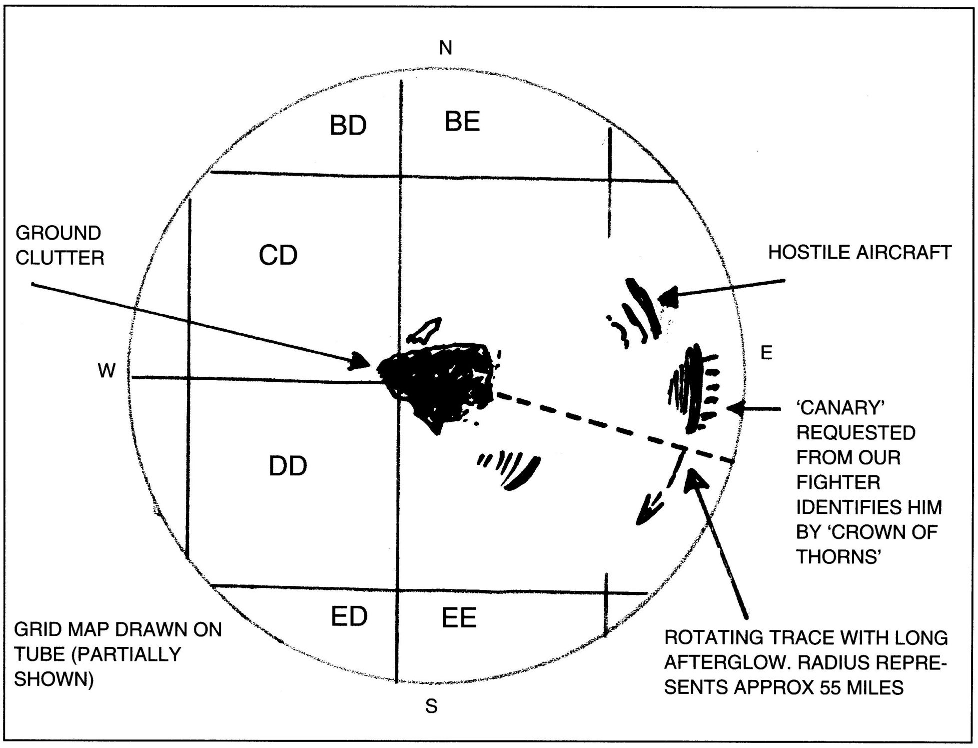


Fig 69. Typical GCI Plan Position indicator (PPI) display, in this case showing traces from a hostile aircraft and also from a friendly fighter, the latter identifying itself by its IFF (codenamed "Canary"). The PPI display, by placing both aircraft on a single screen, made it easier for the ground controller to guide the fighter into a position where its crew could switch on their own AI and acquire the target. (Colin Latham and Anne Stobbs, *Radar: A Wartime Miracle*, Stroud: Sutton, 1996, p.64).

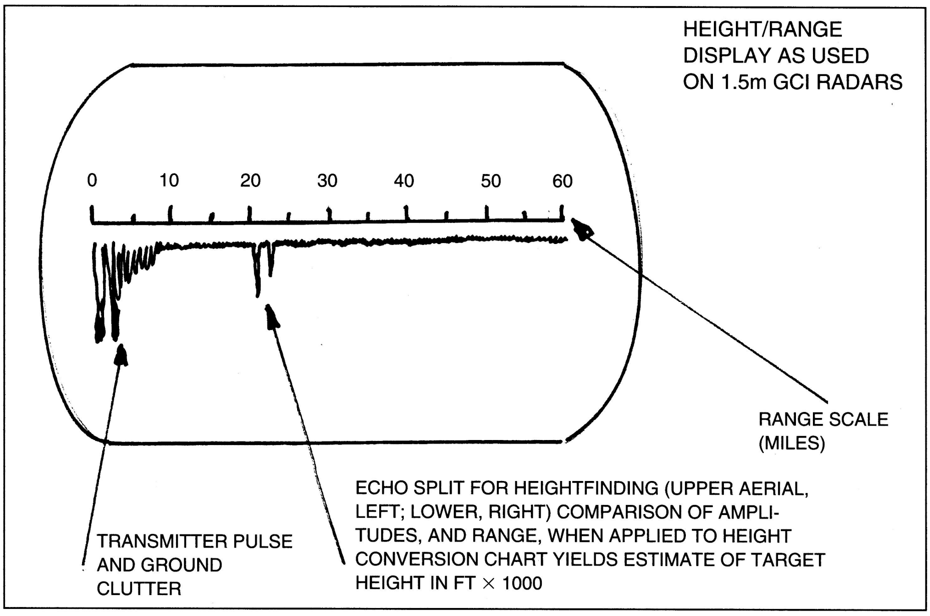


Fig 70. The GCI height/range display. (Ibid.).

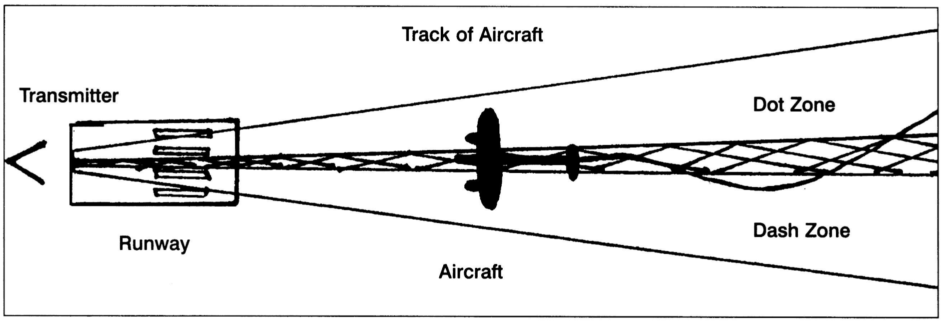


Fig 71. The Lorenz blind landing system from which the Knickebein radio-navigational system was derived. The transmitter aerials were so directed as to transmit a series of morse "dashes" on one side of the runway centre line and a series of "dots" on the other. In line with the centre of the runway, the two merged to create a steady tone in the pilot's headphones. If, therefore, the pilot flew so as to hold a steady tone, he would be in line with the centre of the runway. For navigational purposes, this "equisignal" zone was directed over the target and the bomber was equipped with a very sensitive version of the blind landing receiver. The pilot simply flew along the equisignal line until a second beam crossed it, at which point he was over the target. (Laurie Brettingham, *Royal Air Force Beam Benders No. 80 (Signals) Wing 1940 – 1945*, Leicester: Midland, 1997, Fig. 1).

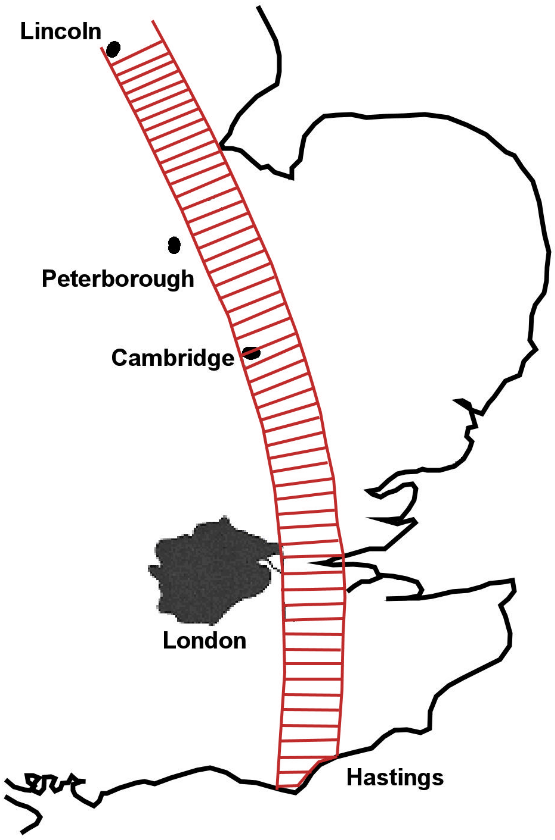


Fig 72. The illuminated "carpet of light", a forerunner of Silhouette, proposed by F.W. Lanchester in 1915. (TNA/PRO AVIA 8/473).

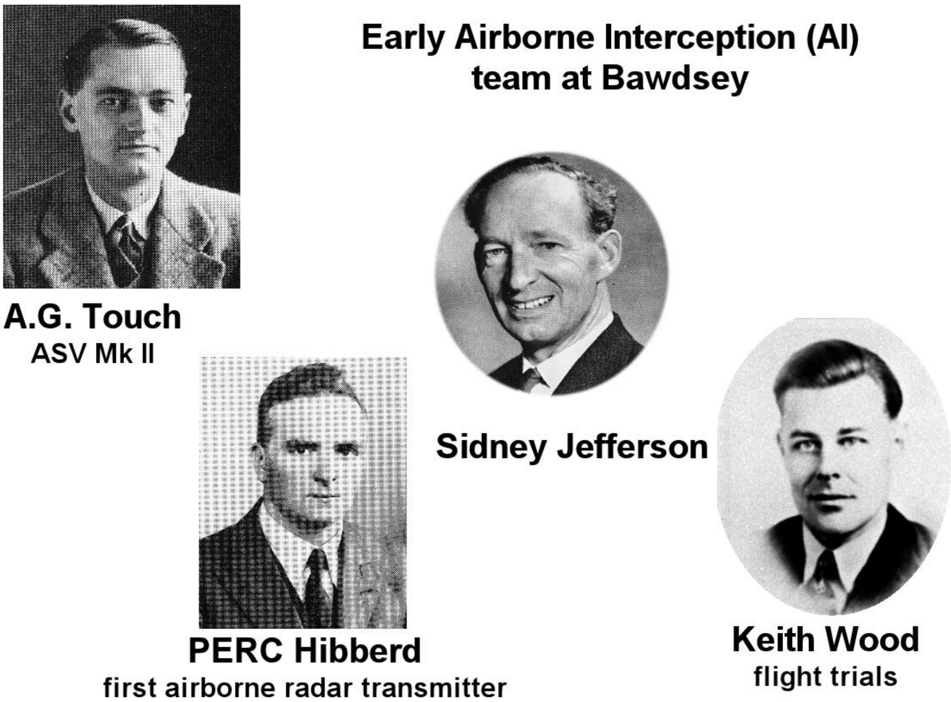


Fig 73. The earliest members of the airborne radar team at Bawdsey. Robert Hanbury Brown, who contributed greatly to AI radar, was at Bawdsey at this time but did not join the airborne radar team until slightly later. (Penley Archive, A/46).

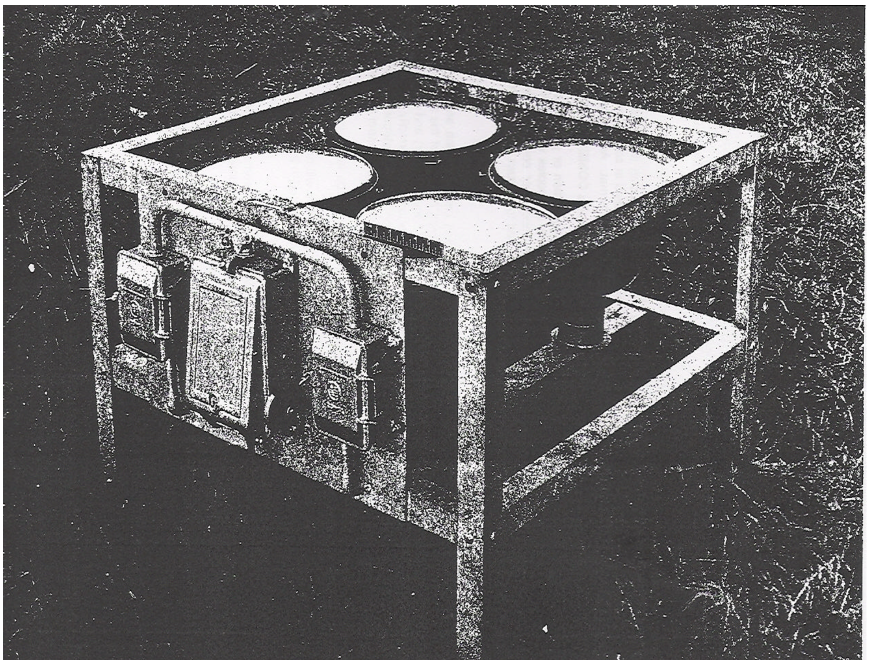


Fig 74. An example of the experimental floodlight units used for the Farnborough trials of Silhouette. The original picture is unfortunately in very poor condition. (TNA/PRO AVIA 6/960, Fig. 6).

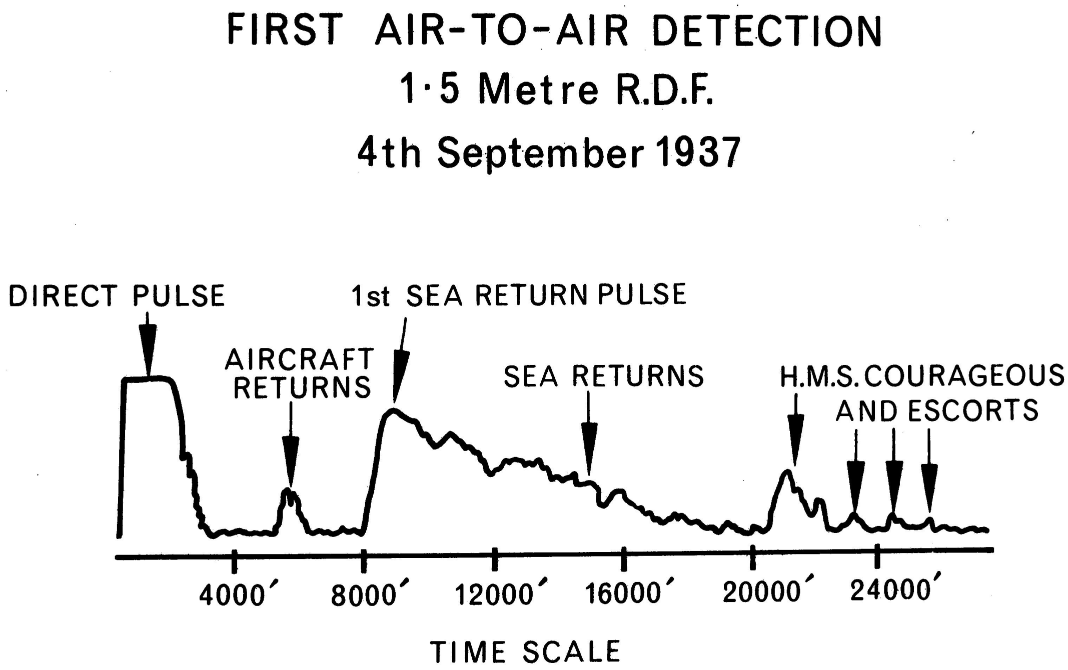


Fig 75. This drawing illustrates the first airborne radar displays, which were of range only – there was no indication of bearing in azimuth or of relative height in elevation. The drawing also shows the fact that sea returns, unlike ground returns, do not completely swamp any other echo, so that over the sea, ranges greater than the height of the aircraft can be obtained. Finally, the trace shown represents the first air-to-air detection of a flight of aircraft, which took off from HMS Courageous to intercept the Anson carrying the Bawdsey airborne radar team which had located them. (Penley Archive A/49).

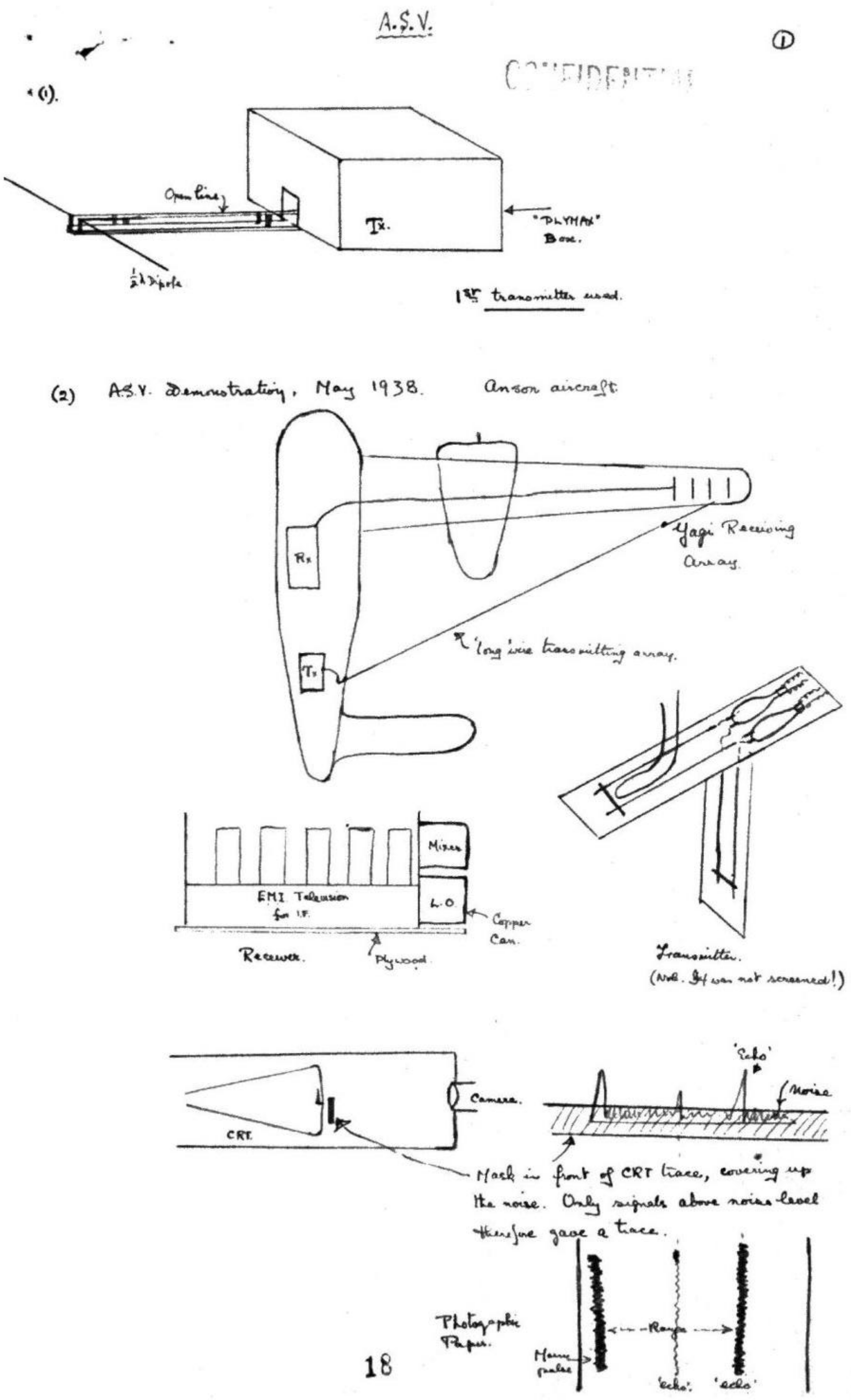


Fig 76. The sketch made by Touch of the equipment used on the early flights survives in extremely poor condition, and is reproduced here for the first time. (TNA/PRO AIR 20/1464).

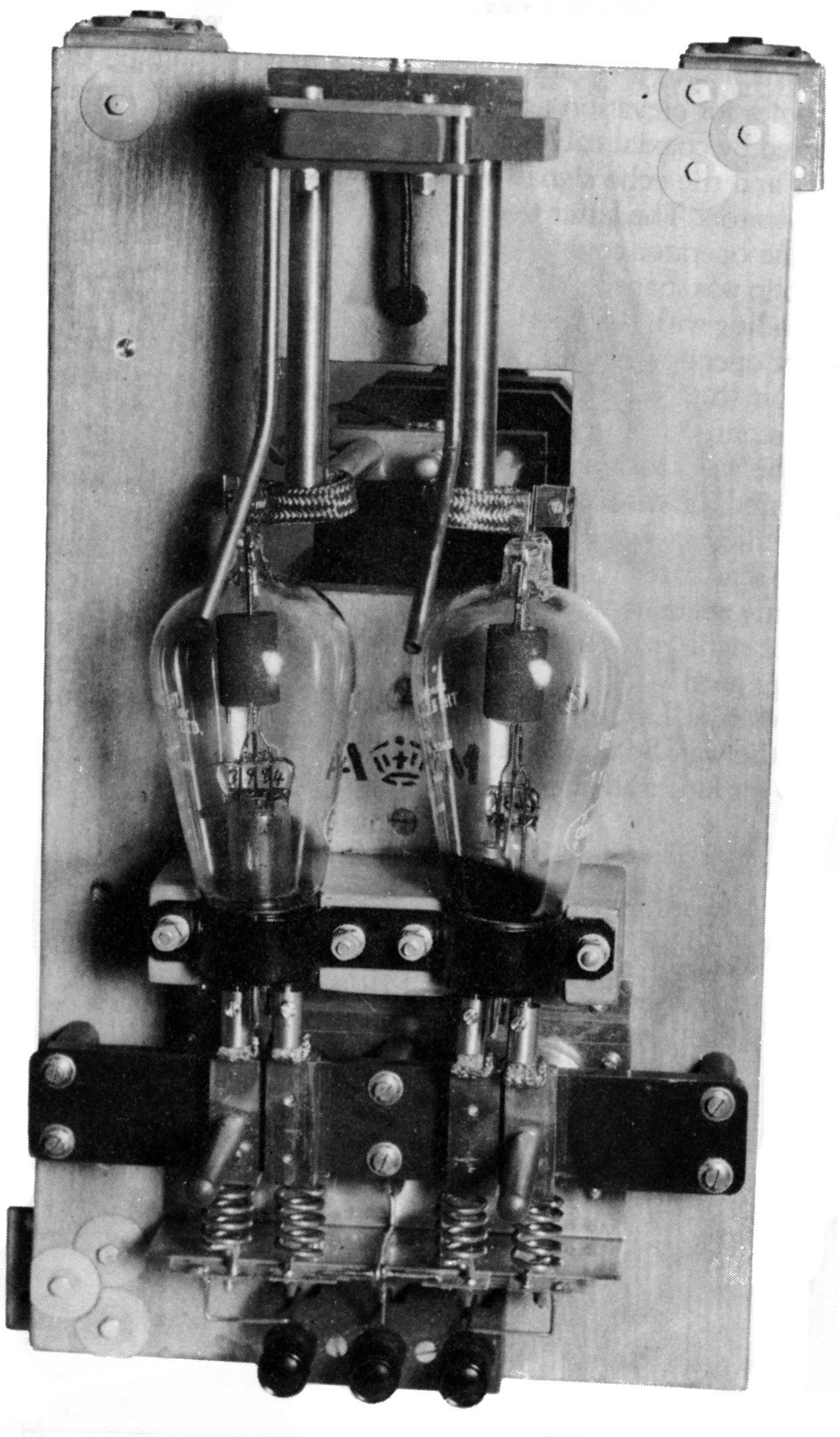


Fig 77. This photograph of the early transmitter used for both ASV and AI experiments is extremely rare, and has previously been published once only, in a limited-edition work. (Norman Cordingly, *Era of the Nocturnal Blip*, Braunton, UK: Merlin Books, 1994, p.16).

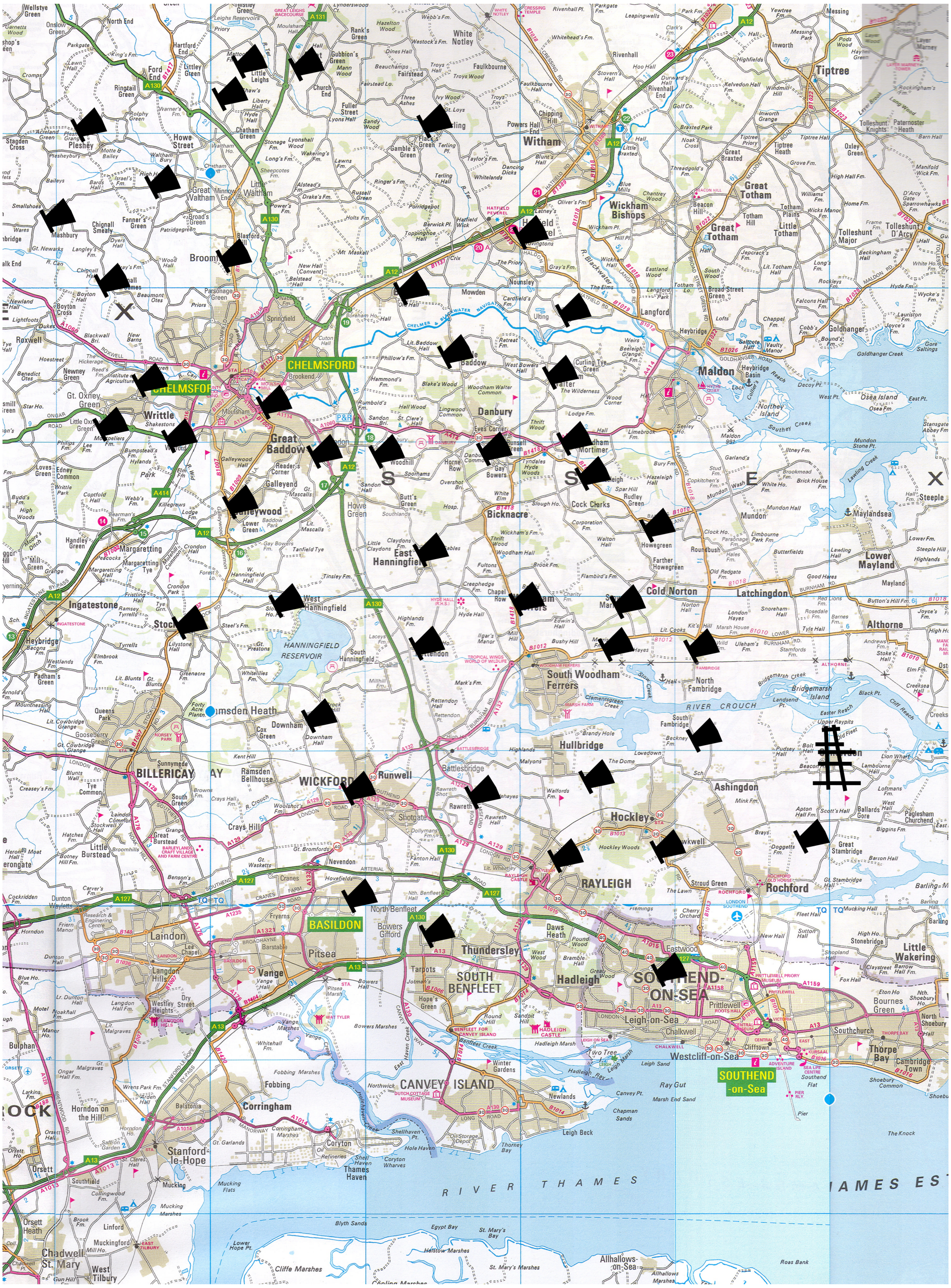


Fig 78. 44 out of the 50 Silhouette sites for the 200 square mile Essex experiment have been identified at parish level, and this is the first publication of this information. The Chain Home radar station at Canewdon is also identified, to the lower right of the map. (Author).

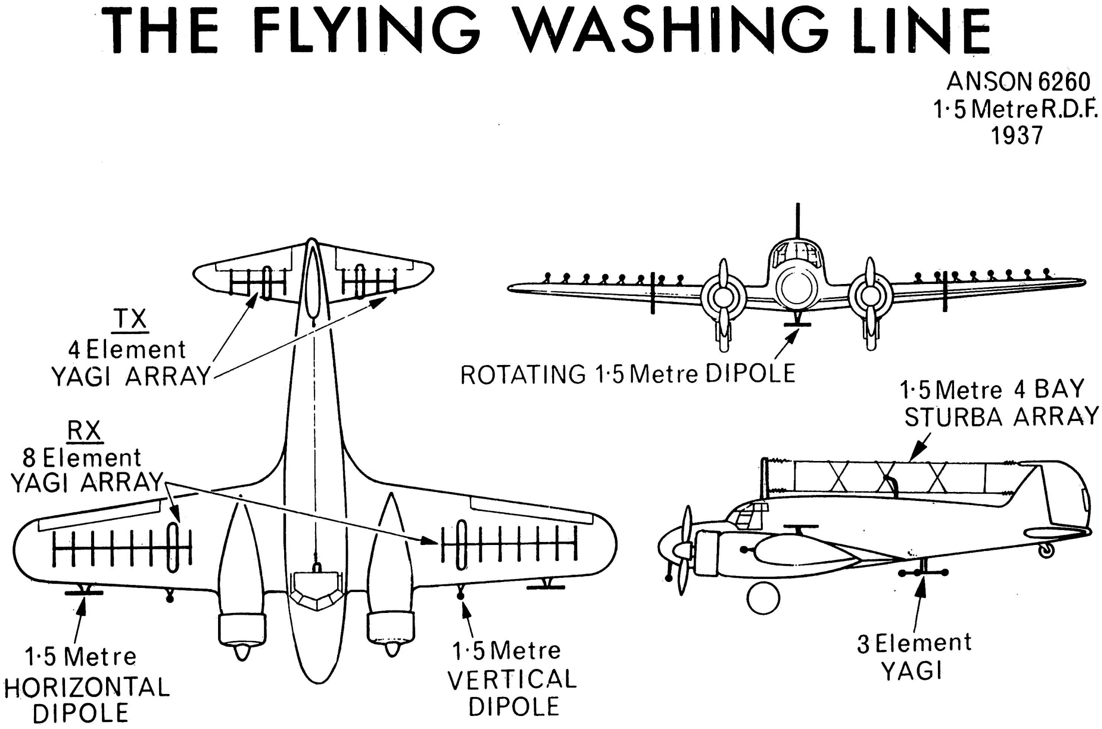


Fig 79. Some indication of the variety of aerial arrays tested can be seen from these drawings by Keith Wood. Not surprisingly, the aircraft became almost unflyable. (Keith Wood, *Echoes and Reflections*, London: Serendipity, 2004, Fig. 14).

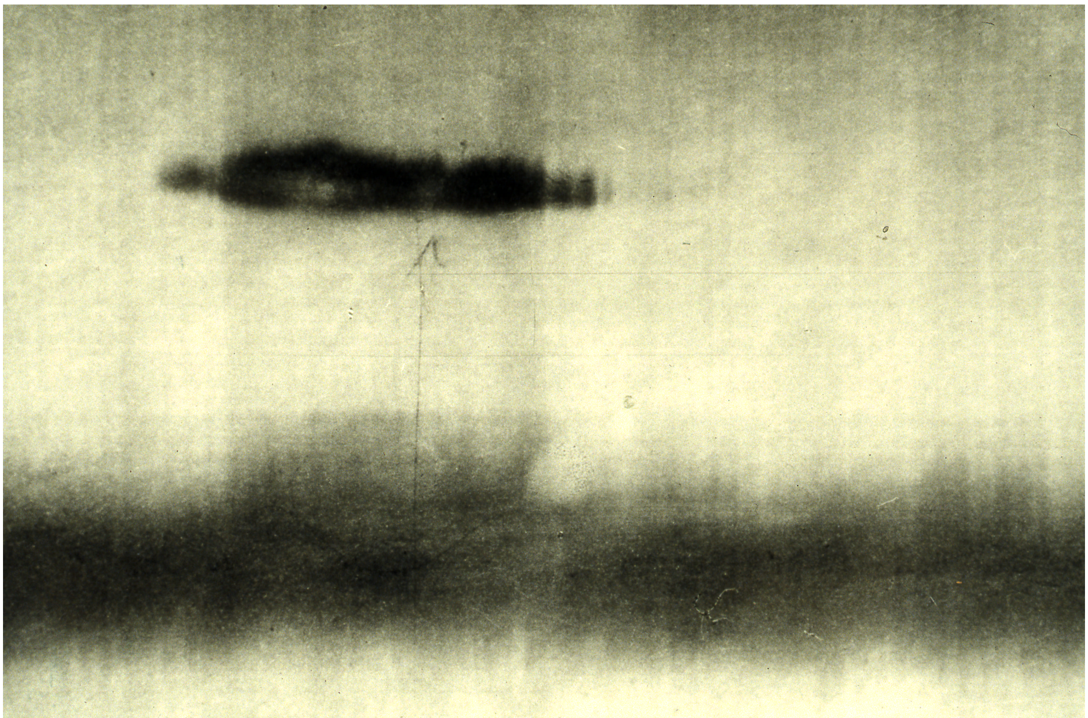


Fig 80. Although indistinct, this photograph is the first "side-scan" radar picture, of HMS Courageous, at an eight mile range. (E.G. Bowen, op. cit, Fig. 3.3).

VI

ACQUIRING RADAR FOR THE NIGHT BATTLE

THE SECOND 1,000 DAYS: 1939-1941

VI.1. Introduction.

On I January 1939, 200 days before declaring war, Britain still had no effective night air defence system. The assumption had been that the main battle would be by day. For any night battle, searchlights or the Silhouette cloud illumination scheme would light up the sky sufficiently for day tactics to be used, and if that were inadequate, Chain Home radar would be capable of guiding night-fighters close enough to sow aerial minefields or wire barrages. The use by night fighters of an Air Interception (AI) radar to help achieve the final “kill” by gunfire had been seen by Dowding as an unexpected novelty only as late as July 1938[1].

In Chapter V, five main strands of analysis were identified, these being the impact on the acquisition of radar of the alternative “Silhouette” cloud floodlighting scheme; the pursuit, within the radar options, of RDF 1.5, as an alternative technique to AI; the issues for AI and ground control radar posed by such alternative concepts of interception as aerial minefields and “bombing the bomber”; the failure to recognise the need for accurate, dedicated Ground Control Interception radar (GCI) to work with AI; and the difficulties caused by the over-rapid introduction of many Marks and variants of AI radar. Chapter V focussed primarily on the first three of these strands; Chapter VI will address the latter two also.

Of these five strands, the conclusion of the Silhouette story occupies little space. In essence, the 200 square mile trial area in Essex was constructed during 1939, found inadequate during trials during the "Phoney War" of Winter 1939/40, and died in a second, truncated, incarnation in Harwich in April 1940, albeit not before an unanticipated side-effect briefly disabled the Canewdon Chain Home station.

RDF 1.5, the "radar alternative" to AI, would continue to be pursued by Bowen as a means of intercepting low-flying German mine-laying aircraft. He made use of the Chain Home Low (CHL) transmitters for this "AIL" scheme, but trials revealed unexpected shortcomings and were discontinued in June, 1940. It should be emphasised that the same idea was also pursued by W.B. Lewis, Rowe's deputy; it certainly was not seen as a wayward obsession of Bowen.

However, the major problem of this second 1,000 days of seeking radar-based night interception capability proved to be the lack of appreciation that a Chain Home/AI combination would not work, and that a dedicated, more accurate, and user-friendly ground control radar, GCI, was needed. This may well have resulted from attempts to develop interception concepts such as aerial minefields, for which Chain Home was adequate. The aerial minefield concept was sustained by the resurgence of Lindemann following Churchill's return to office, and Chain Home guidance by the desire of the Bawdsey pioneers Watson Watt and Wilkins to show that Chain Home alone was capable of directing night interceptions. In this they persisted until October, 1940, delaying attention to the development of GCI.

The development of air interception (AI) radar itself did not seriously begin until May, 1939, when the first AI capable of displaying range, bearing and height of an intruder was assembled in a Fairey Battle. Its progress would be bedevilled by the "minimum range" issue, the demand of the RAF, verbalised by Dowding, to achieve a minimum range of 300 feet or less. Directly linked to this demand was the RAF's lack of adequate Identification Friend or Foe (IFF) equipment, for IFF is plainly a more material problem by night, when humans cannot see well, than for day fighting. In 1940, IFF was not commonly fitted, was unreliable when it was fitted, and in any event did not operate on AI frequencies, but solely on those of Chain Home. One result was that a CHL or GCI ground controller could not tell which display "blip" was fighter and which intruder, making guidance of the fighter almost impossible. The further consequence was that even if the interception did take place, it was necessary to close to visual range to identify that the target was not a friendly aircraft before opening fire, and hence the RAF's demand for a 300 feet minimum figure.

This minimum range requirement is at the root of a charge levelled by the historian David Zimmerman against Bowen, whom he accuses of "deception"[2] when demonstrating AI to Dowding in July 1939. By Zimmerman's account, Dowding was so impressed by statements made by Bowen at this demonstration that Dowding urged the Air Ministry to order AI hardware with excessive haste, a mistake which resulted in a rapid succession of different marks of AI, each and every one proving unreliable and ineffective in air defence. The consequence of this unreliability and ineffectiveness was the failure to achieve night defence against the Blitz of Winter 1940/1, the cause of another dispute between Dowding and the Air Staff, already inflamed by the filtering debate for the day battle described in Chapter IV. Churchill had been greatly impressed by Dowding's achievements in the Battle of Britain. However, seeing the continuing inability of Dowding to fight off the Blitz, Churchill gradually withdrew his support, and Dowding was compulsorily transferred from his post in November, 1940. Dowding's successor, Sholto Douglas, proved to have great plans, but to be incapable of solving the lines of development problems, in particular the human elements of staffing and training. He was saved by the harsh weather of January – March 1941, which by significantly reducing the Luftwaffe attacks bought time for training and tactical development. By April, 1941, trained crews and new equipment began to turn the tide, but at this point the Luftwaffe was already regrouping to fight in Russia.

Viewed in the context of the lines of development necessary to achieve night interception, it is apparent that whatever Bowen may have said to Dowding, the probability of any such capability being acquired in a short time was non-existent. No consideration had been given to how to select operators or ground controllers, how to train them, to the communication equipment needed in the aircraft, to the information displays needed in the fighter and on the ground, and to how to integrate the whole. Most immediately, no thought had been devoted to sustainability – testgear, tools, maintenance staff, and the basic design of the equipment itself. Dowding earned Watson Watt's undying hatred after Watson Watt's expansively promising "hundreds of airborne radars", to which Dowding's succinct rejoinder was "Give me ten that work"[3]. The facts that Silhouette had detained the CSSAD's intellects, that RDF 1.5 was being pursued in parallel to RDF 2, that ASV was the focus of development for more than a year, and that the concept of "interception" was of aerial mine-laying as opposed to combat, had collectively already rendered night interception by AI an almost impossible challenge, and most of these resulted from decisions well beyond Bowen's area of control.

However, it is a further contention of this thesis that Bowen did not deceive Dowding, intentionally or not, and that the over-rapid ordering of poorly engineered AI was factually not instructed by Dowding, but by the Air Ministry advised by Watson Watt. The record is quite explicit. In July 1939, Dowding was simply concerned to ask the Air Ministry for 3-4 AI sets (having no budget of his own, he could not "order" anything), in order to begin the process of identifying tactics and of training, and to discover the operational issues. From his experience of day interception radar, he knew the time necessary to solve the problems of introducing new equipment to service and to train pilots in a new form of interception. That he was correct in seeking such an order for tests and trials was shown by two examples. The first, unexpectedly to Dowding, was the inability of CH to guide a night interception, an inability not accepted by Tizard or, as remarked above, by the radar pioneers until well into 1940, thereby delaying the development of suitable ground radar, GCI. Secondly, once AI Mark I had been flown in aircraft, it was immediately apparent that the intercommunication system cut off for 15 seconds in every minute to allow the "Pipsqueak" direction-finding signal to be transmitted, essential for the day battle but a fatal flaw when the radar operator was trying to guide the pilot at night.

Bowen may well have made some comment about reduction of range. He had cause to do so, because at that time, Gerald Touch was working on his "quenching" circuit, which achieved just such a reduction, as Touch's own memorandum confirms. However, Dowding was, as has been shown, not a credulous man, and would have balanced Bowen's comments against his own need to test the embryonic system; Dowding had seen radar disasters in the 1936 Air Exercises, and was used also to Watson Watt's expansive promises. In context, an order for four sets for testing purposes appears rational and reasonable. It is to the Air Ministry, and to Watson Watt who advised them in this matter, that it is necessary to look for the misjudgement, and not to Bowen.

There are two partly-successful instances of acquisition within this litany of failure. First, in the absence of night fighters, the burden of defence fell upon the guns. Heavy AA was increasingly equipped with GL (Gun Laying) radar, developed by the War Office[4], and accuracy gradually improved as a result. Second, the German radio-navigational beams described above were increasingly, though not totally, disrupted by the radio counter-measures (RCM) of the hastily-established 80 Wing, RAF[5].

This chapter now analyses the complex acquisition of radar for the night battle in 1939-41, setting this out for the first time in parallel with the related acquisitions of GL radar for AA gunnery, and of RCM for the identification and disruption of the German radio-navigational beams. Within the Chapter's chronological treatment are highlighted two critical incidents, the departures of Tizard and of Dowding. Dowding's unwilling transfer from his post has been commented upon above. Tizard's resignation was stimulated by the German radio-navigational beams, for the significance of these beams was not recognised by him. His argument that they did not exist was proven incorrect by Jones in front of Churchill and Lindemann, and brought about his resignation in June 1940. This deprived Dowding of his trusted adviser on radar at precisely the time such advice was most needed, so contributing to Dowding's own downfall.

VI.2. January to September, 1939.

The unreadiness of Britain to mount an effective night defence was confirmed by a meeting of the Air Fighting Committee on 20th January[6]. This focussed on night fighting, and even though neither Dowding nor Tizard was present, affords a useful insight into the state of that art. Sholto Douglas, as Chairman, said once again that "very little work had been done since the last war" and that it was "highly desirable that strenuous efforts be made to study this problem". The Committee's first resolution was to devise exercises to intercept at night, using Chain Home and CRDF, just as by day, but with searchlights; navigation lights would also be used. Silhouette was described for the benefit of the Committee – a revealing action, since apparently its intended service users knew little of it despite its three years in development and massive cost – but could not be used in trials as it would not be ready until July. AI likewise was advised by Watson Watt not to be available as yet, but six laboratory-made sets could be ready "sometime in July". The meeting eventually resolved that night combats would be carried out from April to July, but by only two flights of bombers and one fighter squadron.

Silhouette proceeded under Farnborough's project management, and with an A* priority, flight trials being completed at Rayleigh by February[7]. It is significant to compare this A* rating with Bawdsey's 1939 programme[8], which shows 2.5 staff on ASV (A*), 2.5 on AI, 1 on "bomb the bomber", 1.25 on RDF 1.5 (A), and 1.75 on bomber navigation. IFF had 3 staff , but "until yesterday only one Assistant was engaged on this". For comparison, 41 people worked on Chain Home, 30 on Army GL and CD radars, and 7 on O.R. Rowe particularly commented on his support for "the aiding of bombers, for which I am convinced there is a great future".

To explain what these systems drawing resource from AI were, it is appropriate to refer to both the Touch memorandum[9] and Hanbury Brown's memoirs[10]. Touch describes January to March as a "period of great activity" but the key research projects were "Detection of Towns" and "Navigation by Contours". The scientists had observed that ASV could distinguish towns and also the lie of the land, and the concept was to develop bomber navigation aids on this basis. Considerable progress was made, but metric wave technology was inadequate for the role and the programmes were halted. The experimentation had delayed the AI project by four months, but Rowe, far from being the antagonist Bowen portrays, consciously supported these activities.

It may be that the diversion was triggered by the AI receivers ordered from Cossor arriving early in 1939, and being both insensitive and too heavy for use; “useless”, in Touch’s words[11]. However, Appleton, a CSSAD member, suggested to Bowen that a Pye Ltd. chassis might be immediately available[12]. Bowen visited Pye, and discovered “scores” of suitable chassis. On test, these proved to be both more sensitive and lighter than those of Cossor. They were to be incorporated in almost every metric-wavelength receiver as a 45MHz intermediate frequency amplifier, even though the valves were then manufactured in Holland. That fact would stimulate a military raid in 1940, during the German invasion of Holland, to recover sufficient valves, valve bases, and sub-components to manufacture those radio valves in the UK, the first military action to secure supply of radar components[13].

Silhouette, meanwhile, progressed with the order for all 50 units placed by the end of March, on A* priority[14]; estimated completion, it was reported to the ADRC, would be the end of July[15]. Also in March, Lindemann returned to the attack over night bombing. He wrote a memorandum, sent by Churchill to Kingsley Wood, the Secretary of State for Air, with plans for 30 minelaying aircraft laying a curtain of “minelets” 13 miles long[16]. This, he asserted, would cause a 20% loss rate among the attackers. Wood responded by ordering a full trial, but by mid-May the new “minelets” had proved incapable of damaging even metal airscrews[17].

The Bawdsey team, refocused on AI after their diversion into bombing aids, worked hard to produce the first AI system. They had first to decide upon a suitable data display. They considered three, one a range/azimuth display, one making use of phase comparators, and one switching rapidly between receiver aerials arranged to receive the target echoes in overlapping lobes. This last was existing technology, resulted in a two-tube display comprehensible to the operator (illustrated in Chapter V above), and so was adopted[18]. From May onwards, the team also worked to resolve the minimum range problem[19].

By 1 June the AI system, now capable of displaying range, bearing and elevation, was installed in Fairey Battle K9208; the configuration is for the first time published at Fig. 81[20]. On 14th June it was demonstrated to Rowe, who was most impressed[21], and immediately wrote to Dowding. Before the demonstration to Dowding could be arranged, two significant events occurred – Churchill received an AI demonstration, about which he was highly enthusiastic, and Dowding attended a further Air Ministry conference on interception, again chaired by Sholto Douglas, at which Tizard, Watson Watt, and A.V. Hill were also present.

Illuminatingly, the first topic at that conference[22] was aerial mines, considered by Douglas as a night and bad weather weapon, and by Tizard as a matter for RAF development; Chain Home, he considered, was all that was required for radar guidance in this case. Douglas moved on to restate his mantra that there had been little development of interception technique in the last two years, which Dowding countered by pointing to several equipment deficiencies - of lack of long-range ground/air communications to permit interception out to sea, of CRDF to locate RAF fighters, and in particular of IFF. Watson Watt hastened to offer seven IFF sets by 1 August (which Dowding was "very glad to hear"), and to point to the facts that he had fitted 20 Bomber Command and 10 Coastal Command aircraft. The conference then focussed upon the details of Chain Home control for aerial minelaying, with some discussion also on "bombing the bombers". The debates are significant in illustrating the hold exercised by aerial mine-laying on the minds of both scientists and Service leaders; there is clearly no concept at this point of developing AI tactics for air combat.

Dowding received his AI demonstration on 30th June, and it is during this that Zimmerman considers there to have been a "deception" practised by Bowen on Dowding[23]. Pre-flight, Dowding emphasised the need for a low minimum range[24]. The demonstration interception took then place, in daylight but with a cloth over Dowding and Bowen's (the radar operator's) heads[25]. When the cloth was removed at the end of the interception, Dowding could not see the target until Bowen pointed out that it was vertically above them[26]. On Dowding's account[27], in the afternoon Bowen announced that “a sensational advance had been made” and that the minimum range was now 220 feet. The effect, in Zimmerman’s view[28], was to cause Dowding immediately to urge the Air Ministry to authorise Bowen’s team to produce and fit 21 hand-built units to Blenheims, and so initiate a series of unsatisfactory AIs which caused waste of resources and loss of confidence by the RAF in the AI solution.

There are several objections to this. First and foremost, Dowding did *not* urge that 21 sets be produced and fitted. The file notes are specific – he asked for “three or four sets”[29] repeating this later as “a few”. As described below, it is the Air Ministry, advised by Watson Watt, who order 21 sets made and fitted, and who continue over-ordering for months. Secondly, Bowen’s memoirs[30] go into great detail about a two-hour discussion he and Dowding had that same afternoon, in which Dowding clearly described to Bowen the needs of, and way forward on, night fighting. Bowen’s comment was “I only wish I had heard this earlier”. In Bowen’s description, Dowding identified night fighting as completely different from day fighting, and emphasised the need for a twin-engined plane to house a radar operator. He also pointed out that the pilot would have his night vision destroyed by looking at a display screen, and emphasised once more the need for visual identification. Clearly Dowding, with thirty years’ experience of training and command of fighters, did not generate these ideas during his demonstration, but must have been mulling them over for some time. Thirdly, Dowding had had five years’ experience of scientists and verbal promises, in his role as Air Member for Supply and Research (1930-5). He was the man who had said at the time of the Daventry experiment “These fellows can prove anything with figures, I want a demonstration”[31], and he was also the man who had called Wilkins a charlatan at the time of the 1936 Air Exercises[32] - he was not a credulous person. His letter to Rowe about the day says only that Bowen’s input was “typical of the manner in which difficulties disappear before the intensive and intelligent work of the Bawdsey staffs”[33], hardly an indication of a conversion on the road to Damascus. Fourthly, Bowen was almost certainly alluding to the development by Touch of “quenching” the receiver oscillator when the transmitter was working, which did indeed lead to significant reductions in minimum range, and Touch’s memorandum clearly identifies that the minimum range was then 200 ft[34]. Dowding had also the experience to know the appreciable time delay, and potential failure, between a laboratory advance and an aircraft-ready unit - he was not naïve in the ways of radio research, given his time in Wireless Squadron No. 9 in WW1[35]. Finally, Sir Bernard Lovell, a member of Bowen's team, takes issue with Zimmerman in the Foreword to Zimmerman's book[36], arguing that "other fundamental problems …. required another two years to overcome".

The series of letters and file notes which relate to that demonstration also offer a more convincing explanation, the key being to identify what Dowding was actually seeking from the Air Ministry – for only the Air Ministry had power to place orders, Dowding did not. In the course of a lengthy letter to CAS, DCAS and Tizard on 10 July, Dowding repeats the "220 feet minimum range" statement, noting also that the maximum range is limited to the aircraft's height. He sets a broad context for his eventual request for "three or four sets" of AI[37], for he gives his concern as the inadequacy of searchlights, the consequent need for "this new method of night interception", and his wish to "as soon as possible, determine and issue a specification for a Night Fighter" (which is exactly as he described it to Bowen). He mentions the prospect of using AI for laying aerial minefields, but closes with a plea for "an immediate decision to give me a few sets of the existing type for experimental work in the Blenheim squadrons"[38].

The internal Air Ministry memoranda commenting on this letter are important and so are reproduced in full in Fig. 82[39]. The key points are Dowding's quoted words that "a good deal of development … is still required and … the tactical problems (of AI) …are of course quite new and will take some considerable time to develop…we can disabuse our minds if we think that the development of equipment and tactics … will take less than one year". On 13 July, the Air Ministry Deputy Director of Home Operations, G/Capt. Stevenson, spoke to Watson Watt, who fatefully said[40] that he "could make as many as 21 sets", which Stevenson proposed could equip a squadron in an emergency. However, the further point of significance is that Churchill, mightily impressed by the technology, had plainly raised the point at the recent Air Defence Requirements Committee (Fig. 82 para.1)[41]. Given Churchill's enthusiasm and power of applying pressure, it is more probable that the order for the full 21 sets was made by the Air Ministry on the basis of Churchill’s urging and Watson Watt’s input. Touch, at the operating level, is quite clear that Dowding had agreed to “Service tests … in six Blenheims”[42]. The extra pressure on timescales which then arose, and which created major problems for Bowen, is likely to have sprung from the drafting words used in the Air Ministry’s letter to Freeman (Fig. 82, attachment)[43], the relevant Air Member (and also Bowen and Rowe’s ultimate master). The political context is also relevant - Munich had taken place only ten months before, and the Germans had now occupied the remainder of Czechoslovakia. There was every sign that war was imminent, and Dowding would have been criminal to delay. On 14 July, DCAS agreed that Bowen’s team should produce and fit the 21 equipments[44].

By end-July Blenheims began to arrive at Martlesham to be fitted with AI, the first being intended for 25 Squadron at Hawkinge[45]. The transmitters had arrived from Metro-Vick. These were the equipments where Watson Watt had insisted that an outdated model be copied, and were accordingly two years out of date[46]. The Pye receivers, by contrast, were excellent[47], and were destined to be the model for the receivers for many 200 MHz radars, including CD, CHL and GCI, though there would be significant problems scaling up the production to cope. Time pressures were such that these sets were the only ones which could be fitted, and so Bowen’s entire team, together with five fitters from Farnborough, set to work. The fitting of AI Mk I is illustrated in Fig. 83, and a 25 Squadron Blenheim of the period in Fig. 84. Despite the fact that Bowen’s group had no experience in this field, and that there were neither racks nor cables for the fitting, the first aircraft was completed by mid August and the next five by end August[48].

Simultaneously, the first ever training of airborne radar operators took place, in a hut by the Martlesham runway in August 1939[49]. The group, primarily the gunners of 25 Squadron’s Blenheims with a few pilots, were taught the rudiments of the subject by Hanbury Brown, who had to leave much of importance untouched. This subject is addressed again below.

By contrast with this frantic activity on AI, the Silhouette scheme continued to coast ahead. The 50th CSSAD on 16th August[50] noted that it "should be completed by mid-September" although there are then noted a curious group of statements, with A.V. Hill of the view that "it would be difficult to decide beforehand on the best method of using the lights … a number of different methods should be tried" and Tedder for the Air Ministry inquiring, without receiving an answer, whether Silhouette "might not facilitate the identification of landmarks by enemy aircraft flying below the cloud".

Amid all the panic, on the first night of the war, there was one AI radar equipped fighter aloft to defend London[51]. Its radar was operated by Hanbury Brown, a civilian.

Night Air Defence Lines of Development Position at 3 September 1939.

At the outbreak of war, the acquisition position can be summarised by the statement that there was at last considerable pressure to pursue all lines of development to aid the introduction of radar - but some years too late. The distinct change from January to September 1939 was that AI was now seen at the highest Service level as a primary method for achieving interceptions at night, even if still in part for sowing aerial minefields; but almost every line of development was lacking. Training, for example, consisted of Hanbury Brown in a wooden hut at Northolt, teaching unselected operators and mechanics of 25 squadron without manuals, test gear or any idea of tactics. IFF was under consideration, but as yet no IFF was working on AI frequencies. Ground/air R/T at VHF was arriving for the day fighters, but not yet for night fighters. As yet no requirement for RCM had been conceived, and the verbalisation by Hanbury Brown and Bowen of the need for GCI was several weeks in the future, Chain Home being thought adequate for night fighter guidance. Fortunately, the manufacture of CHL, which would develop into GCI, had now been started, even if for the distinct purpose of detecting low-flying aircraft.

Contrasted with the position of radar for the day battle, it was hardly an appropriate basis on which to start a war.

03.09.1939	AI	GCI	IFF	VHF	RCM
Doctrine and concepts					
Equipment					
Infrastructure					
Sustainability					
Personnel					
Organisation					
Training					
C3I					
Interoperability					

Table 11. Radar-based night interception capability: summary position, 3.9.39.

VI.3. September 1939 – May 1940: The "Phoney War".

In terms of radar for night air defence, the eight months of the so-called "Phoney War", from 3 September 1939 to the German assault in the West of May/June 1940, were a period of intense pressure on both scientists and Service leaders, and one in which a confusion of inconsistent direction, and of individual responses to individual problems, present a complex picture to the researcher. From the acquisition perspective, these crowded months are perhaps best appreciated and understood by bearing ten key points in mind:

?? *The initial attack was not the one predicted - there was no major night assault on Britain's cities*. Instead, both Naval and coastal shipping were threatened by nocturnal low-flying mine-laying aircraft, whose interception was seen as requiring an RDF 1.5 solution. This in turn diverted AI's limited research resources.

?? *Multiple options were pursued to gain night interception capability*. The pre-war doctrinal solution, Silhouette, was tested, modified, retested and abandoned only in April 1940. The alternative of using Chain Home to guide interceptions was also attempted and, though it rarely succeeded, continued to be revisited until October 1940. The solution to night fighter guidance needs, GCI, was propounded in November 1939 by Bowen and Hanbury Brown, and its development then progressed by Lewis, Rowe's deputy. However, because that development took a year, there were frequent attempts to revisit such earlier "solutions" as Chain Home interceptions. Each option pursued diverted resources still further.

?? *The Air Ministry was hardware focussed and ignored lines of development, so mismanaging the ordering process.* The Air Ministry had ordered 21 AI I sets for fitting in August/September, ordered 144 more in September and then 300 AI II sets in October, even though it was impossible to instal them because Bowen's team was small, and impossible to use them because no tactics or training had been devised. Tedder, the Director General of R&D, later admitted this error.

?? *The Air Ministry relocated Bowen's team frequently and unsuitably, and overloaded them with semi-skilled fitting work*. In eight months, Bowen's small team were moved from Bawdsey (Martlesham) to Dundee/Perth (Scone) to St Athan to Swanage/Worth (Christchurch), the latter three airfields being grossly unsuitable for their work. As the only people knowledgeable in airborne radar, they had physically to install AI and its aerials in the aircraft (including making the cabling and fittings), train the service operators and maintainers in its use, and advise on new applications.

?? *There was confusion of priority between ASV and AI, impossible to resolve at Bowen's level*. Touch confirms that ASV design and fitting for Coastal Command and the Navy quickly became as important as AI, doubling the installation burden on Bowen's small team, but without the Air Ministry resolving their priorities. As a result, few fighters could be AI-equipped in this period, and so AI's tactical use and ground control procedures were not quickly developed.

?? *The customer requirement for minimum range was not adequately defined, verified or challenged*. Dowding was both consistent and emphatic in his demand for a 100 yards or better minimum range. However, no-one appears to have asked him **earlier than April 1940** exactly what the 100 yards referred to (in fact it was the range on moonless nights) nor how often this might be the case. In the event, over half the "kills" were by aircraft **not using radar**, and the half acquired by radar were seen at over 1,000 feet range.

?? *There were multiple, short-lived, AI hardware Marks and variants.* In nine months, there were six - AI I, II, III, IIIA, IIIB, and IV – all seeking to resolve the "minimum range problem" and/or poor production engineering. This profusion arose in part because Lewis, Rowe's deputy, pursued his own "minimum range" ideas on AI independently of Bowen's team, and took advantage of Tizard's initiating "outsourcing" research work to GEC and EMI to do so.

?? *Without direction, Bowen's team fragmented internally over priorities.* Touch saw the key challenge as "making metric AI work" and increasingly devoted himself full-time to manufacturer liaison, eventually splitting the team by moving to RAE in this role. By contrast, Bowen sought to intercept the mine-layers by developing RDF 1.5. However, the February 1940 innovation of the high-power resonant cavity magnetron led to further splintering, for Bowen then saw a further AI solution, through centimetric research.

?? *New corporate mechanisms focussed on night interception were only belatedly created.* Six months after the outbreak of war, in March 1940, the RAF initiated a Night Interception Committee which began to iron out doctrinal and conceptual disputes at Command, staff and scientific adviser level. The Fighter Interception Unit (FIU) was formed in April, and only then were structured trials on the operational use of AI commenced.

?? *The critical incident of Tizard's resignation then deprived Dowding of his key scientific resource.* Tizard lost credibility during June 1940, being proven wrong in his assessment of the German radio-navigational beams by R.V. Jones, a protégé of Lindemann. With Churchill now Premier, Lindemann became his scientific adviser, which nullified Tizard's authority. Tizard resigned, and Dowding now had to carry the weight of both the Battle of Britain and of the simultaneous oversight of the development of AI without his trusted scientific adviser.

Keeping these points in mind, the developments of the "Phoney War" are now examined.

The wartime history of the Silhouette scheme is not a long story. Its trials were enlivened by engagingly terse Army comments on their agenda[52] ("How are the crews to be trained" – "Get 'em together and tell 'em" (*sic*)) but otherwise proved a disappointment. One unforeseen side-effect was a mains voltage surge when the floodlights were switched off – the rise of 30% blew up the Canewdon Chain Home power supply[53]. Dowding persisted, and some equipment was transferred to a smaller scheme to protect Harwich[54]. This also failed, and Tizard confirmed Silhouette's unmourned death on 4 April 1940[55].

The first "radar" action of the war was the evacuation of Bawdsey, a move which was disproportionately disruptive to Bowen's group at Martlesham airfield as they were frantically fitting six 25 Squadron and 15 reserve aircraft with AI[56]. Ordered to evacuate to the small airfield at Perth/Scone, they found there no facilities and no foreknowledge of their arrival[57]. The team was obliged to fit aircraft while working partly in the open[58]. Far more disruptively, in those same weeks, a new priority for Bowen's group was to fit ASV in Coastal Command Hudsons, and Navy Fleet Air Arm Walrus aircraft[59]. Rowe, Bowen's line manager, clearly saw ASV as a priority – "we ought to get 50 aircraft fitted with any kind of ASV", he wrote to Tizard[60]. Tizard also shared the view that ASV was a priority[61], unaware perhaps how much it diverted Bowen's group. On the ground, Touch confirms that "ASV, which as a system had been pushed into the background as a result of the AI developments, became a necessity. We were instructed to fit about 30 aircraft immediately"[62]. Bowen designed the 20Kw. ASV I transmitter around the new GEC VT90 "micropup" valve; Ekco made the transmitters, Pye the receivers, and according to Touch both "really bumped out the metal"[63]. Fig. 85 illustrates the ASV I installation, with Figs. 86 and 87 showing the receiver and transmitter respectively.

Four days after this order, the Air Ministry ordered 144 hand-built AI I sets, advising also that 1,000 production sets would be needed to fit all night-fighter Blenheims[64]. Within a month, Ekco were commissioned to manufacture the AI II transmitter, essentially a better-engineered version of MetroVick's AI I. Pye would make the receivers, which incorporated "quenching" circuits to reduce minimum range. 300 AI II sets were ordered on 28 October[65], for delivery by Christmas. In the event, Ekco were in the throes of setting up a new works at Malmesbury[66], and few appeared before February. Fig. 88 shows a sketch of the AI II installation, with Fig. 89 being a photograph of an experimental version.

The quality of the early AI installations can be assessed from a frank letter sent by Lovell to his mentor Blackett[67]:

> "In 6 tests out of about 12 it has caught fire in the air, due to extremely bad design. The power packs flash over, thin flex leads break off etc., etc. The tester knows exactly how to put things right, he is *never* consulted, and has given up trying to be helpful in sheer despair. …The situation is really unbelievable. Here they are shouting for hundreds of aircraft to be fitted. The fitters are working 7 days per week, and occasionally 15 hour days. In their own words "the apparatus is tripe even for a television receiver".

AI Mk. I would be relegated to a training role on 12 December after a service life of only four months in a handful of aircraft; the equipment was "inherently unreliable"[68].

The facilities at Perth were clearly inadequate for large-scale fitting, and Bowen's group was moved again at on 5th November, to the RAF's main fitting site at St Athan in South Wales[69]. Unfortunately, the facilities here comprised large unheated hangars, from which workshop and laboratory space had to be partitioned by using fabric from scrapped aircraft. Bowen's memoirs state "the conditions …. would have produced a riot in a prison farm"[70]. Research was clearly impossible, and even installation was extremely arduous.

It will be recognised that there had by this point developed a detachment from reality on the part of the Air Ministry chain of command, from Freeman as AMDP, through Tedder, Director-General of R&D and Watson Watt as DCD, down to Rowe. All saw the priority as ordering (or promising) more hardware, despite the patent inability to fit it or the lack of tactics for its use. There is some evidence that the Air Ministry later began to regret its actions. An extract of a minute by Tedder is reproduced as Fig. 90[71], and gives the clearest possible indication of the lack of attention to lines of development. Reality amidst this chaos was represented by Bowen's group of "23, including (Bowen's) typist and the cleaning man" working in the Scottish, then the Welsh, winter, often in the open, to make fittings, instal and test AI. The "thoughtless" loads that were placed upon this small team are exemplified by Bowen's account of Watson Watt's advising him, with no prior notice, on a Thursday, that a Navy group would be arriving on Monday for a two-week course and expecting Bowen – whose overstretch on fitting work he had just seen and sympathised with – to cope[72].

In the meantime, Hanbury Brown had been resident with 25 Squadron at Northolt since September[73], a period which had plainly been an eye-opening process for him. First of all, Dowding at once ordered the equipment to be moved to the back of the aircraft, as the transmitter valves, mounted in the nose, emitted a bright light, visible for miles at night and a perfect target for an enemy bomber's gunners[74]. Secondly, Hanbury Brown discovered that the fighter's TR9 "Pipsqueak" cut off the intercom for 15 seconds every minute to give ground stations a position "fix"[75] – an impossible obstacle to the radar operator guiding the pilot. Thirdly, he had had to teach 25 Squadron's mechanics how to maintain the equipment. As he comments in his memoirs[76], this was "not an easy thing to do without any instruction manuals or testgear". Finally, he had had to instruct the operators and pilots how to carry out an interception. He found that none of the prospective operators had so much as used a telephone before, and learned also that asking a squadron to choose people for "special duty" often resulted in low performers being put forward[77].

Nonetheless, Hanbury Brown also researched the information needed to guide interceptions from the ground. After many attempts, he recognised that the need was to know not only the position, but also the relative height, speed and course of a target bomber, simultaneously with the same information for the fighter. He realised that this was impossible to attain with Chain Home, and argued the need for a dedicated ground radar in a seminal paper of 24 November 1939, "A Suggestion for Fighter Control by RDF"[78]. In his statement of that time, "Having watched the homing of an interceptor on a bomber by AI under service conditions, I formed the opinion that unless accurate and rapid ground control is available, the use of AI apparatus is very limited"[79].

By trial and error, Dowding had come to much the same conclusion. Stimulated by Tizard, he had ordered that attempts should be made to drop using "Pipsqueak" and direction-finding to track the fighter, and instead track both fighter and bomber using Chain Home. Tests were made at Bawdsey in October and November 1939 with the highly experienced S/Ldr. Tester at its controls[80]. These quickly showed that Chain Home's mechanisms, described in Chapter III, were simply incapable of being manipulated swiftly enough, and that the system itself was not sufficiently accurate, to position a fighter closer than 5 miles under even the very best conditions. Larnder, the head of Fighter Command O.R., was at a loss to understand why "a man of the C-in-C's undoubted intelligence" believed that Chain Home could ever guide night interceptions, but then discovered that Tizard had been the originator of the idea[81]. Larnder advanced an alternative idea for a system using two Chain Home Low radars, one tracking the fighter and the other the bomber, with both feeding through optical projectors onto a single screen[82]. The solution eventually adopted, which presented a real-time and simplified data display to the ground controller, was put forward by Bowen, who revived his 1935 idea of a "radar lighthouse"[83], a revolving radar beam with a radial trace sweeping round the tube display screen in synchronism with the aerial rotation, illuminating all the targets as it swept (the Plan Position Indicator, PPI); this would become the basis of the GCI radar. He noted in passing that the idea had been "constantly turned down as a competitor of RDF 1".

In the Air Ministry, Tizard had taken up the wartime role of Scientific Adviser to the Chief of the Air Staff, and at this point was chairing a Committee investigating the RAF's radar problems, as Chapter IV records. The diversion of Bowen's team to the fitting of equipment was regarded by Tizard as one of the major issues, and he was not lightly to be deflected. On 9 &10 November he visited Rowe in Dundee with Watson Watt. Tizard emphasised that AI research had stopped, that St Athan had no facilities for it, and that the research should now be outsourced to GEC[84]. Watson Watt objected strongly, but

Tizard pushed ahead. Dowding, when consulted, enthusiastically supported the move, adding EMI ("a very live and up-to-date crowd") to the list[85]; his three main concerns, he said, were "the complete stagnation of the fitting of AI", IFF's being restricted to Chain Home frequencies only, and need for an armour-piercing small calibre gun.

An astonishing letter from Rowe followed, stating that "Bowen says he has got excellent facilities at St Athan"[86], a location Rowe had never himself visited. Tizard did visit Bowen there, on 14 December with Blackett and Watson Watt, and there survive both Bowen's briefing note[87] and Tizard's visit report[88]. Together these confirm the ASV priority, and the relatively few fittings of AI. Previous accounts have implied that the Air Ministry's massive orders (144 Mk I, 300 Mk II) were somehow fitted. This was not so; as late as 23 November, a previously unreferenced manuscript note from Dowding[89] asks "How many AI aircraft have we?", the scribbled answer being "1 or 2 with Hart, 4 with 25 Squadron (1 unserviceable) and 2 St Athan". Eventually three aircraft were found for 600 Squadron to position at Manston, to intercept mine-layers[90]. Bowen told Tizard that he regarded AI I as practically useless against these low-flying aircraft, especially given untrained crews, and he set out to test an RDF 1.5 solution using Chain Home Low transmitters[91]. To Tizard, he also suggested cutting the 300 order for AI II down to initial service trials of up to 6 sets while developing GCI, and researching centimetric solutions for the longer term[92]. His own fitting work, he estimated, would not be finished until the end of March at the earliest. Tizard's notes[93] show that Bowen convinced him, and he wrote to CAS to point out that RDF 1.5, not AI, would be the antidote to the minelayer, and that specially trained crews would be needed for AI "in view of the great importance of interception at night". Tizard saw Dowding on 19 December[94], who agreed that AI I was useless, but he "could not get AI II". He (Dowding) would use the RDF 1.5 solution against the minelayers.

Outsourcing formally commenced on 22nd December with Watson Watt, Bowen, Touch and Hanbury Brown meeting the GEC team[95], to discuss GEC's taking up centimetric AI research. Paterson, the GEC Director, wrote to Rowe about the meeting[96], and Rowe's reply, while professing delight at GEC's involvement, openly said that he was "most unhappy about Bowen's work at St Athan"[97]. EMI were also invited to take part, which brought the inventive Alan Blumlein, "a master of circuit design"[98], into contact with the scientists. Bowen became the liaison link on this task, with the unexpected consequences outlined below. Challenged, as Tizard had hoped, by this outsourcing dimension, Rowe's scientists set to work. In particular, Rowe's deputy, W.B. Lewis, asked Geoffrey Dummer to begin work on a "radial time base" circuit to deliver the PPI display[99], crucial to the ground control of interception.

Throughout January, Bowen's team continued to be hard-pressed. They had in December demonstrated to Admiral Somerville the use of ASV radar for the detection of submarines[100]. ASV I was adjudged successful, and in turn this created a priority workload to fit 30 aircraft, 15 of which were completed by the end of January[101]; the system had been only four months from inception to installation. Yet further distraction came through an inspiration of one S/Ldr. Lugg, to use ASV radar for navigational purposes[102]. The basis of Lugg's idea was to instal a modified IFF set on the airfield. The aircraft could then interrogate this with its ASV, home onto the IFF, and so return to its airfield. Coastal Command immediately wanted both ASV and IFF "beacons" in quantity, creating yet another strain on Bowen and his team. Simultaneously, they were seeking to fit AI II to the Blenheims at St Athan for 25 and 600 Squadrons, and this proved more problematic. Tizard advised Tedder on 22nd January[103] that "AI is unsuitable for successful operation. Further research of the highest class is absolutely essential …. successful solution of the AI problem (is) the big scientific problem of the war". Tedder's reply, reproduced as Fig 91[104], completely accepts "our fatal mistake in rushing ahead …. before it was ready".

Nonetheless, Joubert increased the AI II fitting order to 18 sets[105], spread evenly over 23, 25, 29, 219, 600 and 604 Squadrons. Bowen's team simultaneously sought to develop an improved version by use of ASV I's more powerful transmitter, the result becoming the AI III radar, illustrated in Fig. 92. During the following months, they worked closely with RAE Farnborough[106] to produce properly engineered equipment in standardised sizes to aid fitting. Touch and his group then moved to Farnborough to continue this work, effectively breaking up Bowen's group. For Bowen himself, his future priority was laid down for him in writing on 19th February by Lee, the new DCD[107]: this was RDF 1.5 to counter minelaying, in addition to fitting out aircraft. Bowen's report to Rowe of 24th February[108] shows him as continuing trials of RDF 1.5, and as planning to deliver the first six AI III-equipped aircraft in "3-4 weeks". Bowen continued to fit this RDF 1.5 development in with his other tasks of managing AI/ASV fitting and liaising with the GEC/EMI outsourced centimetric work, until May when Lewis took over the task at Worth Matravers.

The GEC work led to an unexpected diversion. There was agreement among the scientists that the problems of AI would not finally be solved until a tightly focussed radio beam could be directed from the aircraft, and this demanded high power at a very short, centimetric, wavelength. That combination was achieved in February 1940 with the innovation of the resonant cavity magnetron by Randall and Boot at Birmingham University[109], with major improvements then applied by GEC. Figs 93 and 94 show, respectively, the first resonant cavity magnetron and a later-war production version. Its huge impact is chronologically beyond the scope of this thesis; its relevance here is that Bowen increasingly spent time and thought on centimetrics and the magnetron, and would eventually be chosen to take the innovation, and his knowledge of AI, to the USA as part of the "Tizard Mission" of August/September 1940[110], thereby disappearing from the UK radar acquisition picture.

To draw all the AI strands together, a Night Interception Committee was established, under DCAS' chairmanship, with Dowding, Joubert, Watson Watt, Lee and Tizard among the attendees. At the first meeting on 14 March[111], all were agreed with Tizard's statement that "no home defence problem is so important as that of night interception". Dowding had learned that morning from the meeting papers that RDF 1.5 had a minimum range of 1,000 feet, which he felt was "the last nail in the coffin of that device". Thinking of ground control, he saw CHL as "a necessary preliminary to AI, and if CHL does not work, then AI is useless". There was an extensive discussion on minimum range – the first with all parties represented - where Watson Watt complained that he had been told many figures from 80 to 150 yards, the best that could currently be managed being 800 feet. Dowding replied that it depended on visibility – the figure could be anything from 80 yards, up to half a mile in bright moonlight, and he would circulate the figures, as was eventually done on 6th May[112]. Finally and most practically, a Fighter Interception Unit (FIU) would be established, to develop tactics, training, and maintenance routines for AI equipment.

Following the meeting, Lee produced a paper stating that the desired minimum range was, with present AI, impossible to achieve by adjustments alone, and bench work at Dundee would be needed to produce a new Mark of AI[113]. It is from this point that a rift developed between the scientists at Dundee under Rowe and Lewis, and the airborne group under Bowen. Lewis, probably stimulated by Lee, perhaps stung by the GEC outsourcing, perhaps responding to pressure from Dowding through Larnder (the Head of Fighter Command Operational Research), took direct action to develop AI III to address the minimum range issue, without speaking to Bowen[114]. Bowen's team were convinced that minimum range was not a serious problem; Hanbury Brown, himself a pilot, had flown with the equipment as night and did not believe the aircrew could use less than 1,000 feet[115]. The fault, in their view, was the lack of experience and selection among the aircrews, and the lack of ground control. They felt that reliability would be addressed by their having Touch work more and more closely with the manufacturers - Lovell remembers him as "permanently on the phone" at this period[116], and never seen by the rest of the team – and, as stated, Touch eventually transferred to RAE Farnborough to undertake this role on a permanent basis[117].

Despite this, Lewis, whose biographer[118] and Royal Society obituarist[119] both comment on his highly personal approach to problem solving, decide to concentrate upon minimum range, and to pursue two avenues. A receiver modification, shelved for lack of time by Bowen's team, was now incorporated to create AI IIIA, and an attempt was made to shape the transmitter pulse by use of a second, heavily modified, transmitter connected to the output of the first, a system called AI IIIB[120].

The fourth Night Interception Committee, of 2nd May[121], at last gave AI overall priority, taking over ASV transmitters destined for Coastal Command to fit 100 Blenheims, 60 with AI IIIA and 40 with AI IIIB. AI IIIB did not, however, enjoy a long life; Ekco commented adversely on its production engineering needs, and test-flights showed it contributing little for its weight and complexity. On 17th May, Lewis placed a development contract with EMI and the talented Blumlein[122]. As commercial manufacturers, EMI understood production engineering. Blumlein rapidly produced the idea for a "modulator" to shape the transmitted pulse, an idea discarded by Bowen in 1936 for weight reasons; but technique had advanced in the meanwhile. As early as 27 May, Lewis was able to advise the Air Ministry that EMI were succeeding[123], and that "it is unlikely that we shall ever press for" AI IIIB. Flight-tested at the end of June, Blumlein's system was destined to become AI IV, the standard metric AI; its component units, showing the modulator, are illustrated, with an AI-fitted Beaufighter, in Fig. 95.

However, for 1940 the RAF had to manage as best it could with AI III. Its attempts to create a trained AI night fighting force had earlier been repeatedly frustrated by operational demands. 600 Squadron had been fitted with AI in November, but then despatched to help the Finns, and their expertise lost along with the Squadron in February[124]. A re-formed 600 were again fitted with AI in March, but then posted to aid Belgium, to be lost in May[125]. Now, following the first Night Interception Committee, Fighter Command established the Fighter Interception Unit (FIU) at Tangmere on 10 April[126], with six AI III Blenheims, Bowen, and as its leader the energetic and decisive G/Capt. Chamberlain, formerly Coastal Command Signals Officer. They had to hand 600 Squadron's data that AI II, under the best conditions, could achieve 1,000 ft. minimum and 6,000ft. maximum range[127]. Chamberlain first of all experimented with the equipment himself. An astonished Hanbury Brown relates[128] how that experimentation uncovered an undiscovered major fault of early AI – its display, in certain circumstances, of targets to the right as on the left, and those in front as behind. That "squint" problem would eventually be resolved in July, by changing all the aerials from horizontal to vertical polarisation[129]. Horizontal polarisation had been a decision taken in ASV research to reduce "sea clutter", as explained in Chapter V, and is one example of the problems unwittingly caused by diversion on to ASV. FIU's flight tests also identified that AI IIIA was still an extremely temperamental equipment, prone to overheating, and with a display tube life of under ten hours and only one in ten of the manufactures' tubes working when fitted[130].

Tizard probably best summarised the position at the end of May in a paper for the fifth Night Interception Committee[131], when he advised that the RAF was trying to run before it could walk. The equipment was unreliable, and should now be properly engineered; the minimum range problem was perhaps over-emphasised, and the appropriate course of action was to use AI to attempt daytime interceptions first of all. The night problem at this stage he saw as soluble only by using searchlights, to which radar should be applied. Rowe, rather irritably, wrote to the Air Ministry to point out that relieving the pressure on minimum range at this stage was frustrating[132]. His letter to Tizard was more measured[133] - Dowding, he said, had told him in his office that for a hundred foot minimum he would accept a quarter-mile maximum, and that this "would almost win the war".

The solutions were, however, slowly beginning to align together. On 8th June, the FIU issued the first detailed instructions on AI interception[134]. The orders to fit AI III to eight squadrons were issued a day later[135], and by the end of the month 31 Blenheims were fully equipped with AI IIIA, and even VHF radios[136] at a time when the day Battle of Britain fighters had too few. What must be noted in the lines of development context was that there were still no maintenance manuals or test-gear, that almost all the operators were drawn from the RAF's lowest ranks and hence unlikely to be well-qualified, and that AI III still possessed its "squint"; the Air Ministry had decided that the polarisation would only be corrected when AI IV was fitted.

However, a final and truly startling observation from Bowen's memoirs is that at this late date he was "amusing himself by generating a theory of airborne interception"[137], an activity one might consider he should have pursued with some seriousness in 1936, four years before.

VI.4. German radio beams and the departure of Tizard.

At this point – June, 1940 – the Luftwaffe was beginning to address the problem of attacking Britain. It has been pointed out above that the Luftwaffe placed considerable reliance upon navigational beams for guiding bombers to their targets, and with the fall of France moved quickly to set these up. Developments in this area moved very quickly during June, and Dr. R.V. Jones was a key participant.

Following the cancellation of his infra-red researches, Dr. R.V. Jones had begun to pursue a career in scientific intelligence, where he was for much of the time a single person operation inside the Air Ministry. As early as December 1939, relying upon evidence for radar found in the wreck of the scuttled Graf Spee, he had pointed out that German transmissions were not monitored for evidence of radar[138]. In March and April he had gained evidence of the possibilities of radio beams from PoW conversations and search of crashed aircraft, and had discussed this with Touch of the AI team[139].

June 1940 saw the pace of events speed up considerably. Intercept evidence on the 12th appeared to show such a beam being set up, and a chance PoW remark led to the discovery that the Lorenz blind landing receiver in every German bomber acted as the airborne component of such a system. On 14th June, Sinclair appointed Joubert to investigate[140]. At a meeting of the Night Interception Committee the following day, Dowding gave his advice as "Jam!"[141], but an exchange of correspondence between Dowding and Tizard immediately afterwards shows them both as unconvinced that these beams were either important or relevant to night bombing[142]. Nonetheless, a listening watch was set up on the CH towers to detect the beam signals on the Lorenz frequencies (30.0, 31.5 and 33.3 MHz), and an investigating aircraft readied to conduct an aerial search[143].

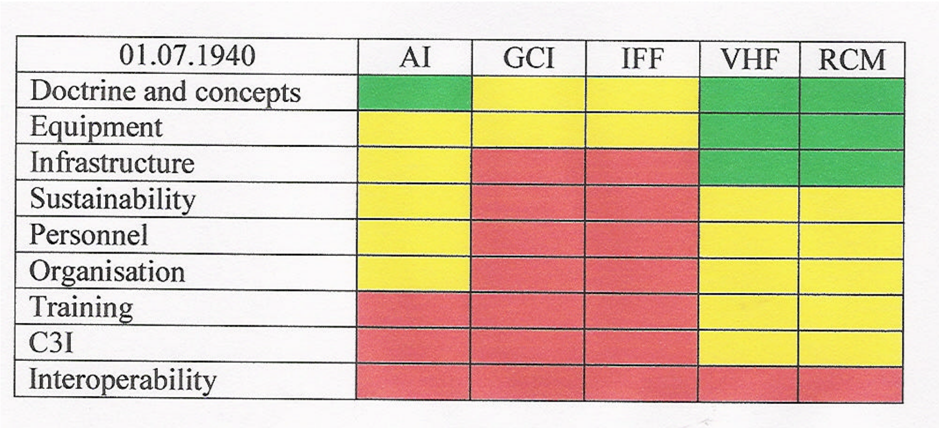
On 20th June, only eight days after the intercept evidence, Churchill convened a meeting, attended among others by Dowding, Joubert and Watson Watt, to discuss the beams[144]. Jones was called in as the specialist, and convinced the meeting of their existence. Tizard openly demurred, but Churchill was convinced, perhaps for the wrong reasons – "if the Germans fly on beams, we can sow (Lindemann's) aerial minefields" – and ordered the ELINT investigation flight. Despite the opposition of Lywood, Deputy Director of RAF Signals, this went ahead and discovered a Lorenz beam, aligned that night on the Rolls-Royce works, Derby[145].

One result was that Tizard, recognising that his authority was gone after his mistaken and public opposition, resigned[146]. It has not been generally observed that this deprived Dowding of his major and trusted source of expertise on radar. From this point, those with most experience of radar – Watson Watt and Joubert – were in the Air Ministry, and neither were his supporters. At this point, the end of June 1940, Dowding's own time was more than fully committed in directing the daylight Battle of Britain. Now, simultaneously and without scientific support, he had to attempt, as user, to develop the most effective method of radar interception at night.

Within a week, Jones had circulated a comprehensive paper on the first of the beams to be discovered, "Knickebein"[147]. A second beam had already been identified from Enigma decrypts. Lywood, once convinced of their existence, acted quickly to establish a radio counter-measures (RCM) unit, 80 Wing, at Radlett under W/Cdr. Addison[148]. Aided by Robert Cockburn one of the Worth scientists, jamming transmitters were rapidly improvised. These developments will be considered below, in their correct timeframe.

Night Air Defence Lines of Development Position at July 1940.

As the first night attacks which would gradually build into the Blitz took place, the air defence position was changing rapidly – indeed, rather too rapidly for the sound acquisition of such a complex capability. The first significant success had been scored, in the confined and specialist area of RCM where a small number of skilled individuals and rapid improvisation could make a significant difference. AI had by now been conceptually accepted as a likely mechanism for achieving night air interception. By July, an increasing number of night-fighters had been fitted with AI III and were making some form of start on addressing the issue, with tactical leadership provided by the newly-established Fighter Interception Unit. Both VHF R/T and IFF were very slowly coming into the night-fighter squadrons. The need for GCI was increasingly accepted and the scientists were developing the equipment, although the Chain Home pioneers would continue to contest the need for anything other than Chain Home.



01.07.1940	AI	GCI	IFF	VHF	RCM
Doctrine and concepts					
Equipment					
Infrastructure					
Sustainability					
Personnel					
Organisation					
Training					
C3I					
Interoperability					

Table 12. Radar-based night interception capability: summary position, 1 July 1940.

VI.5. June to November, 1940: The Developing Blitz.

Given the increasing fittings of AI III, the advent in prototype of AI IV with a low minimum range, and the successful demonstration of the Plan Position Indicator (PPI), it might be anticipated that the coming months would represent a period of stable progress towards acquisition of night interception capability. It was not to be so, for there ensued a “lines of development gap”, when the neglected non-hardware lines of development such as sustainability, staffing and training had to be set in place and given time to generate quality output. However, during this gap, the increasing volume of night attacks and casualties also stimulated a plethora of short-term defence “fixes”, which in their turn further delayed the eventual achievement of night interception capability.

In this second period of complex events, therefore, there are from an acquisition perspective ten items worthy of especial note:

?? *Excessive dependency between key personalities had created a weakness in the acquisition.* Following Tizard’s resignation, Dowding, who had developed no close relationship with other scientists, had to take the entire burden of development on himself.

?? *Diversion of key personalities to operational issues compounds weakness in acquisition.* The extreme case here is that Dowding was simultaneously directing the Battle of Britain by day, and driving to airfields at night to observe the results of AI trials. By November, he was "almost blind with fatigue" and in no state to control any acquisition process.

?? *Early and public acquisition success may create unrealistic expectations for related acquisitions.* The acquisition of radar for the day Battle of Britain, where attention was paid to lines of development, led to conspicuous success highly visible to the public, who consequently expected the same degree of protection by night. High and continuing civilian casualties caused Churchill's support for Dowding to weaken and fail.

?? *Lines of development gaps - 1: GCI.* To achieve GCI, there had to be developed not only three technical solutions additional to PPI – 360 degree powered rotation, continuous height-finding, and gap-filling – but also the tactics and training necessary to achieve effective ground control.

?? *Lines of development gaps – 2: AI.* AI III in Blenheims suffered "squint", overheated and was unreliable. However, the Air Ministry did not wish to fit vertically-polarised aerials to correct the "squint", but to wait and fit them simultaneously with AI IV, which again was delayed. The Blitz was therefore fought with known-imperfect equipment. AI IV also suffered from poor maintenance, and untrained and poorly-selected operators were common to both Marks.

?? *During lines of development gaps, attempted "quick fixes" hindered real progress.* Scientific effort was diverted to re-attempting the failed use of Chain Home to guide interceptions, and to re-experimenting with RDF 1.5.

?? *Multiple AI systems were developed, diverting attention from correcting faults in each.* In these months there were in use or development AI III, AI IV, AI IVA, AI V and AI VI. The latter three were attempts to provide a pilot display, which would have facilitated the use of single-seat fighters at night; they were in fact never introduced, or were little used.

?? *Small-scale, high-skill programmes can result in highly successful acquisition.* The rapid development of radio-counter measures (RCM) to jam or confuse German radio-navigation beams is a successful example in this period.

?? *Simple systems building rapidly upon older technology can also be successful.* The Army's GL I radar for AA gun ranging did not initially give elevation, but an EMI adaptation to improve sound locator sensitivity allowed this equipment to provide the necessary information until a later GL equipment furnished a complete solution.

?? *Lack of continuing success, even after major achievement, ensures loss of political support.* Churchill regarded Dowding's success in the Battle of Britain as magnificent, but lack of visible success against the night Blitz caused him to incline to the views of his scientific adviser Lindemann, whose credibility was increased because of the achievements of his protégé, R.V. Jones, against the German beams. Accordingly, time was wasted on Lindemann's aerial minefields concept.

Though by July 1940 Dowding had been deprived of Tizard, there were many indications of sound progress in the acquisition of night interception capability. By 31 July, 69 of the 72 night fighters of 23, 25, 29, 219, 600 and 604 Squadrons had been equipped with AI III[149]; AI IV had passed its trials at the FIU, and gave a minimum range of 450 feet[150]; and the GCI specification had been approved by the Interception Committee on the 18th[151]. The scientists involved had also been brought together again at Worth Matravers, Swanage, even though the airfield for tests at Christchurch was less than perfect, and Bowen was superseded as the head of the airborne radar team by John Pringle, one of the wartime university influx of scientists[152]. Combat success also appeared possible – in the first significant night raid in full moonlight on 18/19 June, the raiders flew low, and five were shot down[153]. By the end of the month, the Luftwaffe had lost 11 bombers – but the RAF had lost 10 fighters, including 6 Blenheims and their crews[154]. The first AI III kill had also taken place, to F/Lt. "Jumbo" Ashfield on the night of 22/3 July[155].

Unfortunately, this apparently positive scenario proved illusory. As Dowding had written to Churchill on the 16th July[156], AI might be under development, but the Blenheim which carried it was too slow – the Beaufighter, an AI-equipped version of which is shown in Fig. 96, was needed. Defence against German bombing beams could, he said, only be achieved by jamming them, and night defence was a matter of co-operation between searchlights and AI-equipped aircraft. Single-seat fighters would not be useful in the coming long winter nights (they were likely to get lost) and the best defence was strategic attacks against the German air industry.

An argument was now opening up between Dowding and the Air Ministry, more specifically Joubert and Douglas, over the use of single-engined fighters at night. In part, the Ministry may have observed the RAF's few night fighters and their slow speed, and wished to see day fighters (who would be under-occupied in the long winter nights) utilised. It may also be that they wished to find a role for the Defiant turret fighter, withdrawn from day operations, which they had thrust on an unwilling Dowding. Joubert descended upon Worth and demanded AI fitting to single-engined fighters such as the Defiant, Hurricane, and Spitfire[157]. An AI-equipped Defiant is illustrated at Fig. 97. Bowen, in one of his last notes[158] before departing to brief the US forces on AI and the cavity magnetron, outlined possible AI developments for this purpose, while warning of many problems and delays in producing it. A photograph of Bowen in his final weeks at Worth Matravers, at lunch in the local "Square and Compass" pub with Hanbury Brown and Alan Hodgkin, is shown at Fig. 98.

The attempt to fit single-engined fighters with radar was to lead to the diversion of much scientific effort onto developing three further Marks of AI – AI IVA, AI V, and AI VI. These would arrive too late for the Blitz, and draw the comment that "there appeared to be a certain lack of liaison between the Ministry of Aircraft Production and the Director of Signals both as regards the functions of the various Marks of AI and the types of aircraft to be fitted with those Marks"[159]. Sholto Douglas persisted with efforts to get as many fighters of whatever type into the night sky as possible. In a note to CAS, he advised that Dowding was putting too much reliance on the Beaufighter, and had only 40 – 50 aircraft flying at night when 3 to 4 times as many were needed. He did not, however, explain where the necessary qualified night flying pilots were to be found. A preferable course of action might have been to correct the known failings of AI III, as Hanbury Brown had found that its "squint" could be cured by installing vertical rather than horizontally polarised aerials[160]. The first Blenheim so fitted arrived at the FIU in August, but the Air Ministry did not wish to instal new aerials, preferring instead to fit these when also fitting AI IV[161]. As a result, the known-problematic horizontal aerials were used for much of the Blitz period, for the delivery of Beaufighters equipped with AI IV was delayed, in part due to a major night raid on the manufacturers at Filton on 25th September.

Ground Control Interception (GCI) radar was now developing quickly. The introduction of 360-degree power rotation was helped by work carried out by Penley at Douglas Wood earlier in the year[162], and designs to suit an Army turntable were produced by RAE in August[163]. However, as the RAF Signals History points out, "GCI was not without its competitors"[164]. There were two – use of a radar called GM, which absorbed Worth's entire workshop resource from June to September before being found of little value; and revisiting the failed attempt to use Chain Home, a concept favoured by the pioneers Watson Watt and Wilkins. This again consumed time and skilled people until early November, when the success of GCI laid bare its shortcomings.

Meanwhile, Addison had been developing radio counter-measures against the German navigational aids. He concentrated on the two identified to date – German radio "beacons", similar to present-day civil air traffic beacons, and "Knickebein". To combat the beacons, he installed "masking" beacons, "Meacons", in which the German beacon's radio signal was received in Britain and re-broadcast at high power from a British transmitter[165]. The effect was to cause the German radio aid to "unlock" from the German beacon and either drift aimlessly or "lock" onto a British beacon. In consequence, several German aircraft would land in Britain. Against "Knickebein", his first response was to adapt hospital diathermy machines as noise jammers, followed quickly by modifying

RAF Lorenz beam landing transmitters as more sophisticated and powerful jamming tools[166]. By late August, a German pilot reported "Knickebein (was) subjected to intense interference and (was) useless for navigation. The British were getting cleverer and cleverer at breaking into our radio-navigational systems"[167].

However, the Germans had two other beam systems, and Kampfgruppe (KGr) 100, a Pathfinder squadron using the first of these, arrived in Vannes from Germany on 11 August[168]. By the 13th, and ominously, they had raided the Castle Bromwich Spitfire factory with 11 of their bomb loads exactly on target[169]. They were guided by X-Verfahren, described in Chapter V, which was codenamed "Wotan-I" by the Germans, but was as yet unidentified by the British[170].

As long nights approached and the Night Battle began in earnest, therefore, the British had one victory, over the initial German radio-navigation aids. Despite this, for night fighting the RAF was as yet reliant on the slow Blenheim with its unreliable AI III and inefficient aerials, without the benefit of suitable ground radar for guidance (though GCI was being developed). Dowding, as "equipment capability customer", had gained enormous credibility by victory in the day Battle of Britain, an epic struggle which had left him drained. However, he would without respite now be operating alone to try to speed up the hitherto neglected lines of development, most particularly those of selection, training and sustainability.

The first major night raid took place in the late afternoon and evening of 7 September. In the absence of ground control, two Hurricanes were left aimlessly circling Tangmere[171]. Without GCI, and with CH unable to give the precision needed for control of fighters at night, Dowding tried an experiment in the Kenley sector, on the usual flight path of the Germans towards London[172]. Taking over a number of the Army's GL radars, he sited them near searchlights in the hope of illuminating bombers with their aid. However, these proved "unexpectedly capricious" in operation and the experiment was not a success.

The "Battle of the Beams" was meanwhile moving on apace. On the 11th, an Enigma decrypt identified X-Geraet as a new radio-navigational aid, distinct from Knickebein, and operating in the 60-70 MHz frequency band[173]. That same day, Dowding attended a meeting of the Night Interception Committee, where his contribution was marked by explanation rather than remedy[174]. Again on that same day, Beaverbrook, Minister for Aircraft Production, concerned at major bomb damage to the Vickers works at Weybridge a week earlier, received a paper on night fighting[175] from Sir John Salmond, his Director of Armaments Production. Salmond was a retired Marshal of the RAF, and no friend of Dowding. That paper was quickly followed by a note from Churchill on the German navigational beams[176]. Beaverbrook wasted no time. He asked Salmond to investigate night fighting, and wrote to Sinclair, Secretary of State for Air, asking for full facilities to carry this out[177]. Newall, as CAS, agreed and advised Dowding[178]. The progress of the "Salmond Report" was outlined in Chapter IV above. That report[179] was notable partly in recommending decentralisation of filtering, the point of relevance to night-fighting being a claimed saving of 5-6 minutes delay, in which a bomber might have flown 24 miles. More importantly, it recommended the formation of more squadrons of Hurricane night fighters now that the day battle was ending; AI radar for single engined fighters; the creation of a Night Fighting Operational Training Unit; the rapid manufacture of 600 GL I AA radars, and the accelerated production of the AI IV equipped Beaufighter. Quaintly, it also recommended officer pilots should have officer AI operators, and NCO pilots NCO operators. The Air Council agreed the bulk of the report, and wrote to Dowding seeking urgent implementation[180]. It is noteworthy that they made special reference to wishing to introduce aerial minefields as soon as possible, to Defiant squadrons, and to Chain Home guidance, no doubt influenced by Wilkins' experiments at Pevensey. Dowding, in his reply[181], pointed out the difficulty of using single-engined aircraft without night navigation aids; that Chain Home was unsuitable for ground guidance; and that radar-guided searchlights were more useful than a "premature" order for 600 GL sets.

Dowding did, however, bend to the Committee's will at least in part. He chaired a Fighter Command meeting on 18th September[182] to assign priorities to the AI scientists. The minutes show him as content with AI, wishing to push ahead on centimetric research, but regarding the need for AI in single-seat fighters and Defiants as "very pressing indeed, and … of higher priority". Discussion of the potential of 10 centimetre research was quickly stopped – "the C-in-C emphasised that his major requirement is for a system for single-engined fighters", and "all energy should be devoted to devising pilot operated AI suitable for Defiant and single-engined fighter aircraft".

In the meanwhile Dowding persisted with AI III in night fighters. In a series of circulars to his Fighter Groups, his close interest in the development of tactics, and his step-by-step detailed search for solutions, can readily be seen. On 11th October[183], he lists the Beaufighter's teething problems, and calls for radar-guided searchlights. Nine days later, the Beaufighters are still giving trouble – 219 Squadron has 4 ready to fly at 4pm but by the evening all are unserviceable[184]. The AI is found to interfere with the intercom, but a suppressor is found; night navigation is to be helped by an AI beacon at Kenley. He adds, depressingly, "the Germans can fly and bomb with considerable accuracy in weather in which our fighters cannot leave the ground".

There survive, uniquely, previously unreferenced records illustrating two different views of an Air Ministry visit to an operational squadron at this time. The Ministry staff visit 219 and 600 Squadrons, who feel that AI IV is a "retrograde step" as it still has flaws to be ironed out[185]. The Ministry team accompany the aircrew on flights, and assess their general competence, and that of the maintainers, as "poor"[186]. By contrast, the manuscript Squadron logbook records that "no results were obtained except that an AI "Expert" succeeded in setting the apparatus on fire" (Fig. 99)[187] – a result not recorded by the Air Ministry team. Similarly, 600 Squadron complain that the AI trainer hardware "for which we have waited so long" is "utterly useless for AI training as the picture it presented bore no relationship to reality"[188]; earlier papers in the file reveal complete confusion as to the Air Ministry department in charge, even to the level of arranging a visit to the manufacturers, Cossor[189].

Since the Salmond report, Dowding's actions were under intense scrutiny. He dined twice with Churchill at Chequers, on 21 September and 13 October[190]. Each time, he made rejoinders to challenges to his night fighting tactics, on the first occasion to Salmond's report, on the second to a report by Admiral Phillips. That report[191] commented that "At the beginning of the war, AI was said to be a month or two ahead. After more than a year, we still hear that in a month or two it may really achieve results". He notes that Defiants have shot down only two German aircraft for "5 Defiants that have crashed". His solution is to divert at least 3 day fighter squadrons for night defence. Dowding in his reply[192] comments that "Phillips suggests no method of employment of fighters, but would merely revert to a Micawber-like method of ordering them to fly about and wait for something to turn up". Churchill, impressed by Dowding's Battle of Britain victory, called his responses "masterly". Only on 14 October, however, did Churchill add Dowding to the list of those approved to receive Enigma decrypts[193]. It was becoming apparent to Churchill that Dowding was offering little hope against night bombing, other than that of persisting with training with GCI and AI in night fighters. These actions had produced only 4 kills in September, and on the night of 19 October, as an example, none of the AI Beaufighters flew, for all were unserviceable. The day before, Churchill had instructed that three squadrons of Hurricanes be transferred to night-fighting duties[194], even though Dowding had expressed reluctance to do that only 24 hours earlier.

On the 28th Dowding's circular records some successes[195], and welcomes the arrival of prototype radar-equipped searchlights (Search Light Control, SLC, or familiarly, "Elsie", illustrated at Figs 100a & b). A week later[196], he is forced to regard their performance as "most disappointing", and complains about the number of Beaufighters held in Maintenance Units. Some relief, however, was at hand. The missing piece of the night interception jigsaw in equipment terms, GCI, was first delivered on 16 October, at Durrington[197]; it is shown at Fig. 101, with an early GCI Operations Room of the period, at Sopley, depicted in Fig. 102. However, the need to establish an interception procedure and to train both controllers and aircrew, together with the lamentable standards of maintenance, would take months to make good. Nonetheless, Dowding pointed out that[198] "The power of securing continuous tracks has infused a new spirit into the Tangmere

Operations Room, and good results may soon be expected"; the first GCI-directed kill would in fact take place a month later, on 19th November.

In the meantime, the Luftwaffe flew almost unchallenged. During the two months 7 September to 13 November, the Luftwaffe flew 12,000 sorties. 66 kills were claimed, of which 54 fell to guns and 4 to barrage balloons, with only 8 going to fighters. There were few kills with AI III radar. The dangerous accuracy of German beam-aided bombing was underlined by KGr 100's "pathfinding" for an especially destructive raid on 26/7 October[199]. Concern was heightened further by an Enigma decrypt relating to a fourth German blind bombing aid, "Wotan II"[200]. This system would be identified as Y-Verfahren (Y-Geraet), a beam system which automatically triggered release of the bomb. However, this automatic operation was to become its Achilles heel, for once the system was "unlocked", bombing with its aid became impossible [201.]

Dowding's physical tiredness was now beginning to show. His statements[202] that German bombing aids were "so effective that ….(Hitler) will be able to bomb this country with sufficient accuracy for his purpose without even emerging from the clouds" and that the Luftwaffe could fly when the RAF was grounded, "a most depressing fact", were hardly likely to inspire Churchill's confidence.

VI.6. November 1940: The departure of Dowding.

On November 6th, Enigma decrypts gave warning of a raid on a target code-named "Korn", which might be Coventry[203]. On the same day, the crash of a KGr 100 Heinkel 111 on West Bay foreshore, Bridport, Dorset, presented the British with the X-Geraet equipment[204] – or should have done. There ensued a dispute between the Army and Navy over the "ownership" of the wreck, which led to its being immersed at high tide, and valuable time lost in identifying that X-Geraet contained sensitive 2 KHz filters. The British jamming equipment was set for the correct transmission frequency, but with a 1.5 KHz modulating tone. The consequence was that the filters rendered British jamming ineffective, and the Coventry raid caused major devastation of the industrial area and the city. As GCI night fighting was in its infancy – the first GCI kill would take place several days later – the air defence system had to date proven a dismal failure.

On the morning before the raid, Dowding had in fact been transferred, against his will, from his role as C-in-C Fighter Command to head a procurement mission to the USA[205]. Despite his victory in the Battle of Britain, the months without comparable success in the night battle, coupled with his unwillingness either to generate new solutions or to adopt those proposed to him, had finally weakened the staunch support he had received from Churchill. Churchill, of course, had to balance civilian losses and damage to war industries against what appeared to be a tired Dowding, drained of ideas but opposing every alternative advanced. That pressure had become too great, and Sholto Douglas was appointed to succeed Dowding. It is of interest to note Jones' comment[206] that Watson Watt was pleased at Dowding's departure, a reaction which Jones links with Dowding's scepticism of Watson Watt's promises on AI.

The Night Air Defence Lines of Development Position at Dowding's Departure.

In summarising the position at Dowding's departure, it is apparent how much had been achieved, but also how much remained to be done. In terms of AI, AI III was widely installed and AI IV was arriving in increasing numbers, but there was as yet no systematic selection and no training of operators or maintainers. The first GCI was in place at Durrington, but there were no ground control routines or any other support element. Both VHF R/T and RCM were now in place and fully operational. IFF was increasingly common, although the variant operating on AI and GCI frequencies was not yet available; for the time being, a local Chain Home station had to identify aircraft for both GCI controller and night-fighter pilot. What was needed now was time for the users to train in the interception system, smooth out its problems and be ready to use it operationally. By good fortune, the bad weather of winter 1940-1 would provide that.

17.11.1940.	AI	GCI	IFF	VHF	RCM
Doctrine and concepts	Green	Green	Green	Green	Green
Equipment	Green	Yellow	Yellow	Green	Green
Infrastructure	Green	Yellow	Yellow	Green	Green
Sustainability	Yellow	Yellow	Yellow	Green	Green
Personnel	Yellow	Red	Yellow	Green	Green
Organisation	Yellow	Red	Yellow	Green	Green
Training	Yellow	Red	Yellow	Green	Green
C3I	Yellow	Yellow	Red	Green	Green
Interoperability	Yellow	Yellow	Red	Green	Green

Table 13. Radar-based night interception capability: summary position, 17.11.1940

VI.7. November 1940 – June 1941: the Impact of Sholto Douglas.

The newly-appointed Sholto Douglas brought his own experiences and outlook to the role of C-in-C Fighter Command. As outlined in Chapter III, those experiences included command of training and operational units and staff roles at the Imperial Defence College and the Air Ministry. They included no direct experience of acquisition or of managing lines of development, about which he appears to have been unrealistically optimistic. One example, already discussed in Chapter IV, was his desire to decentralise filtering[207], which would be delayed by the infrastructural issues of telephone lines until September 1941. By outlook, he was inclined to the attack rather than the defensive: six weeks after taking up his post, he began to attack German bases in France by fighter sweeps (“Rhubarbs”) or fighter and bomber attacks (“Circuses”), and these may have caused a little damage[208], although the losses in British aircrew were significant – 426 were to die, be posted missing or be taken prisoner during 1941, a figure that Douglas notes was “slightly more than the number of pilots killed in the Battle of Britain”[209]. His memoirs include reference to the shock he felt on realising that, as C-in-C of a major Command, he would now be engaged in bitter arguments with the Air Ministry staff who had been his colleagues when he was DCAS[210].

It must therefore have been particularly galling to him to open his first Report to the War Cabinet on 8th December[211]:

> "It cannot be said that, since my predecessor's last report on 17th November, any great success in night interception has been achieved".

From 500 sorties, exactly one aircraft was claimed destroyed, this being the first aircraft destroyed by an AI IV-equipped night fighter, on 19/20th November. Douglas attributed this lack of success to poor overland tracking and height estimation. He was, however, "most impressed" by the GCIs at Durrington and Worth; the early delivery of more was seen as "the most important immediate aid to progress". His forces comprised 6 AI-equipped Squadrons, plus two of Defiants and 3 of Hurricanes operating on a "cat's eyes" visual basis. He demanded more[212] - another 6 AI, and 3 more Defiant/Hurricane, squadrons, and also extra maintenance, training and aerodrome infrastructural resources – and added a genuflection in the formation of a squadron for aerial mining. A conference he chaired later shows him repeating the demand for a total of 20 night fighter squadrons, and special training facilities for night fighting. However, by February 1941, only one extra squadron could be formed, and that only with Blenheims which had been replaced by new-production Beaufighters elsewhere[213]. The production of the Beaufighter and the USA-sourced Havoc "had not come up to expectations". Equally as important, there was at that point a shortage of 74 night flying trained fighter pilots, a figure which may be scaled against the total of 84 in the existing nine night fighter Squadrons[214].

GCI had developed extremely rapidly over the previous six weeks, spurred on by the Coventry raid, of which one result had been a decision to hand-build six GCIs by Christmas[215], though without power rotation – the pedal-turning "binders" of Chapter IV's CHL would have to suffice. Between 29 November and 3 December the prototype was used to test six different guidance methods[216], derived from the earlier experiments with Chain Home and CHL guidance. The scientists worked night and day on hand-crafting, and the first set was indeed completed on Christmas Day[217] with the remaining five following in the next fortnight, to be positioned around the country as illustrated in Fig.103[218]. It was also not until January that the GCI installed at Sopley, under S/Ldr Brown, developed an effective technique for controlling fighter-bomber interception directly from the PPI display[219], and it is from that point that the success of the Beaufighter squadrons in particular began very slowly to develop. The key staff members, the controllers, were selected from existing Sector Controllers, and trained at Debden, Biggin Hill and Middle Wallop from 15th January onwards[220]. A decision was made on the same day[221] to construct 47 GCIs– 22 mobile, 12 transportable and 13 fixed - by June 1941. In the event, only 17 were operational by July[222], although by that date the demand had risen again, to an astonishing178 sets[223].

The Germans had during these months introduced further radio-navigation and blind bombing beams, known as X-Verfahren and Y-Verfahren, and described above. It is questionable whether the radio countermeasures (RCM) of 80 Wing were as successful in combating these newer German beams as they had been with Meacons and Knickebein. Certainly RCM transmitters to jam X-Verfahren had been set in place, codenamed "Bromide". However, even when these had been correctly adjusted after the Coventry debacle, post-war Luftwaffe veterans have stated to recent research questioners that the interference was at best partial[224]. Many were unaware that they were supposed to have been being jammed! Y-Verfahren, by contrast, was satisfactorily dealt with. The idle BBC TV transmitter at Alexandra Palace was employed to retransmit the instruction signals from the German control station[225]. The high power of that BBC transmitter, codenamed "Domino", broke the "lock" of the Y-Verfahren system and its use was eventually discontinued. R.V. Jones, who had published a long report on X-Verfahren in January, later attributed the lack of success against that system to the poor standards of construction and maintenance of the British RCM equipment[226]. Even when apparently adjusted to the frequencies used by the Germans, British equipment was so poorly constructed and calibrated as to be transmitting on frequencies close to, but not exactly on, the beam frequencies – an "irritation, not a threat" to the bombers.

Nonetheless, as Douglas recounts in his memoirs[227], the Luftwaffe were perfectly capable of mounting an "incendiary classic" raid on 29/30 against London, and the air defence was "still depressingly ineffective". He summarises the point by stating that

> "by the end of 1940 we had found no answer … airborne radar, though in operation, had yet to prove its worth … the necessary type of radar control from the ground had not yet been worked out".

His criticism of Dowding had been that Dowding had become “a little blinded to the hit-and-miss, trial-and-error use of single-engined fighters” but then admits the point that such fighters were “only useful when the moon was well above the horizon”. Tellingly, he attributes delays to Lindemann being “sceptical too long about the use of radar in night fighters” and too focussed on aerial minefields.

At the turn of the year, Tizard, returned from his American mission and in a new role of Scientific Adviser to the Air Staff, penned an instructive summary note[228]. Setting a target of inflicting a 10% loss rate on attackers, he argues that this is achievable by better calibration of the GL AA radars, applying Elsie radar in its present form to searchlights, avoiding proliferation of AI Marks (he was not a believer in centimetric radar as a panacea), fitting an IFF which responded to AI frequencies, and extensive day training of night fighter crews. He closes, interestingly, by stating that aerial mining is not “operationally feasible to use … on a sufficient scale to have an effective tactical result”.

Within days, the Inspector-General contributes a lengthy and previously unreferenced note[229] on the interception of enemy aircraft at night, following visits to 604 Squadron and to Worth GCI. He also sees the preconditions for success as exhaustive daylight trials for GCI/AI and practice for the operators, but adds resolving problems with the Beaufighter. He illustrates his argument with its serviceability at 604 Squadron. On 3rd January, of 22 aircraft, only 8 are serviceable, and after night operations on 4/5th, this is down to one. He points out that weather is the major contributory factor, that little use is being made of heaters to keep the cabins and the AI dry, while the engine maintenance shelters for work at dispersal are “too small to allow room for maintenance work on the engine”, an excellent example of neglect of the sustainability line of development. Training at Prestwick for mechanics has only just started, he observes, and a school for operators is “being organised”, but both need to be expedited. Much fuller information is required for tactics and for minimum visual range under different conditions. He emphasises the need to plan these matters ahead to avoid the same problems recurring when centimetric AI is introduced. In a separate note[230], on searchlight co-operation with fighters, he singles out the lack of trained officers, of inter-site communications, and of delays in the "Elsie" radar as the critical problems.

Perhaps fortunately for the British, the weather in January and February 1941 - the worst winter for many years – was so appalling that there were relatively few raids in either month. The breathing space permitted the British to set up the GCI equipment, instal more AI Mk IV in fighters, select and train more pilots and operators, and refine ground control procedures. Douglas' second War Cabinet report[231], covering December and January, comments on the adverse weather, and claims 6 "kills" (1 from AI fighters, 5 from "Cat's eyes") after 1,139 sorties, 313 being AI – an average of 5 a night - and 789 Cat's eyes. His new intruder tactics suffered a loss of three aircraft for two enemy aircraft "probably destroyed". He expresses concern at the slow build-up of squadrons – there are 15, nine being "Cat's eyes", but 4 of the 15 are still under training, and in his AI squadrons, he has only 73 operational pilots against an establishment of 138. He pleads for transfer of bomber pilots and pilots with civil aviation experience to him.

During this period AI Marks again proliferate and absorb the time of scientists, developers, manufacturers and the FIU. An attempt to provide a pilot's display had, as described above, led to a dozen hand-made units, called AI IVA[232]; their successors, 36 units built by Dynatron as AI V, were tested by FIU in May[233], and achieved their first "kill" on 25/6 June. However, the equipment was complex, demanding very skilled maintenance, and was so often unserviceable that aircrews preferred the simpler AI IV. A version for single-seat fighters known as AI VI was also rushed forward in this time, over 2,000 being ordered[234]. However, the Air Ministry then ruled in April that single-seat fighters were not to be fitted with AI[235], the equipment then becoming destined for the obsolescent Defiant. This proving unsuccessful, the hardware was eventually passed to Bomber Command to use as tail warning radars.

February 1941 continued January's bad weather conditions. During these months, British countermeasures expanded to include the establishment of decoy sites, close to large towns, with fake fires to attract German bomb aimers ("QF" or "Starfish" sites) or simulated street lighting for the same purpose[236]. By this time, almost all heavy anti-aircraft guns were now radar directed by the GL radar, increasingly in its more powerful GL1* (GL1-Star) variant with a Cossor-designed "Bedford attachment" for height finding[237]. "Elsie" radars were also finally becoming available in greater numbers for searchlight control by re-use of surplus AI and ASV transmitters displaced by later models[238].

The result was increasing success for the defenders. When major raids resumed in March, 22 of the 43 kills were claimed by night fighters and 17 by AA. Luftwaffe records agree, showing 42 bombers as lost for all reasons over Britain and the Continent in that period[239]. Douglas' third Report[240], covering February and March, attributes much of the success to GCI. He comments that an IFF set which responds to the GCI is at last available (the Mark IIG) and demands a "greatly increased supply". It is noticeable that he was also pressing to convert Defiant squadrons to Beaufighters, and he places great hope in a Havoc-aircraft mounted searchlight, the "Turbinlite". His offensive Intruder operations have achieved three "kills" for two British losses.

The following month, fighters claim a total of 48.5 and AA 39.5, a total of 88 against a Luftwaffe recorded loss of 77[241], while in May there are 96 claims from night fighters *alone* against a Luftwaffe total recorded loss *from all causes* of 81[242]. As in the latter stages of the Battle of Britain, some exuberance of claiming was perhaps creeping in, but the trend was unmistakable. Douglas' reports of this period[243] press the Air Ministry to cut back Beaufighter allocations to Coastal Command in favour of night-fighters. He praises the GCIs and argues for drastic action to speed up the production of "Elsie". An interesting further contribution on selection and training is made by the Air Member for Personnel, who finally agrees to relax aircrew medical requirements so that potential AI operators of high intelligence but modest eyesight defects can be selected. His note of 25th June[244] records also that there have been "delays, quite unnecessarily, which have been caused by arguments at low level as to the status and pay both of the airmen and officers who are trained as AI operators", a reflection perhaps of the Salmond Committee's views on this matter.

At this date, however, the Luftwaffe, however, had other strategic missions to carry out. Three days earlier, Hitler had attacked Russia, and the bulk of the Luftwaffe's air fleet were being transferred away to the Eastern Front. The consequence – significantly fewer night attacks, no resumption of the day battle – allowed a British claim for victory in both day and night phases of the Battle of Britain, since the enemy had quit the field in both cases.

It is instructive at this stage to consider an analysis of claimed "kills" of AI-equipped, as opposed to "cat's eyes", fighters up to the end of June[245], the date of "Barbarossa":

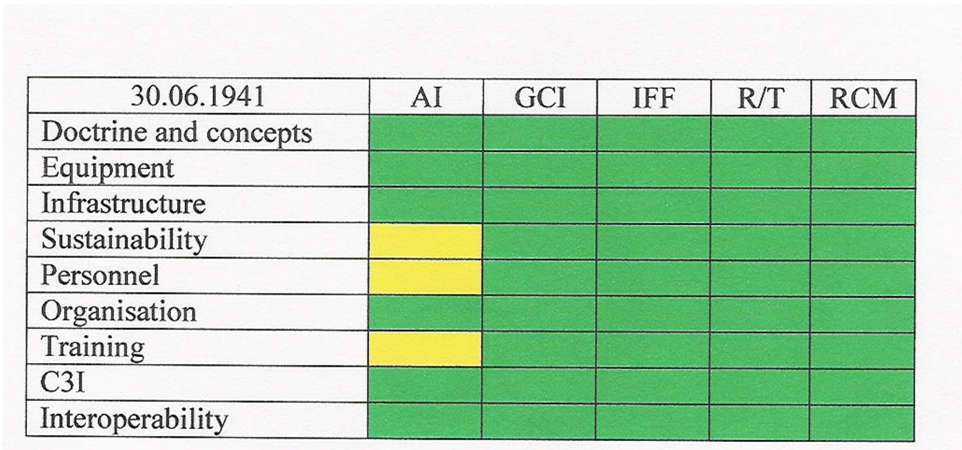
	AI	Cats eye
1940: November	1	1
December	-	3
1941: January	-	3
February	2	2
March	11	11
April	27	20.5
May	34	62
June	19	8
Total	94	110.5

Table 14. Claimed "Kills" of AI versus "Cat's eyes" Fighters, 1.11.1940 – 30.6.1941.

The conclusion to be drawn here is not that AI was ineffective, for cat's eyes fighters operated only on moonlight nights, AI fighters on all nights; and the kill rate per sortie for AI fighters was double that for "Cat's eyes". It is rather that, had Dowding accepted the concept of "Cat's eyes" fighters enjoined upon him, or had improved GCI been a focus rather than proliferated Marks of AI, or even had the Chain Home pioneers' insistence on Chain Home guidance been disregarded earlier, then GCI-guided "Cat's eyes" fighters might well have blunted the Blitz much earlier. The rebuke is implied in newspaper cartoons of the period, one example being illustrated at Fig. 104.

Night Air Defence Lines of Development Position, 30 June 1941.

The position at the end of June, 1941 shows a pattern which would have been highly desirable, and arguably achievable, only six months earlier. GCIs were now installed to give national coverage, as also were the radio counter-measures of 80 Wing, RAF. VHF R/T and IFF were in common use. In the night-fighters, more of which were the powerful Beaufighter, the reliable AI IV was the standard equipment, and even though selection and training of individuals to form aircrew teams was still lagging, highly positive results were being achieved. Whether the enemy was ever truly "defeated", given that the Luftwaffe was now being refocused eastwards for the invasion of Russia, is a separate debate. What is certain is the damage inflicted during the Night Blitz of 1940-41.



30.06.1941	AI	GCI	IFF	R/T	RCM
Doctrine and concepts					
Equipment					
Infrastructure					
Sustainability					
Personnel					
Organisation					
Training					
C3I					
Interoperability					

Table 15. Radar-based night interception capability: summary position, 30.6.1941.

VI.8. Summary and Conclusion.

The acquisition of a radar-based night interception capability represents an acquisition in which almost everything which could go wrong, did go wrong. This conclusion focuses upon analysis of the historical evidence to identify whether current MoD acquisition concepts, in particular lines of development, are supported by that evidence, and if so, whether further insights may be gained from it.

It is clear from the historical evidence that neglect of lines of development materially delayed the introduction of AI. The equipment itself was not properly production engineered until Mk IV, and earlier Marks were poorly constructed. From the unfortunate episode of the 1938 orders, it can be seen that blueprints, specifications, production controls and even factory visits were absent. So far as aerial infrastructure was concerned, there had been no agreement until mid-1939 that the standard platform would be a twin-engined two-crew fighter, as opposed to a single-engined single seat machine. As described above, Bowen had to take unorthodox action even to ensure adequate on-board electrical power. There was no selection of suitable aircrew, and no thought had been given to training before late 1939. There were no spares, tools, manuals or trained support technicians on the airfields. Communications in the aircraft were inadequate, as when the intercom was useless for 15 seconds every minute while Pipsqueak was transmitting, and tests of interoperability of the entire system could not even begin until the first GCI was tested in October 1940, at least six months too late.

Given this litany of specific omissions, it is appropriate to pause and identify the problems at a high level.

One primary issue was that the scientists regarded themselves, and were regarded, as solving a *hardware* problem – "making airborne radar work" – rather than the *capability* issue – "creating a system for night interception". This focus had three origins. The first was the CSSAD's pursuit to a very advanced stage of alternative solutions such as Silhouette, a pursuit which positioned AI as merely one component of an alternative possible, but less preferable, solution. Second, the perspective of Watson Watt and Tizard was that the Chain Home system would suffice for any ground control requirement, in part because they conceptualised "interception" as being to sow aerial minefields, not to engage in close combat. Given such a Chain Home premise, GCI was not necessary - an AI hardware solution was all that was needed. Third, the challenge of simply "making airborne radar work" was itself more than sufficient for Bowen's small team – the much larger Chain Home team had focussed completely on the CH hardware, while Watson Watt and Tizard handled the wider issues involved in delivering capability

Self-evidently, Bowen's hardware task was huge and all-absorbing. Nonetheless, by 1937 his modest group was well on the way to solving the airborne component of night fighter interception - but were then diverted onto the more straightforward ASV application, influenced by the senior level attention paid by Joubert. It is important to note that during this time neither CSSAD, nor Tizard, nor Dowding sought to re-focus the team's attention back to AI; Silhouette was their solution to night interception. By 1938, their support was less than total, and a re-focussing was beginning to be seen as necessary, but it was not until May 1939 that Bowen's team assembled a fully-functional AI and settled on its display configuration. This was after a significant delay caused by exploration of airborne radar for navigation and blind bombing, supported by Rowe, until rebuked by Tizard[246].

There was also no test of interoperability, that is, how a night interception might be achieved solely with CH and AI, until October 1939. It might have been expected that Hanbury Brown, himself a pilot, might have been curious about this, for as described above, he emphasises the theoretical thought devoted to it. However, no such test took place. It was in fact only *after* war broke out that Hanbury Brown produced his seminal paper on night interception, and Dowding ordered Tester to attempt a CH-guided night interception, that the need for GCI emerged, even then to be disputed by the Chain Home pioneers. As Hanbury Brown remarks elsewhere of others, "You don't have to wait for a war to find that out"[247].

However, the scientific team are not to be blamed for omissions lying beyond their scope, nor for "deceptions" they did not commit. *Pace* Zimmerman, Bowen was hardly likely to deceive Dowding – Dowding was long experienced, as has been shown, in the promises of scientists as against delivery. The descriptions by both Bowen and by Dowding of the July 1939 demonstration contain no element of deception, their only real point of difference being Bowen's afternoon statement of a "sensational advance" to reduce the minimum range achievable. Three points of emphasis are necessary. First, such a statement was well-founded, given that it was almost certainly based on Touch's development of “quenching” which did indeed have that effect. Second, of itself, such a statement was hardly likely to persuade Dowding to order equipment to be hand-made by Bowen’s team – Dowding, and for that matter Tizard, had stated well before that demonstration that night interception was a pressing priority. It is simply far more credible that Dowding wanted to get AI into a fighter, devise tactics and discover (and solve) problems. Three years before, he had been a leader in the Biggin Hill day interception experiments, and he was well aware of the lengthy timescales needed for devising tactics and new training. His decision is vindicated by the fact that the lack of ground control would only surface in November 1939, after AI was fitted and tests flown. Third, as to Dowding’s diversion of the scientists to fit equipment, Dowding was specific in his request to have 3-4 aircraft equipped. It was the Air Ministry, perhaps pressured by Churchill, certainly advised by Watson Watt, who then ordered 21 sets, rapidly increased to 144, and 21 aircraft fitted. The problem of diversion originated there, and then became overwhelming by the *continuing* use of Bowen’s group to fit ASV to many different types of Coastal Command aircraft – again, an Air Ministry/Watson Watt responsibility for the scale of orders, for not assessing the impact on the small team, for three bungled relocations in a row, and for not assigning clear priorities to AI and ASV.

What becomes apparent is a dual issue. First, Tizard and Watson Watt were comfortable with the adequacy of CH for ground control, which delayed the introduction of GCI – Wilkins, on behalf of Watson Watt, was still conducting such experiments with CH as late as September 1940. Second, the apparent inability of the RAF – in this case, in the form of the Air Ministry and Watson Watt - to cope in a structured fashion with the introduction of AI contrasts with its earlier, almost model, introduction of Chain Home – in that case, in the persons of Dowding and Tizard. In the case of Chain Home, the RAF had been effective in establishing the Bawdsey Radar School at an early date, and of using a variety of expedients to find enough operators and maintain the hardware. In the case of AI, there was no such early move to testing and to training. The entire structure, it appears, was developed ad hoc, from the tardy establishment of the Fighter Interception Unit to develop tactics (and incidentally debug AI of problems undetected by its scientists) to the last-minute establishment of 80 Wing to develop radio counter-measures.

It is difficult not to attribute this to two factors. First, Tizard was for far too long strongly acceptive of Silhouette, then of RDF 1.5, then of the untested “CH/AI” night interception formula. Second, the delays these caused meant that Dowding, under great pressure, did not devote the same thought to staffing and training for night interception as he had done for day interception, even though the day interception experience was there to guide him; Silhouette, RDF 1.5 and CH/AI would have had far fewer human needs. After June 1940, when GCI/AI were clearly the solution, Dowding, deprived of Tizard, was seeking to claw back time in both areas, but by that stage the “lines of development gap”, the long timescales inherent in such lines of development, were against him, and short term “fixes” merely compounded the problem.

The reader, having considered the time delays inherent in operating a CH receiver to take its three readings for a target plot and in then guiding a night fighter to within five miles of it, and contemplating also the inherent inaccuracy of CH, might suppose that it was obvious long before 1939 that CH could not match this challenge. Yet throughout this period “CH/AI” was perceived, without test, as capable of meeting a night attack. From at least February 1939, Tizard was confirming to Dowding that “he was mainly occupied with the night problem now”[248] and “we do want much more (sic) experiments”[249], but whatever was done does not seem to have addressed the total problem of night interception nor to have tested the fundamental assumption of defence against it, that CH/AI would work seamlessly together.

It must however be noted that where a problem *was* capable of a quick ad hoc resolution, the improvisation was outstanding- the introduction of RCM jammers to defeat Knickebein, of Meacons to mask German beacons and the use of the Alexandra Palace TV transmitter to defeat Y-Verfahren are examples. Where, however, the problem was systemic, there was no such response. “Silhouette” cast a very long shadow, as did RDF 1.5 and the “CH/AI” solution

The extra insights gained from this study of failure may therefore be distilled as:

- *Concentration on simplistic alternatives may divert attention from innovative solutions.* In this case, Silhouette was an option involving no new doctrine, concepts, training or airborne equipment, and was pursued for exactly those reasons. RDF 1.5 then appeared to be a simpler solution than AI, and was pursued for that reason also. Finally, the CH/AI combination appeared to dispose of the need for developing GCI, and so was pursued well into the Blitz itself.
- *Persistent effort must be devoted to achieving the prime capability sought*. Here, that capability was night air interception. Early in the research, the team was diverted to ASV, at first because ASV was easier to achieve and subsequently because of senior level interest. More seriously, the task of physically fitting AI from September 1939 onwards formed a massive diversion at a critical moment for AI.
- *"Dysfunctional diffusion" must either be closed off or properly resourced*. When an innovative concept such as radar appears, a host of uses will emerge, many bearing only little or no relationship to the capability sought. Such diversions – here ASV, the use of IFF to act as a radio-navigation beacon for ASV, the 1939 investigations of airborne radar as a navigation/bombing tool – again diverted the thoughts and time of the small research group. An appropriate action would have been properly to record the opportunity for work by others, or adequately to resource the alternative application. If neither is done, "dysfunctional diffusion" occurs, where a novel application is pursued by the small team to the detriment of the main capability achievement.
- *"Outsourcing", here the involvement of private firms, should be sought on a competency basis: it is not a panacea.* Here, EMI and the talented Blumlein produced the effective AI IV. However, the first commercial attempts to produce AI hardware, by MetroVick and Cossor who had both produced excellent Chain Home equipment, failed. Neither had experience of the demanding aircraft environment. The second attempts, by Ekco and Pye, at first fared little better. EMI's Blumlein was already recognised as a world-class circuit genius with

many patents to his name. Not all commercial firms possessed this competency – in fact, very few did. The requirement was for the competency, rather than for outsourcing *per se*.

?? *Excessive interpersonal dependencies create a major acquisition risk.* Dowding relied heavily on Tizard, and the two enjoyed great mutual respect. Deprived of Tizard, Dowding attempted managing AI development and use at the same time as managing the Battle of Britain. The result was extreme fatigue and the consequent personalisation of criticisms and refusal to consider options which accompany that state. Had the proffered options of extra "cat's eyes" fighters been adopted, the evidence of the results tabulated above indicates that it might well have been effective.

The most forceful lessons, however, are that management of an acquisition is the effective management of lines of development. The night interception failure was ultimately a failure of inter-operability, to prove the system across all its elements, a challenge so successfully anticipated and so successfully resolved in the case of day interception radar. It is possible, but unjust, to attribute this to a failure of the scientific curiosity of Bowen and his team, who were diverted down many other paths. The main responsibility has to be attributed to a higher level. In conceptual terms, the lapse was that of Tizard and the CSSAD, whose success in resolving the day interception issue had provided them with an example to guide their steps. In practical terms, the omissions were primarily those of the Air Ministry, and secondly those of Dowding. The Air Ministry adopted a hardware focus, massively over-ordering equipment regardless of the lack of developed tactics or of people to fit, use and maintain it. They paid little regard to Bowen's small team, did not allocate priorities between AI and ASV, and utterly bungled the physical relocations to Perth/Scone, St. Athan, and Worth/Christchurch. Without priorities to guide them, Bowen's team disagreed over making their own, and fragmented. As the Air Ministry's adviser, Watson Watt is the individual primarily accountable, but neither Tizard nor Joubert are blameless. The omissions of Dowding are secondary, but important. His obsession with minimum range and the lack of testing of this basic assumption bedevilled the entire process. The record of interceptions eventually achieved, in all cases with a visual range over 1,000 feet, proves the point. Again, the scientific community should have tested and challenged the assumption. The earlier acquisition of day interception capability was there as a model for many of these points, but was not followed. Sadly, the consequence was that publicly-visible success in day interception in the Battle of Britain created an over-high expectation for the night battle, and the disappointment was so much the greater. The consequence for Dowding was the end of his career, and for the country, major war industry damage and 43,000 dead.

In the following final chapter, this thesis proceeds to balance the conclusions to be drawn from its comparative analysis of the acquisitions of both day and night air interception capability.

VI.9.

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152. R. Hanbury Brown, op. cit, p. 46, 61, and E.G. Bowen, op. cit, pp. 137-8, on Christchurch airfield; Alan Hodgkin, *Chance and Design*, Cambridge: Cambridge University Press, 1992, pp. 154-5 on Bowen's replacement.

153. John Ray, *The Night Blitz 1940 – 1941,* London: Arms & Armour Press, 1996.

154. TNA/PRO AIR 41/17.

155. E.G. Bowen, op. cit, pp. 124-5.

156. TNA/PRO AIR 16/662.

157. TNA/PRO AVIA 7/106.

158. Ibid.

159. TNA/PRO AIR 10/5485 p.136.

160. R. Hanbury Brown, op. cit, p. 58.

161. Ibid, p.61; TNA/PRO AIR 10/5485 p. 127.

162. Dr. W.H. Penley CBE, oral interview with the author, 6 June 2007; John Duckworth, *Weighty Matters, Worthy People*, Stanhope, UK: Memoir Club, 2007, pp.31-2.

163. TNA/PRO AIR 10/5485 p. 185.

164. Ibid, p.186.

165. Laurie Brettingham, op. cit, pp. 17-8.

166. Ibid, pp. 13-7.
167. Wolfgang Dierich, *Kampfgeschwader Edelweiss*, London: Ian Allen, 1975.
168. John Ray, op. cit, p.93.
169. Ibid.
170. Laurie Brettingham, op. cit, pp. 19-22.
171. John Ray, op. cit, Chapter 1.
172. TNA/PRO AIR 8/863.
173. R.V. Jones, op. cit, p.135.
174. TNA/PRO AIR 20/4298.
175. John Ray, op. cit, p.113.
176. Ibid.
177. Ibid, p.114, quoting Beaverbrook papers BBK D/442 of 14 September 1940.
178. TNA/PRO AIR 2/7341.
179. TNA/PRO AIR 16/387.
180. Ibid.
181. Ibid.
182. TNA/PRO AVIA 7/137.
183. Royal Air Force Museum Archive, Hendon, London, Dowding papers, Circulars FC/S 21197, 11.10.1940.
184. Ibid, 20.10.1940.
185. TNA/PRO AVIA 13/1054.
186. Ibid.
187. Manuscript logbook in possession of the author; relevant page is reproduced as Fig. 18.
188. TNA/PRO AIR 2/7445.
189. Ibid.
190. John Ray, op. cit, pp. 116-8.
191. TNA/PRO AIR 16/676.
192. Ibid.
193. Martin Gilbert, *Churchill Vol. VI Finest Hour 1939-41*, London: Macmillan, 1983, p.849.

194. TNA/PRO AIR 20/2062.
195. Royal Air Force Museum Archive, Hendon, London, Dowding papers, Circulars FC/S 21197, 28.10.1940
196. Ibid, 3.11.1940.
197. R. Hanbury Brown, op. cit, p.63.
198. Royal Air Force Museum Archive, Hendon, London, Dowding papers, Circulars FC/S 21197, 11.11.1940
199. R.V. Jones, op. cit, p. 142 and Fig. 4.
200. Ibid, pp. 172-3.
201. Ibid. pp. 172-8: Laurie Brettingham, op. cit, pp. 22-6.
202. Royal Air Force Museum Archive, Hendon, London, Dowding papers, Circulars FC/S 21197, 20.10.1940. paras. 14, 18.
203. R.V. Jones, op. cit, Chapter 18.
204. Ibid, pp. 146-7.
205. John Ray, *The Battle of Britain: New Perspectives*, London: Arms & Armour 1994, pp. 124 – 169.
206. R.V. Jones, op. cit
207. See Chapter IV, pp. 218 – 221.
208. John Ray, *The Night Blitz*, op. cit, pp. 241-3.
209. Sholto Douglas with Robert Wright, *Years of Command*, London: Collins, 1966, p.116.
210. Ibid, p.101.
211. TNA/PRO CAB 81/22.
212. Ibid.
213. John Ray, *The Night Blitz*, op. cit, p. 190.
214. TNA/PRO AIR 41/17.
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217. Ibid, pp. 191-2.
218. Ibid, p. 190.

219. W. Penley and R. Batt, *Dorset's Radar Days,* Swanage: Purbeck Radar Museum Trust, 1994, p.8.
220. TNA/PRO AIR 10/5485 p. 193.
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224. Dr. A. Price, 'A New Look at the Wizard War', *Transmission Lines* Vol. 8 No. 2. June 2003, pp. 1, 2 and 8.
225. Laurie Brettingham, op. cit, pp. 22-6.
226. R.V. Jones op. cit.
227. Sholto Douglas with Robert Wright, op. cit, pp.102-7.
228. TNA/PRO AIR 20/1489.
229. TNA/PRO AIR 33/4, Minute 12.
230. Ibid, Minute 13.
231. TNA/PRO CAB 81/22.
232. TNA/PRO AIR 10/5485, pp. 135-7.
233. Ibid, pp. 137-8.
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235. Ibid, pp. 138-9.
236. Colin Dobinson, *Fields of Deception,* London: Methuen, 2000.
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239. Ibid, pp 237-9.
240. TNA/PRO CAB 81/22.
241. John Ray, op. cit, pp. 237-9.
242. Ibid.
243. TNA/PRO CAB 81/22.
244. TNA/PRO AIR 20/3514.
245. TNA/PRO AIR 10/5485, Appendix 13, p.277.
246. TNA/PRO AVIA 7/2009.
247. R. Hanbury Brown, op. cit, p.42.

248. Ronald Clark, op. cit, pp. 159-160.

249. Ibid.

VI.10. FIGURES.

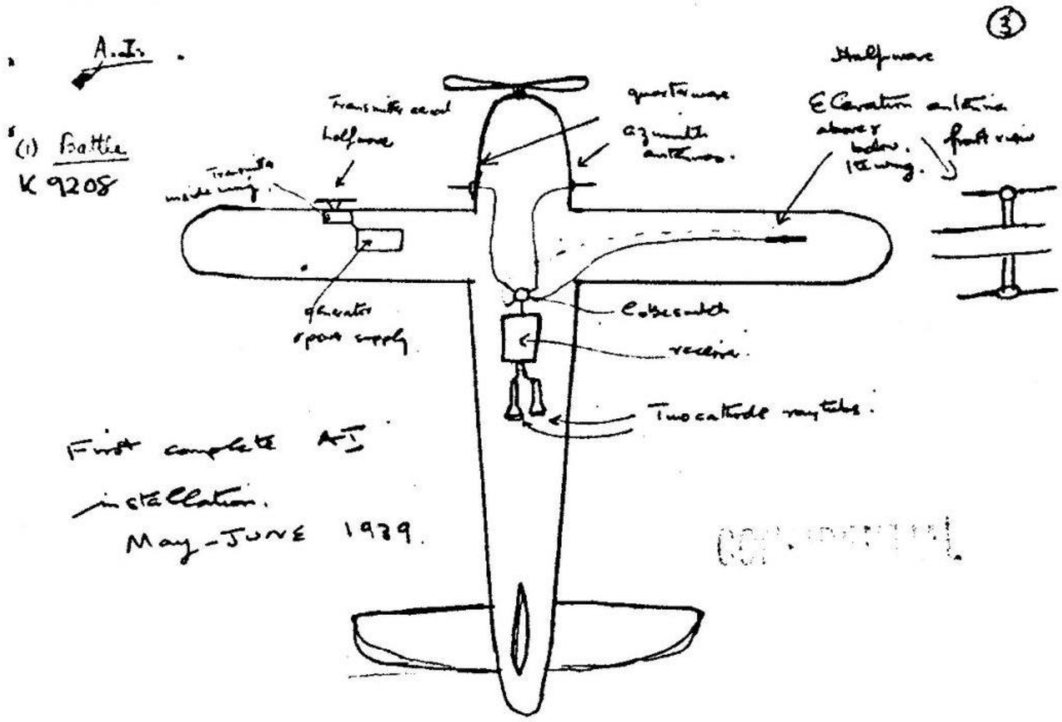

Fig. 81. The experimental installation of AI, as demonstrated to Dowding, sketched in the Touch memorandum (TNA/PRO AIR 20/1464).

SECRET (1A) 60

D.C.A.S.

I have spoken to Sir Hugh Dowding on the point raised by Mr. Winston Churchill at the A.D.R. 11/7. His view is that the set, at present installed in a Battle, is still in the experimental stage but that the development shown by this set is most significant. He says however, that a good deal of development in regard to the apparatus is still required and that the tactical problems incidental to the proper use of air to air R.D.F. are of course quite new and will take some considerable time to develop. He says the apparatus is tricky to use and personnel will require special training. It must be used of course in a multi-seater fighter. He said that we can disabuse our minds if we think that the development of equipment and tactics to the stage where air to air R.D.F. can be used universally and effectively in the Fighter line will take less than one year.

2. H e recommends that four sets of apparatus should be supplied at once to a Blenheim Squadron, that the Blenheim should be properly screened - this will take a short time - and when I spoke to him this morning he said that he would put them into 25 Squadron at Hawkinge - a convenient place for operating night fighters over the sea.

3. I have spoken to D.C.D. this morning and he says that 4 to 6 lash-up sets similar to those installed in the Battle could be got on with and completed soon after 15th August. He could make as many as 21 sets, say by the end of September but this would delay a little the development of the final version of this set, on which a lot has got to be done. For instance two tubes are used at present and further, we shall want a solution to the problem of changing over from "head on" position to "follow up" position.

4. There is no suitable aircraft at present in the Service in which the set could be installed except the Hudson, and the

Fig. 82 (5 pages) The Air Ministry's proposed action after the Dowding demonstration, showing that Churchill may have stimulated the Air Ministry and that Watson Watt had been asked and over-committed. Note that Dowding was thinking of development and tests over a year, and wanted only 4 sets – the Air Ministry takes the decision for 21. (TNA/PRO AIR 20/222).

Hudson, with a top speed of 240 m.p.h. and a cruising speed of ??0 m.p.h. is hardly good enough for us. The Blenheims have to be modified and it would be possible to screen four quite quickly. The only aircraft coming into the Fighter line which is satisfactory is the Beau fighter. A.M.D.P. has already given instructions that if we want the Blenheims screened Farnborough is to proceed with them as a first priority.

5. The lash-up set at present in the Battle gives the performance described in C.-in-C.'s letter attached. It is, of course, experimental and wants tidying up a bit. Operating over the land the range of the set is 250 ft. less than the height of the aircraft above the ground - operating over the sea the range goes up to the maximum of the set, i.e. about 5 miles. D.C.D. informs me, and C.-in-C.'s letter confirms, that the fighter can be homed on to the enemy bomber (when within range) up to a closing distance of 250 ft - or some 80 yards.

6. You should read C.-in-C.'s letter and from this you will see that he favours immediate tactical development and points the fact that if and when satisfactory, R.D.F. air to air will lead to great savings in our searchlight layout. I discussed this angle of the problem with Loch yesterday and in his view even when R.D.F. is working satisfactorily we shall still want a number of searchlights in the layout in order to aid the fighters equipped with R.D.F.2. As a short term policy he agreed that nothing should be done to delay the provision of illumination in accordance with approved programmes until we are certain of the effectiveness of R.D.F air to air. He makes further points - which we know. The Defiant is no good for this kind of equipment. The Blenheim can and should be modified but the Beau fighter is likely to prove the immediate answer and he makes the point that it will be helpful in mine laying.

7. I suggest therefore that in view of the political situation no delay should take place in providing <u>6 sets immediately</u> for Fighter Command and a further <u>15 to follow</u> as soon as possible, development and production on the technical side

side to go ahead thereafter. The 6 sets to be used for the 4 Blenheims (from production) at Hawkinge with 2 in reserve and the remaining 15 as a standby in case of war during September to enable us to fit one Squadron of Blenheims with this device. A further 20 to 25 Blenheims should be screened so that the sets could be used immediately if an emergency developed.

8. If you approve the above the Policy would be:-

(a) Fighter Command to develop R.D.F. air to air tactics on highest priority

(b) Short term interim policy to have available sufficient equipment to enable one Blenheim 5 gun fighter Squadron to be fitted with air to air R.D.F. - against an emergency arising this year.

To enable this to be done.

(a) 4 Blenheims (ex production) to be screened at Farnborough at once and delivered in exchange to 25 Squadron, Hawkinge;

(b) 21 R.D.F. sets air to air to be copied from the Martlesham "lash-up"

(c) A further 17 Blenheims to be screened.

The reply to S. of S.'s minute would be on the lines of the attached draftA. Draft B is a minute to A.M.R.D. and A.C.A.S to put the policy into effect.

13.7.39. D.D.Ops.(H)

(21) (59)

DRAFT **SECRET**

S. of S.

I have got Sir Hugh Dowding's views on the point which Mr. Winston Churchill raised at the conclusion of the A.D.R. Meeting on 11th July.

2. The result of the recent trials of the R.D.F. air to air set installed in the Battle at Martlesham was, as you are aware, most promising. Arrangements have accordingly been made for 21 copies of this "lash-up" set to be made. Four of these sets will be installed in specially screened Blenheims to enable Sir Hugh Dowding to undertake the development of R.D.F. air to air tactics on the highest priority. We hope that the equipment and aircraft for this will be available during the last half of August.

3. A further 17 Blenheims are being screened which, with the remainder of the sets (likely to be available in September) will enable a full Squadron to be initially equipped in the event of a sudden emergency arising.

7.39. D.C.A.S.

(3A) 58

DRAFT **SECRET**

A.H.P.D.
A.C.A.S.

In view of the promising nature of the recent trials of the R.D.F. air to air sets installed in the Battle Martlesham and in view of the present relative weakness of our night defence, C.A.S. has decided that Fighter Command should proceed with the development of R.D.F. air to air tactics in the highest priority and that we should be prepared at short notice to equip one Blenheim 5 gun Fighter Squadron with this equipment.

2. I have C.-in-C., Fighter Command's views and would be glad if the following action could be taken:-

(a) Fighter Command would be informed accordingly in reply to their letter FC/16838 dated 10th July

(b) 4 Blenheims (ex production) should be screened in the highest priority and delivered in exchange to 25 Squadron, Hawkinge

(c) A further 17 Blenheims to be screened as soon as practicable

(d) 21 copies of the R.D.F. sets air to air should be made as soon as possible - the first six of which should be delivered to Fighter Command, the remainder being held against emergency requirements.

(e) After the production of the 21 sets referred to, research and development of R.D.F. air to air to continue on the highest priority.

7.39. D.C.A.S.

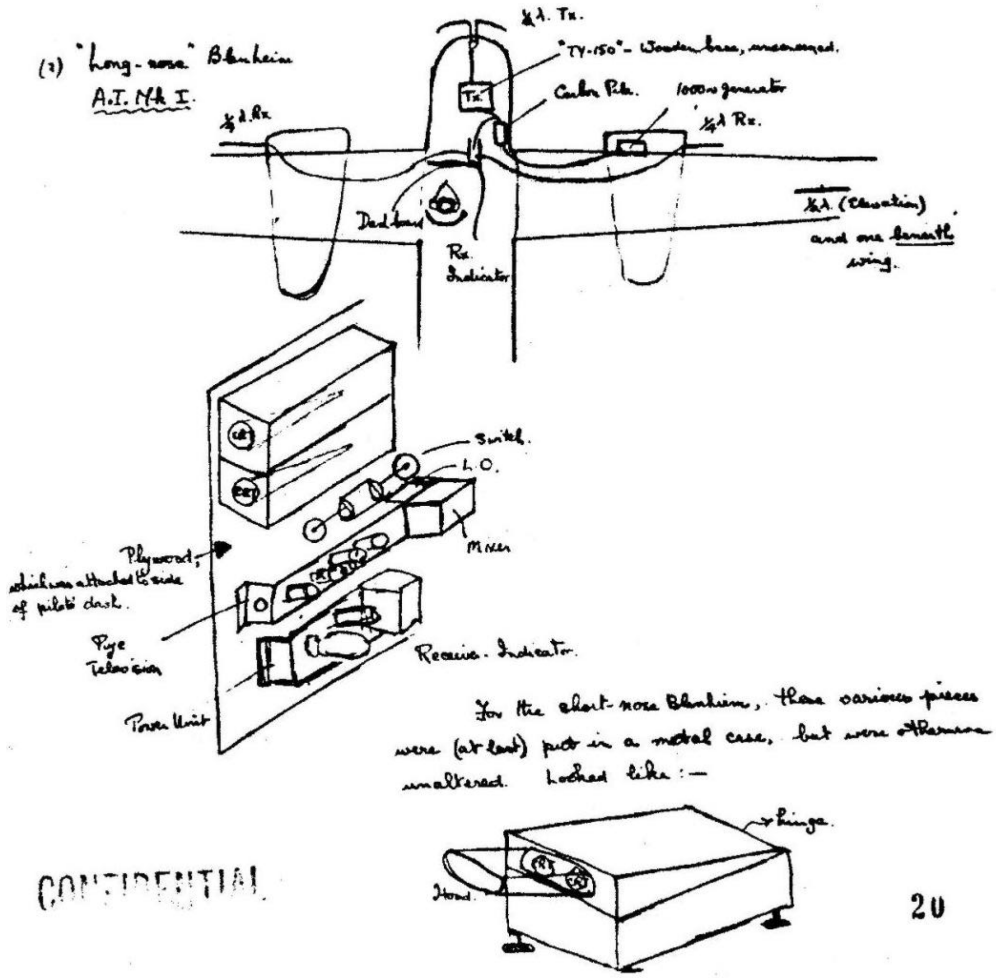

Fig. 83. Illustration of the fitting of AI Mk I in Blenheims, from the Touch memorandum. (TNA/PRO AIR 20/1464)

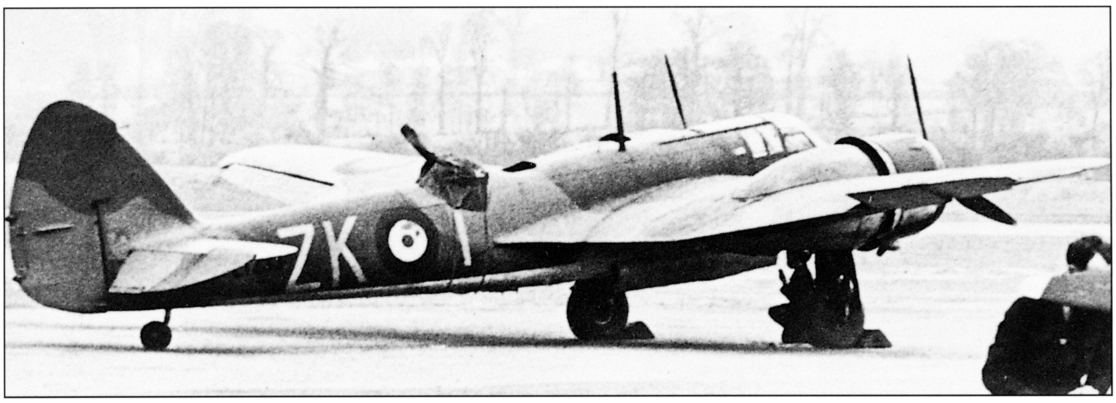

Fig. 84. 25 Squadron Blenheim in February 1940. The aircraft does not appear to have the underbelly gun-pack fitted as the bomb doors are open. (Jon Lake, *Blenheim Squadrons of World War 2*, London: Osprey Publications, 1998, p. 62)

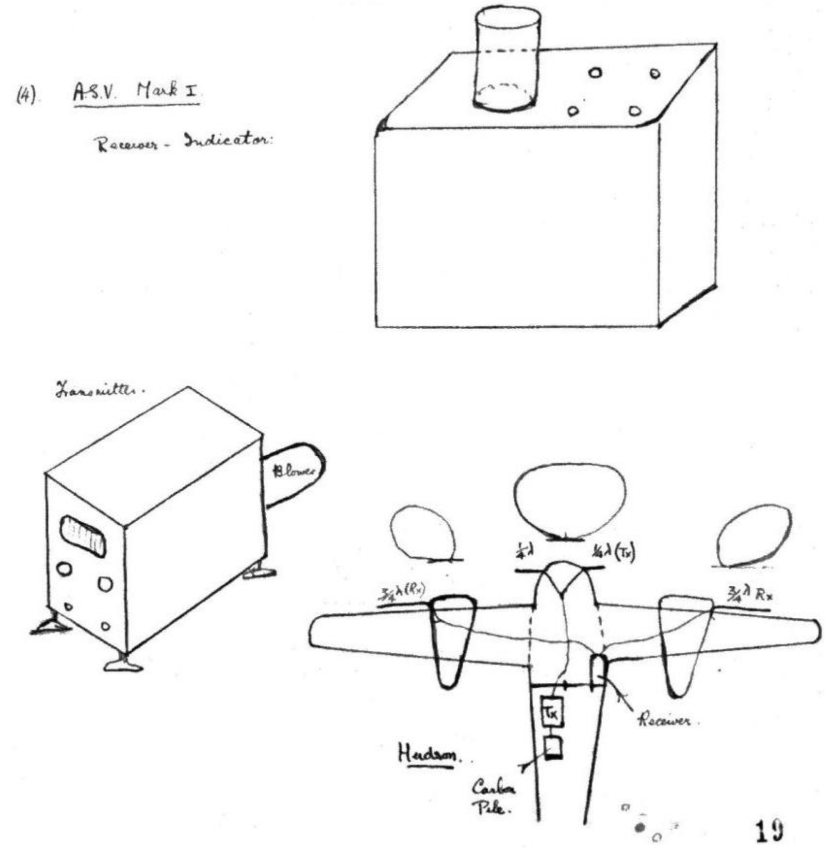

Fig. 85. ASV I fitting as shown in the Touch memorandum (TNA/PRO AIR 20/1464)

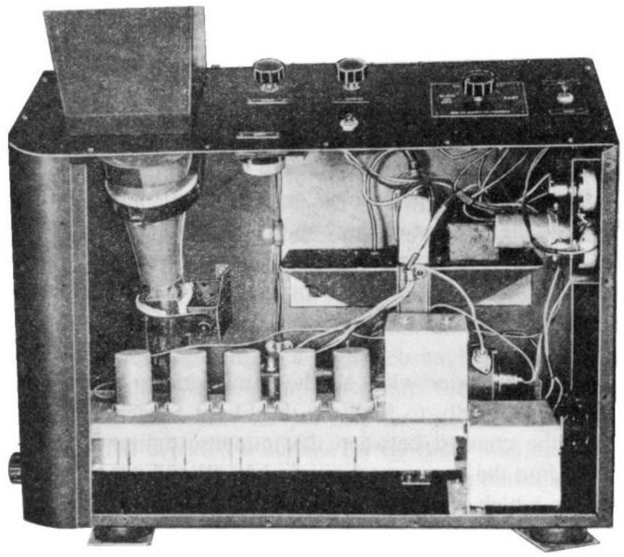

Fig. 86. ASV I receiver/indicator (R. Hanbury Brown, *Boffin*, Bristol: Adam Hilger, 1991, Fig. 4.1)

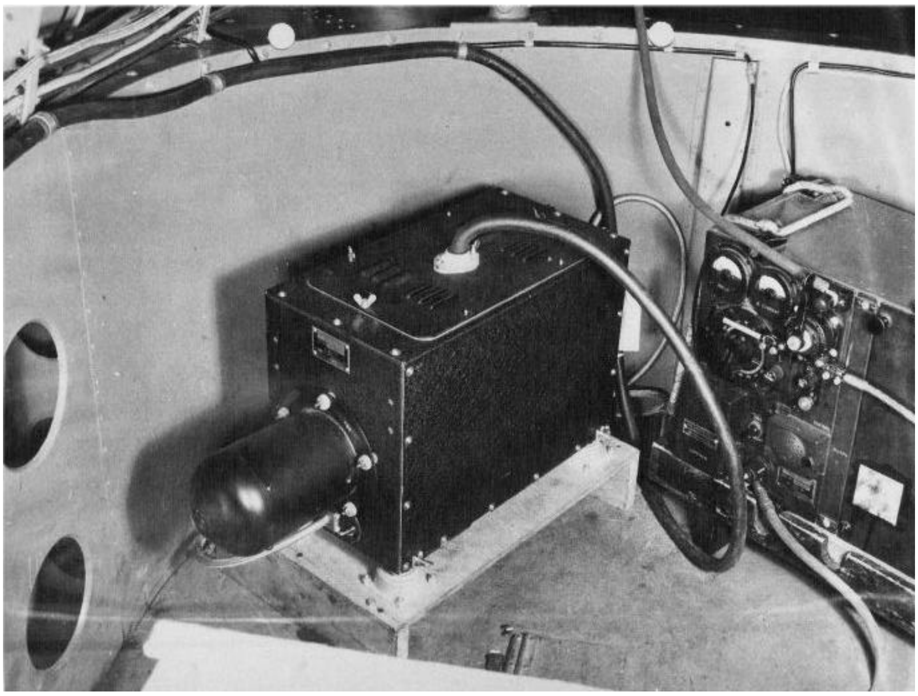

Fig. 87 ASV I transmitter; the equipment to the right is a TR9 R/T. (Racher Archive)

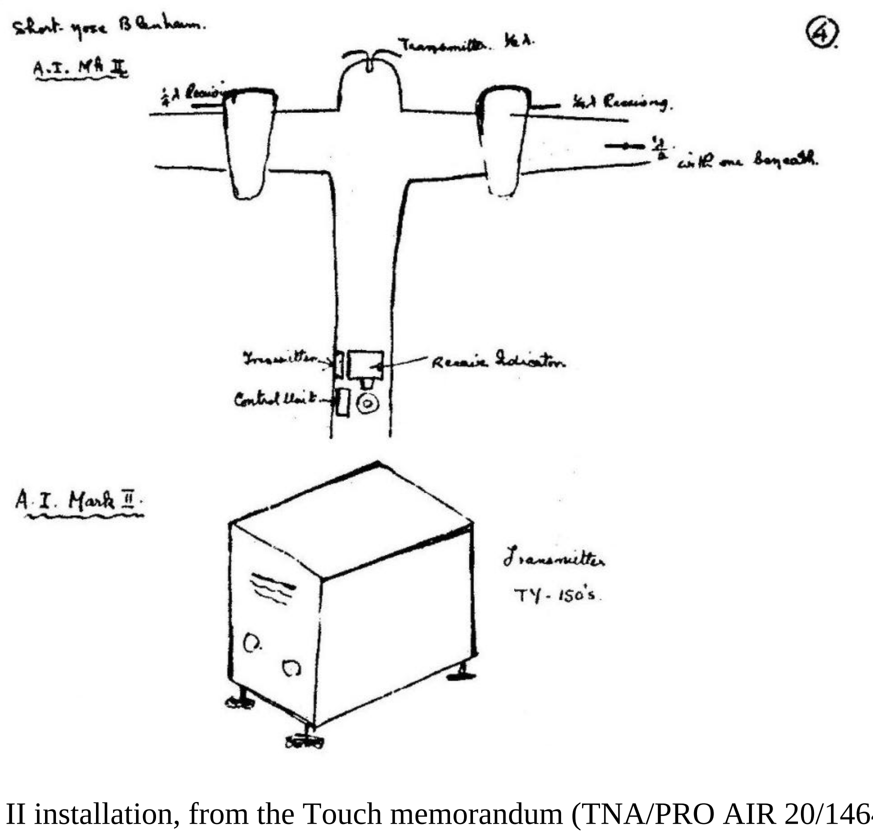

Fig. 88. AI II installation, from the Touch memorandum (TNA/PRO AIR 20/1464)

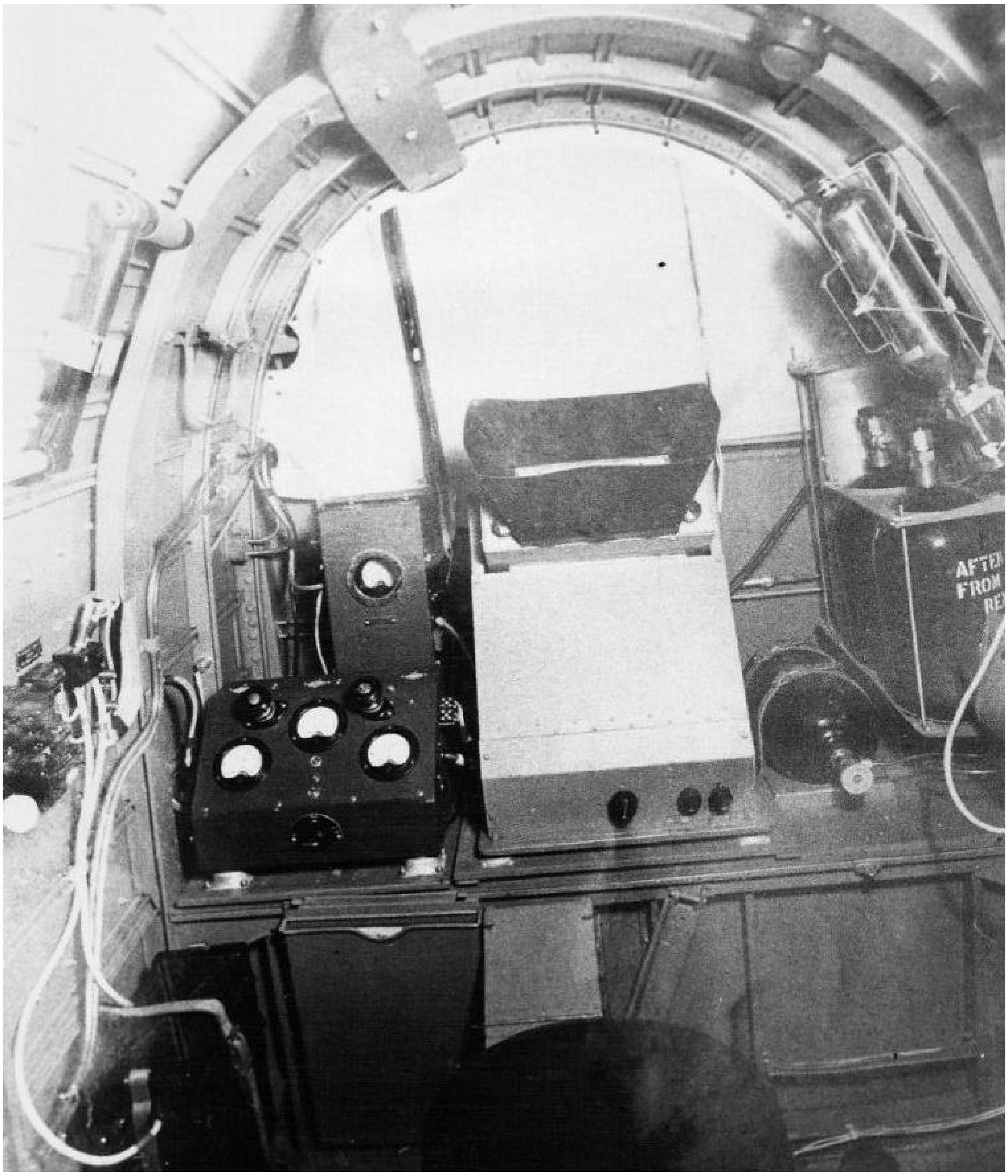

Fig. 89 AI II installation at the rear of a Blenheim. (Racher Archive)

- 2 -

A.M.D.P.

Up to the present, R.D.F. has gone direct from research to production. There is no doubt that in so far as this has given the scientists who have been carrying out research full freedom, this has been a wise and, in fact, the only possible policy. The practice, however, of going straight into large scale production of equipment which is really still in the research stage (though inevitable in view of the need for speed) has led us, and will lead us into many difficulties when it comes to the practical application of R.D.F. We are now in the position of having to install R.D.F. equipment on a large scale in practically every type of aircraft. In order to do this, practically the whole capacity of the aircraft depot at St. Athan is being absorbed for an indefinite period. The equipment itself in its various forms is not yet standardised, installation problems are

/still

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still largely unknown, and it has been necessary to divert a vital part of the research team to carry out this installation programme.

2. This situation is, as I have said, due to the fact that up to the present, we have had no R.D.F. Development Unit. It should be noted that both the Army and the Navy have now formed Development Units of their own to deal with the development problems of applying R.D.F. to their particular requirements. There is, in my opinion, no doubt whatever that it is urgently necessary and that we should establish a similar Development Unit for our own purposes. As things are at present, we have no guarantee whatever that the equipment we are now fitting into Service aircraft will, in fact, prove to be suitable for use by Service personnel on operations.

3. There are at present no fully detailed specifications (such as are required for planned production), no schedules of parts, no installation layouts, and no provision for interchangeability. All these are essential for R.D.F. as for all other Service equipment. Attempts have been made to safeguard these various points, but no systematic planning to cover them has been possible. Independent and largely unco-ordinated work in these directions is being carried out at Dundee, by the manufacturers, at Leyton Buzzard, at St. Athan, at Kidbrooke and at Christchurch. It is the function of the Development Unit to guarantee and control all this work.

Fig 90. Tedder's copy to Tizard of his 8th November 1939 minute to Freeman, Air Member for Development and Production, paragraphs 1-3 (the remaining paragraphs deal with the details of the formation of an RDF Development unit and are not relevant). (IWM/HTT 236).

(Dept. ZA)

T/M

Harrogate.

24th January, 1940.

Dear Tizard [handwritten]

Many thanks for your letter of the 22nd instant, on the subject of A.I. and St. Athan.

I have been only too well aware for some time that all was not well at St. Athan. I have done what I could by writing to Boyle who was in command there to try and improve the conditions of our people who are working there. On the general issue, however, I am afraid much, if not most, of the trouble is due to our fatal mistake in rushing ahead into production and installation of A.I. before it was ready for production, for installation, or for use. This unfortunate precipitancy necessarily wrecked research work on A.I. since it involved diverting the research team from research proper to installation.

As I see it, apart from the establishment of proper research facilities at Swanage and proper development facilities at Christchurch (Farnborough for the meantime), there are two main things to be done. Firstly, to try and develop the existing A.I. designs to make them practical from the operational point of view. This is literally the only way in which we have a hope of getting A.I. into operational use in the immediate future. Secondly, to press on with fundamental research on the A.I. problem as such. This, I agree, needs the concentration of the best brains and facilities we can find. If we are fortunate on the ultra short wave work, we may possibly get something, the installation aspect of which may not be prohibitive and might, perhaps, come into use in 18 months or later.

I have discussed this with Lee and he fully appreciates that this is the most urgent job to tackle, and as a result, he went down to St. Athan on Monday of this week with Watson Watt and de Burgh with the precise object of concentrating all our efforts on the solution to this dual problem.

We are concentrating on A.I., but I think we must wait and see what Lee's ideas are and what can be arranged. In other words, we must give the new management a chance.

Yours ever

A W Tedder [signature]

Sir Henry Tizard, K.C.B., F.R.S.,
Air Ministry,
Department OA,
King Charles Street,
Whitehall,
London, S.W.1.

Fig 91. Tedder to Tizard on 24th January 1940. Note the words “our fatal mistake” in para. 2. (IWM/HTT 15/17).

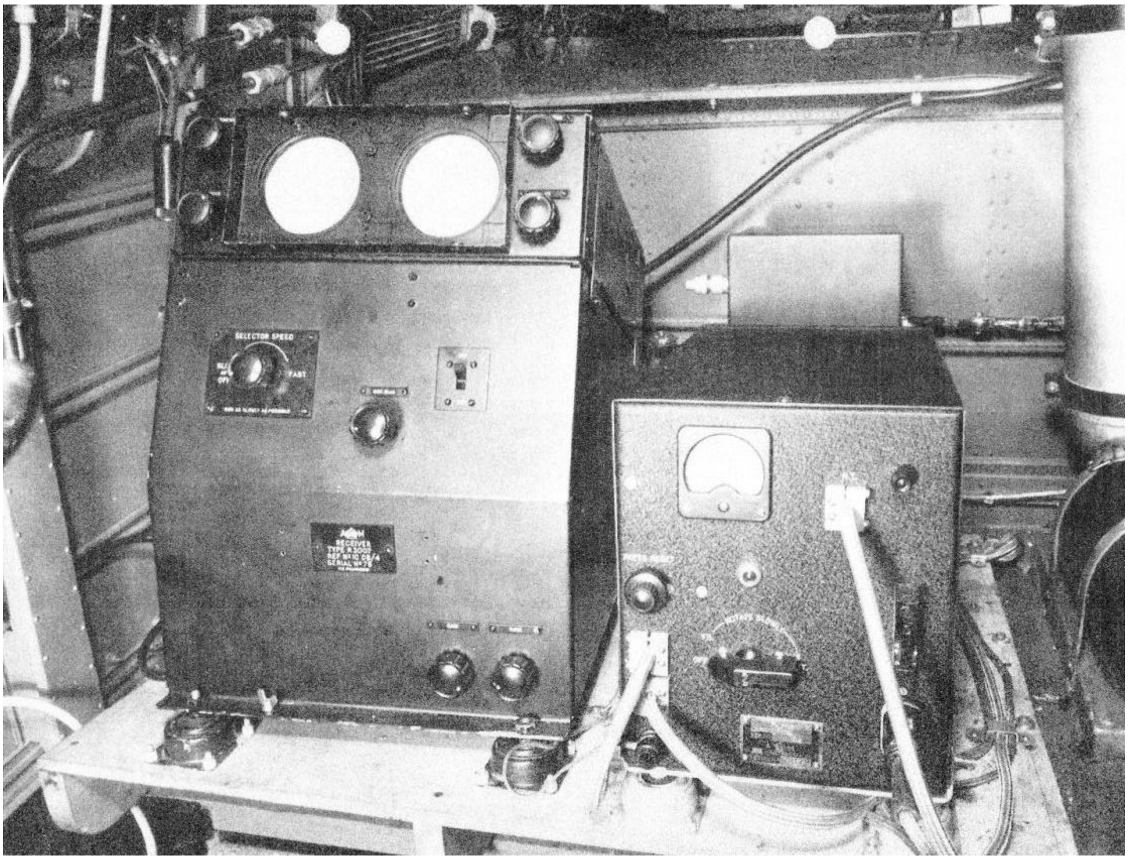


Fig.92. AI III receiver and indicator (right) and power unit (left). (Alfred Price, *Blitz on Britain*, London: Ian Allen, 1977, p.50).

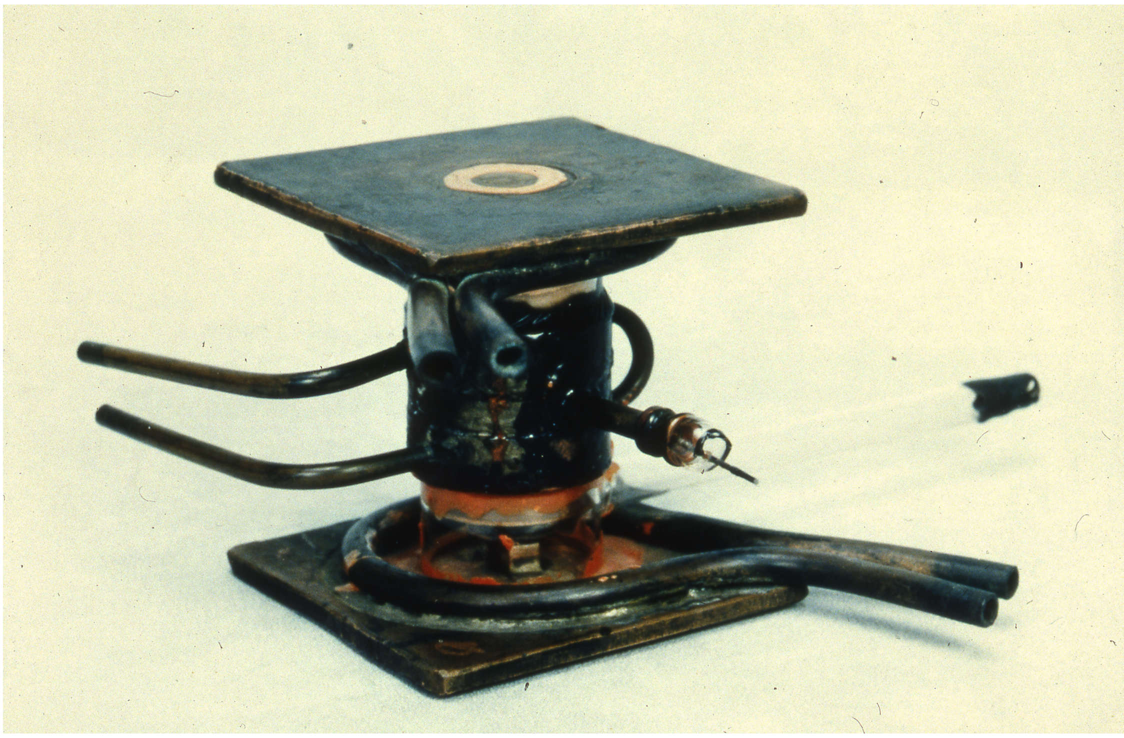


Fig. 93. The original resonant cavity magnetron developed by Randall and Boot at Birmingham. (University of Birmingham)

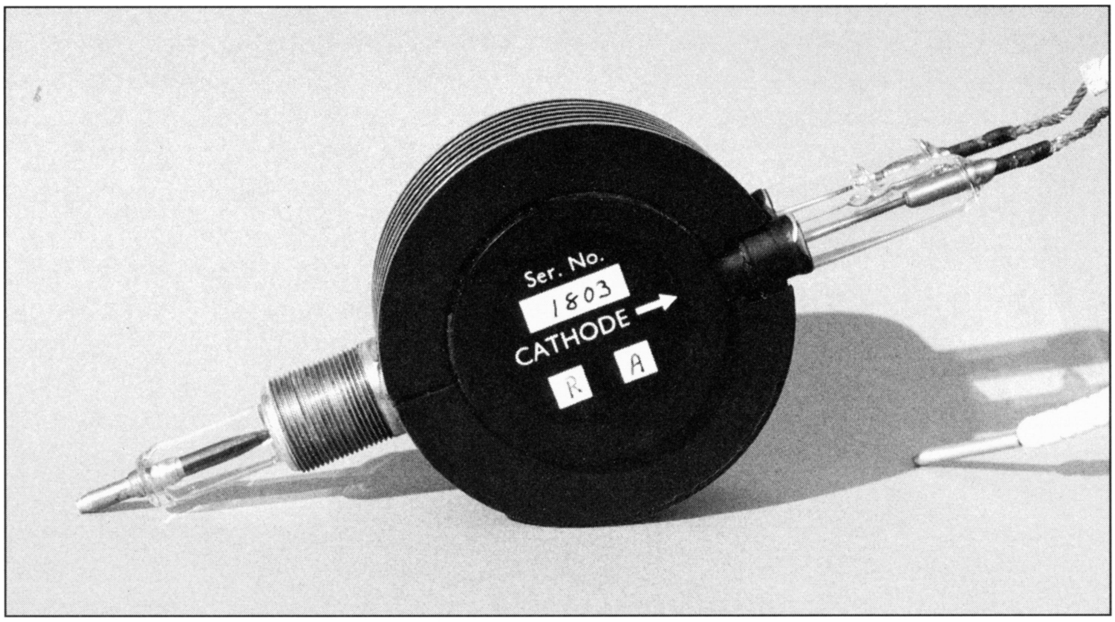


Fig. 94 Typical wartime production magnetron, after improvements by Guitton and Sayers at GEC. (Colin Latham and Anne Stobbs, *Pioneers of Radar,* Stroud: Sutton Publishing, 1999, p.83)

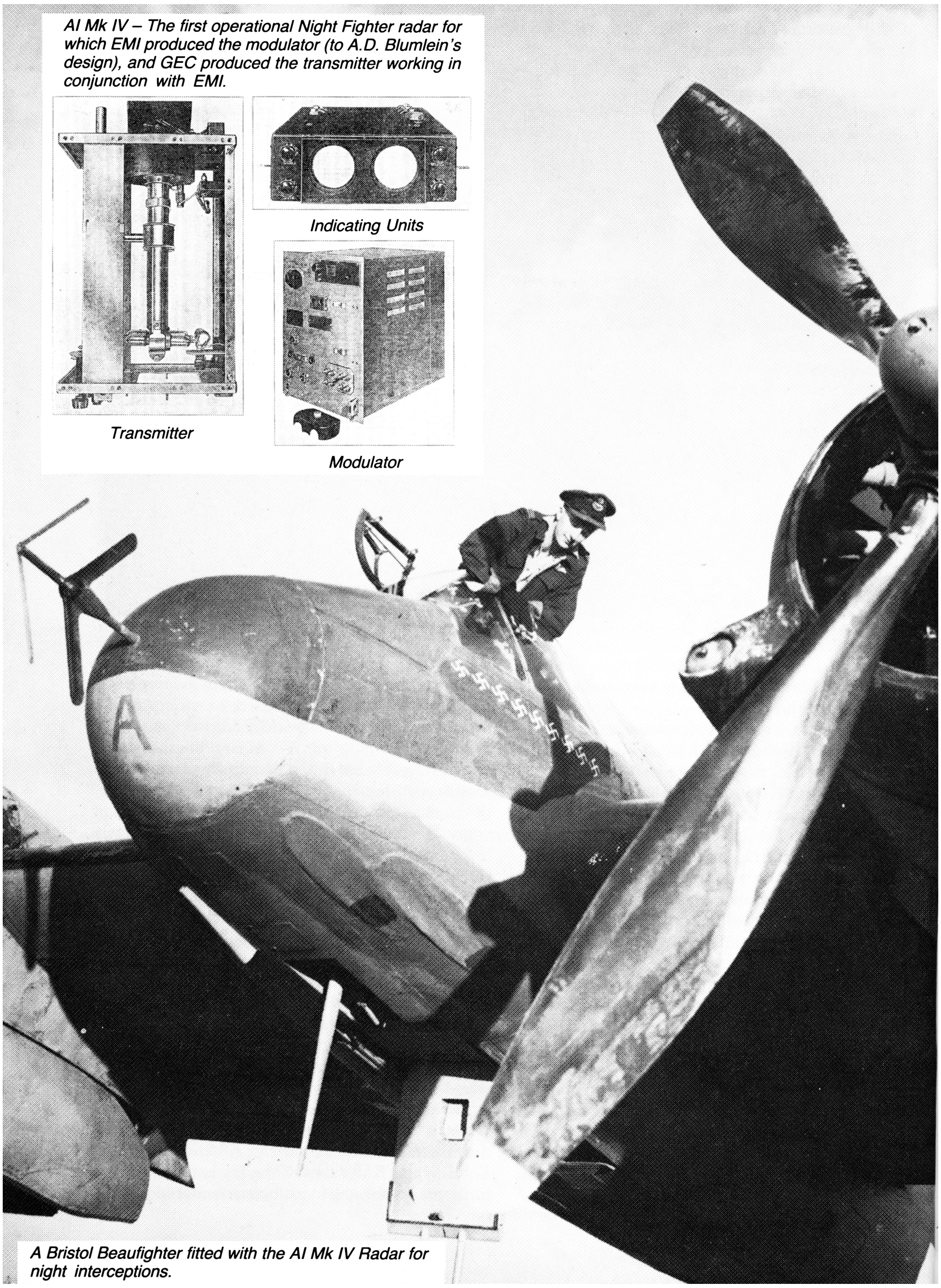
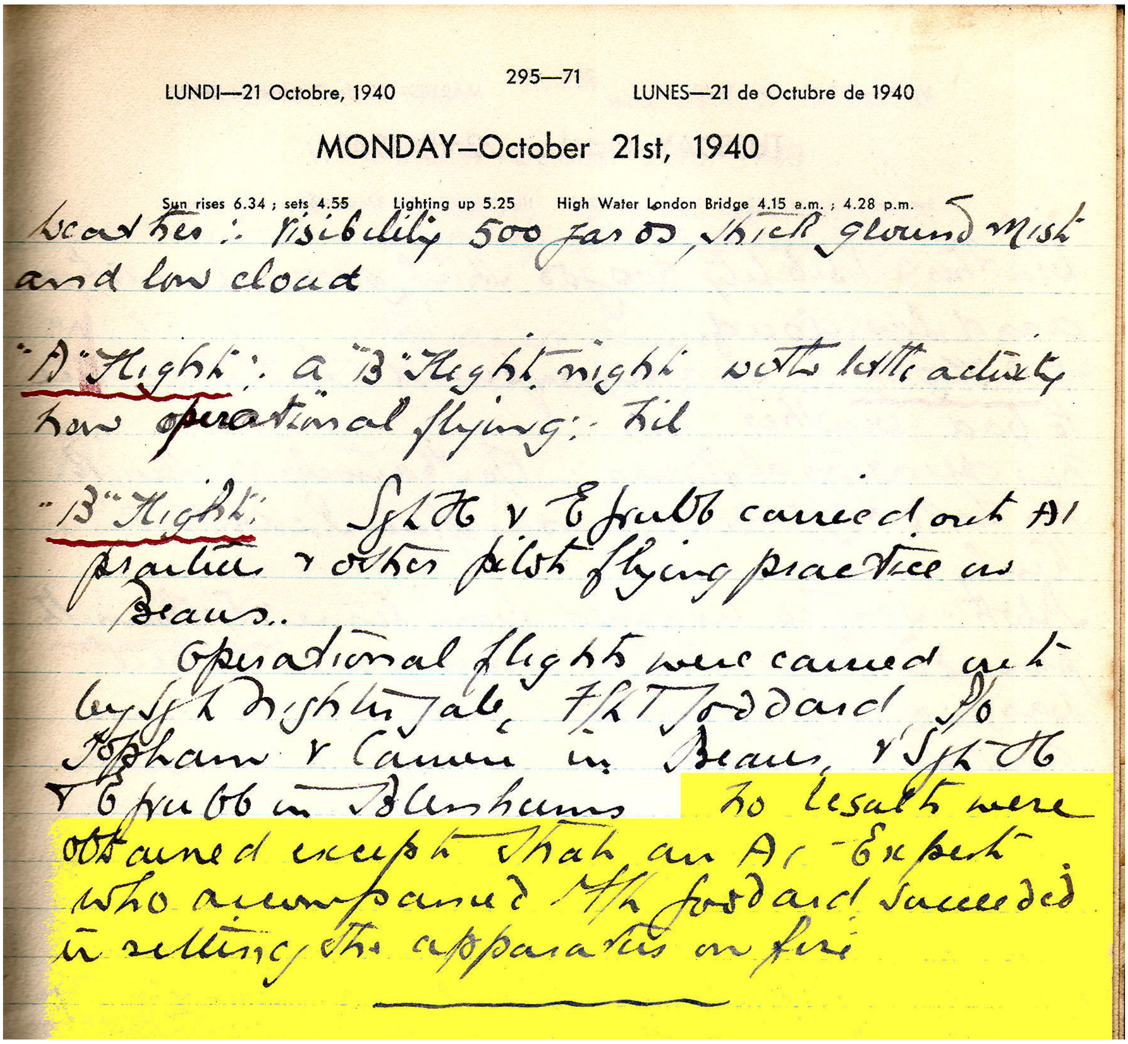


Fig. 95 AI IV units, showing the modulator, at top left; AI IV transmitting aerial in the nose of a Beaufighter, main picture. (D.J. Martin, in Russell Burns, *The Life and Times of A.D. Blumlein*, London: Institution of Electrical Engineers, 2000, p.336)

Fig. 96 Beaufighter with AI IV vertically-polarised aerials visible on the nose (transmitter) and wing (receiver). (Bristol Aeroplane Company /BAe).

Fig. 97 Defiant fitted with AI IV – the transmitter aerial is visible on the nearer wing. (Phillip Jarrett /Robert Jackson, *Air War at Night*, Shrewsbury: Airlife, 2000, p.46).

Fig. 98. Lunch at the “Square and Compass” (called the “Sine and Cosine” by the scientists) in Summer 1940 – from the left, Taffy Bowen, Robert Hanbury Brown and Alan Hodgkin. All three would become Fellows of the Royal Society, and Hodgkin a Nobel Laureate. (Colin Latham and Anne Stobbs, op. cit, p.158).



LUNDI—21 Octobre, 1940 | 295—71 | LUNES—21 de Octubre de 1940

MONDAY—October 21st, 1940

Sun rises 6.34 ; sets 4.55 | Lighting up 5.25 | High Water London Bridge 4.15 a.m. ; 4.28 p.m.

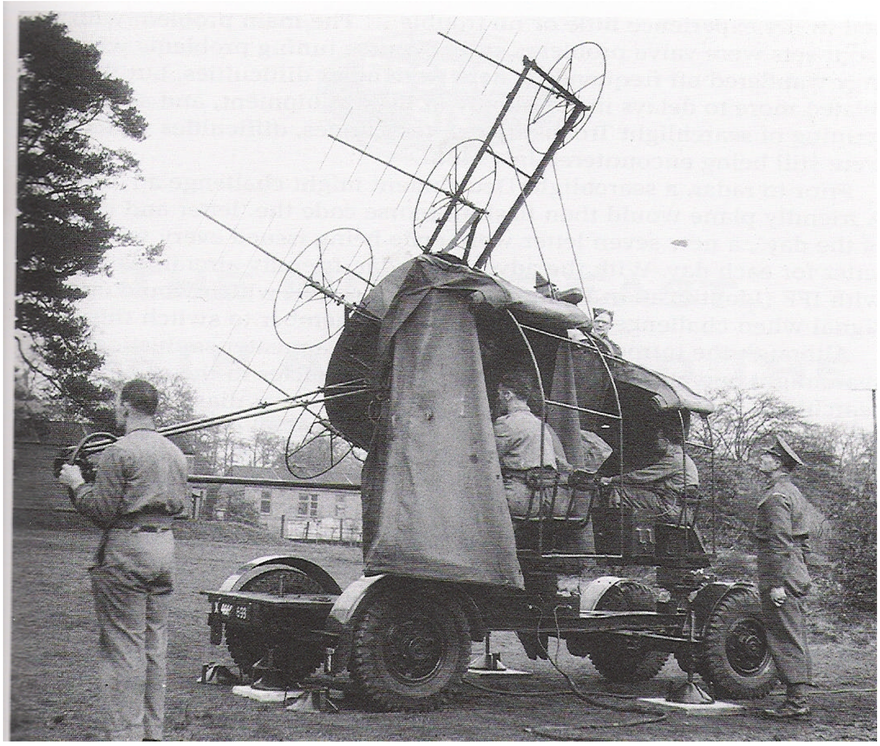
Weather: Visibility 500 yards, thick ground mist and low cloud

"A" Flight: a "B" Flight night with little activity
Non operational flying: Nil

"B" Flight: Sgt [illegible] & E Grubb carried out AI practice & other pilots flying practice in Beaus.

Operational flights were carried out by Sgt Nightingale, F/Lt Goddard, P/O Topham & Cannon in Beaus, & Sgt [illegible] & E Grubb in Blenheims. No results were obtained except that an AI "Expert" who accompanied F/Lt Goddard succeeded in setting the apparatus on fire

Fig. 99. 219 Squadron's original daybook, recording the visit from the Air Ministry's AI specialists. "No results were obtained except that an AI "Expert" who accompanied F/L Goddard succeeded in setting the apparatus on fire". The episode does not appear in the Air Ministry's notes of the visit. (Author's collection).



Figs. 100 a,b. Two views of the radar-assisted searchlight "SLC" (inevitably called "Elsie") (Upper view: IWM, London No. H35908; lower view: IWM).

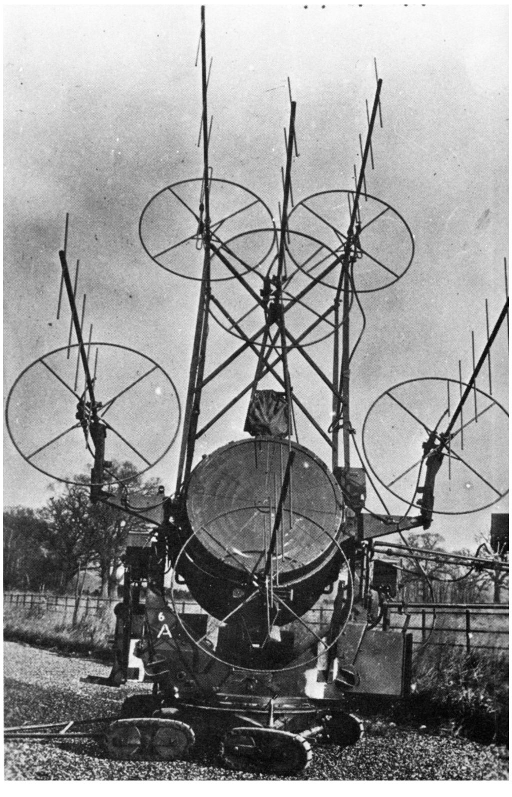


Fig. 101. The GCI radar installed at Durrington (Penley Archive, B/35).

Fig 102. The Operations Room at Sopley in its 1940 form, housed in a truck. (Penley Archive, B/39).

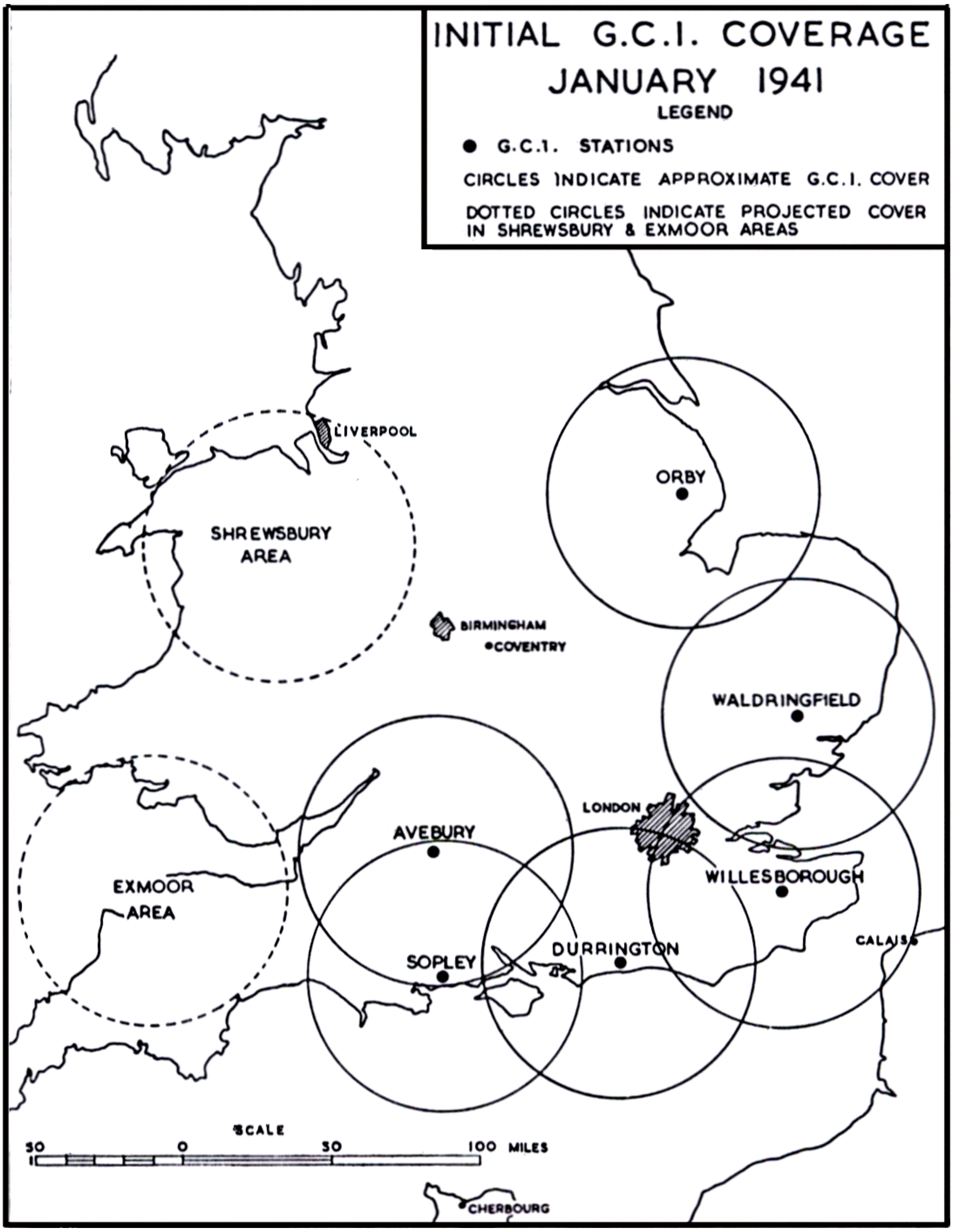


Fig. 103. The first six GCI stations to be opened, as at January 1941 (TNA/PRO AIR 10/5485 p. 190).

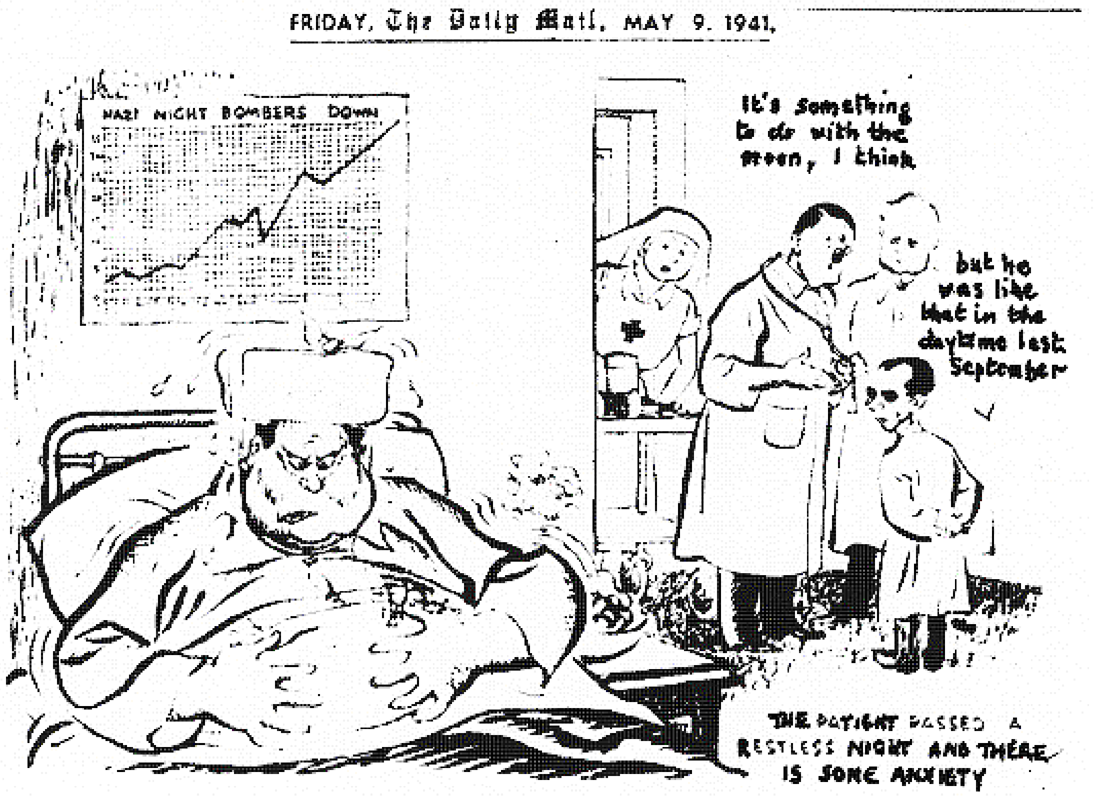


Fig. 104. This Daily Mail cartoon is typical of the period – the contrast with the day Battle of Britain contains a hint of reproof. (Daily Mail Newspapers)

VII.

DISCUSSION AND CONCLUSIONS.

VII.1. Introduction.

Current MoD acquisition thinking is based upon an acquisition model codified, extended and deepened since 1997 with each successive iteration of the MoD Acquisition Handbook[1]. That model is founded primarily upon experience in the UK, including experience of problematic acquisitions[2], and upon systematic thought applied to those experiences.

This thesis poses three major questions. First, does analysis of the history of the acquisition by the UK of a radar-based air defence system, 1935-41, validate that MoD model? If so, one supplementary question is whether, arising from this analysis, there may be identified yet further factors, not presently incorporated in the MoD model, which impact the successful delivery of a military capability. The second major question is whether the application of this model as an analytical tool to those events of 1935-41 offer useful insights, not only for the future practice of military capability acquisition, but also for historical study of such events. Finally, the question to be posed is whether the model might be applied to topics other than radar, and periods other than 1935-41.

The observation may first be made that today's definition of success in acquisition rests heavily upon the three pillars of "Time, Performance and Cost" (the "TPC Triumvirate"), and arguably upon the visible and quantifiable element of cost. In the case of the acquisition of radar, success came increasingly to be defined as the closely-related, but not identical, concept of readiness for the contingency of war. The contention may of course be advanced that time and performance are relevant to readiness for war, but this is true only with certain caveats:

- ?? "timeliness" in war depends significantly on the actions of the aggressor, rather than the defender. In the case of radar, fortunately the main daylight attacks were not mounted until nine months after the outbreak of war, and Chapter IV showed how critical the intervening months were for delivering day interception capability. For night interception, timeliness was of the essence, and the capability arrived too late.
- ?? "performance" in war is also partly in the hands of the aggressor, who may choose to employ tactics or devices completely unspecified in defence performance terms. A minor example is the German use of low-flying mine-laying aircraft; two significant examples are the German use by day of massive formations of bombers accompanied by fighters (defeated by the expedient of "macroscopic" plotting) and by night of radio-navigation beams (defeated in part by RCM).
- ?? Cost becomes less significant if national survival is at stake, but Chapters III and IV have shown that cost was never irrelevant in the acquisition of radar; only in the immediate pre-war months was cost constraint significantly relaxed, and by that time most of the lines of development which would determine success or failure were decided. Indeed, the cost relaxation may have been a negative factor – the Air Ministry's massive and counter-productive over-ordering of AI might then have been checked.

It is next appropriate to set the question of historical insights into an overall context. Many studies have been made of the Battle of Britain[3] and of the Blitz[4]. In the case of the Battle of Britain, these invariably make reference to the role played by radar in day interception, usually accompanied by a short description of the radar-based air defence system[5]. Night interception not having been conspicuously successful for most of the Blitz period, there are fewer references to radar in Blitz histories, which focus instead upon anti-aircraft gunnery and upon the courage of the civilian population[6]. Until relatively recently, Battle of Britain discussion focussed upon whether "Big Wings" were or were not a valid interception tactic[7]. Dowding's non-resolution of that tactical debate between his two squabbling subordinates (Park and Leigh-Mallory) was seen as a significant element in his removal from his post as C-in-C Fighter Command[8]. Indeed, publications on that theme continue to the present day[9]. However, academically, the seminal work by John Ray in his Ph. D. thesis, and his book which flowed from that research[10], re-directed interest to a new question – why was Dowding was unable to defend Britain by night, in the Blitz, as effectively as he had done by day, in the Battle of Britain. In its turn, that question has brought a sharper focus upon the technologies which underpinned the day success and the night failure, among which the most significant was perhaps radar.

One historian subsequently to examine the application of radar technology to British air defence in this period has been David Zimmerman[11]. Zimmerman's previous relevant publication was on the later experiences of Henry Tizard[12], a key personality in the acquisition of radar. A focus of Zimmerman's radar study was the 1936 clash between Tizard and his opponents Lindemann and Churchill. At that time, radar was still in its infancy and seen as a weapon primarily for day interception. Zimmerman's study therefore concentrates upon radar for day interception, primarily Chain Home, with only one short chapter (of thirteen) devoted to night interception radar and the Blitz[13]. There is also a lack of emphasis on a primary point, which is that from 1934 onwards Lindemann was essentially concerned with night interception and Tizard with day interception – the two rivals were "talking past", rather than "talking at", each other. The present thesis, therefore, is original in that, for the first time, the acquisitions of radar for day interception and for night interception are presented as the parallel events which in reality they were, affording equal treatment to each and explaining why one was successful and the other less so. Also within this thesis, the application of the same analytical model to both acquisitions has resulted in the identification of material previously untilled, for example the Touch memorandum[14], or unreferenced, such as the Essex Sites and Monuments Record of Silhouette sites[15], and newly-obtained oral histories[16], which have yielded new insights into both technological and historical developments.

VII.2. The Validity of the MoD Acquisition Model.

Before proceeding to discuss the lines of development which underpin today's MoD acquisition model, it is appropriate to examine a basic premise upon which that model is founded. This premise is that an acquisition should be of a military *capability* and not of an item of hardware or equipment[17]. It is instructive to apply that basic premise to the 1930s acquisition of radar-based air defence.

At its inception in 1935, the terms of reference of the Committee for the Scientific Survey of Air Defence were deliberately broad – "to consider how far recent advances in scientific and technical knowledge can be used to strengthen present methods of defence against hostile aircraft"[18] – and the subjects examined ranged from death rays to gunnery, missiles and searchlights. When radar was being shown to be practicable as equipment, the focus for day interception remained at the *capability* level – as early as autumn 1935, Tizard was structuring the Biggin Hill experiments to identify optimal tactics, communications and fighter location and guidance[19]. The emphasis throughout Chain Home's development would remain the creation of a working total system to create a day interception capability.

For the night battle, the objective began at the same level, the creation of a night interception capability. However, though Bowen visited both Fighter Command and the Air Ministry to discuss night interception[20], he received so little input that his focus quickly devolved into "develop airborne radar". This was not unreasonable, for such a project was a task appropriate to a scientist, with a scope suited to Bowen's level, and one which was vast in its scientific and technical challenge to him. At the elevated level of the CSSAD, where capability might be more properly be considered, there held sway first the Silhouette illumination scheme[21], then RDF 1.5, and subsequently the untested night interception "CH/AI" concept of "Chain Home ground control handing seamlessly over to airborne radar". However, for much of this time, at the research level Bowen was spending his resources on Air to Surface Vessel (ASV) hardware[22], or on its application to town finding and contour navigation. When in 1939 Bowen's team were re-focussed on AI, and in particular when Hanbury Brown began to work on night interception capability with 25 Squadron at Northolt after the war had started[23], the result was plainly a culture shock of the first magnitude for the scientists. It should be emphasised that the focus on airborne radar hardware from 1936-9 was hardly a fault to be laid at the door of Bowen, a Scientific Officer in his early 20's recruited directly after his Ph. D. Tizard in particular was too long reliant on the Silhouette alternative, but when that faltered, was culpable in not immediately testing the basic CH/AI interoperability assumption. The lesson to be drawn is that a change in acquisition focus from "capability" to "hardware" may indeed result in "*capable hardware*" (Bowen had developed the world's first airborne radar hardware, in both its air interception (AI) and air to surface vessel (ASV) applications – a dazzling technical achievement), but the *capability* actually needed, here night interception, may well not be achieved. In this case, the scientific analysis proving that ground control interception (GCI) radar was an essential component of a night interception system was not carried out until after war had begun[24]. In consequence, the night interception capability was not attained until spring 1941, after major damage to war industries and civilian casualties.

VII.3. Lines of Development.

Today's MoD acquisition model places emphasis on the need to plan eight "lines of development" to achieve a military capability. These lines of development were set out in Chapter I[25] and cover doctrine and concepts, infrastructure, equipment, sustainability, personnel, organisation, training and information, plus the overarching theme of interoperability. The applicability of each will now be assessed in the context of Britain's 1930s acquisition of a radar-based air defence system, balancing the lessons from both the successful acquisition of day interception capability and the less successful acquisition of night interception capability.

It is appropriate to begin by examination of concepts and doctrine. The strategic doctrine of the RAF was, in 1934, one of deterrence through the power of strategic bombing – the "Trenchard doctrine"[26]. The best defence against air attack was seen as bombing the enemy's airfields[27], and this applied whether the enemy contemplated day or night assault.

With the advent of the CSSAD and the success of radar development, the concept of air defence began to modify the RAF's doctrinal position, resource allocation and organisation structures – much, it should be said, to the annoyance of its "elder statesmen" such as Trenchard[28]. The concept of day defence was quite clear - the capability needed was interception by day fighters, which in turn demanded *inter alia* knowledge of the aggressors' location, course, speed and height, and a guidance system to bring British fighters to intercept them. The concept of night defence should have been identical, with the refinement of extra precision in that it is, and was in 1935, a known physiological fact that human beings do not see well in the dark. However, the impression remains that the RAF assumed that the doctrinal counters of airfield bombing and, if that failed, of searchlights and of the Silhouette system which so strongly resembled them, would suffice. There is an interesting inter-service comparison here; the Army, who knew that sound locators were inadequate to guide anti-aircraft fire by night, appear to have been more attuned conceptually to the help radar could give, and their introduction of GL radar forms one positive note in early WW2 night defence history[29].

Three lines of development are concerned with essentially physical aspects of radar – infrastructure; equipment; and logistics/ sustainability.

Infrastructural issues, especially where construction ("Works and Bricks") is involved, may have long timescales. Where infrastructural problems are neglected, therefore, we might expect acquisition of a capability to be delayed. There were relatively few infrastructural issues in the acquisition of day interception radar, for its sites were not large and the buildings upon them not complex. However, in two instances where insufficient attention was paid to infrastructural matters, delays did indeed occur; those instances were site acquisition, and aerial mast construction. As described in Chapters III and IV, site acquisition raised environmental issues, and opposition resulted in lengthy search for alternative sites and delays to the building programme. Aerial mast construction, however, proved more intractable. Watson Watt's early experience of mast construction had been straightforward, thanks to his capable assistant Joe Airey and his WW1 derived design, recorded in this thesis for the first time[31]. Because of this, Watson Watt was not anticipating problems; but subsequently the contractors Harland & Wolff, then C.F. Elwell[32], and later the turntable ladder specialists Merryweather[33], proved unable to construct suitable masts on time. The problem of sufficient stocks of seasoned wood for the receiver masts was also not foreseen, and recourse had to be had to Canada[34] when British timber was exhausted early in the programme. Delays in seasoning and importing meant that towers were still being erected in 1940, so that aerials were erected and calibrated just in time for the Battle of Britain. Indeed, in some instances calibration and phasing were carried out too late, as this research has also identified for the first time[35]. Additionally, the previously unregarded problem of defective aerial insulators, here recorded for the first time also[35], compounded the issue, for as the insulators absorbed moisture the aerials slipped out of calibration, and the entire process had to be repeated. The consequence was that the system was inaccurate for much of the Battle of Britain, but fine, clear days with long visual ranges often compensated for this.

Turning to the case of night interception, we may consider infrastructure to include the aircraft in which AI was installed. Here, lack of attention to this issue created a huge problem. Since the scientists did not know whether the night fighter was to be a single or a twin-seat aircraft, they did not know whether to design data displays for use by the pilot or for an observer. Since they also did not know the model of aircraft, they could not design the aerials and cable-runs with which to fit AI to it. Significant delays could be caused by design differences between different marks of the same aircraft; for example, between the "short-nose" and the "long-nose" Blenheim[36]. The overall result was to delay the introduction of AI significantly, perhaps by 3-4 months. A second infrastructural issue was the lack of adequate power supplies on aircraft. As described in Chapter VI[37], Bowen took unilateral action to resolve this issue by directly commissioning the high-cycle AC generator. However, although this was to become an RAF standard, it did not arrive in any quantity until late in 1940.

Specific equipment considerations in terms of radar development have been fully considered in the body of this thesis. The present discussion now reviews two more general aspects – the timely involvement of private industry, and the question of detailed contract specifications.

It is perhaps useful to state that the specifications in use at this period would today be regarded as a mix of a detailed functional specification (with industry left to conceive the means of meeting it) and of a technical specification/ blueprinted design (with industry left merely to construct). In the case of radar, the specifications identified, for example, operating frequency and sensitivity, together with power supply voltages available. The Government scientists then shared with the manufacturer their own ways of achieving the result, including key design data or parts, but left it to the manufacturer to develop their own ideas. Much of the body of the contract then dealt with details such as the colour finish for the equipment, valve life expectancy and component marking. However, in the case of the AI specification, neither input sensitivity nor weight constraints were detailed, and in what was perhaps a fatal error the order was linked with a much larger order for Army AA radars and Coastal Command ASV receivers, where in both cases input sensitivity and weight were not as critical as for AI.

It is a contention of Zimmerman[38], who refers in turn to the work of Corelli Barnett[39], that private industry should have been involved at an earlier stage of radar development, particularly on AI. One significant reason why this was not done was Watson Watt's opposition on the grounds of security[40], which is seen as mistaken, especially since his staff were neither production engineers nor electronic circuit specialists. However, the facts as set out in this thesis argue for a different conclusion. In the case of day interception radar (CH) detailed specifications were drawn up by Dixon[41], and discussions held with MetroVick and Cossors by the experienced G/Capt. Leedham[42] accompanying Watson Watt. The results in terms of CH transmitter and receiver hardware performed well. Night interception radar (AI) was allocated to the same two contractors, but they had little experience with airborne equipment. As illustrated above, there were no sufficiently detailed specifications, the contractors were left to their own devices with only a "talk-through" of the receiver and an out-of-date model of the transmitter, no visits were made to the factories, and Watson Watt, without reference to Bowen, ordered MetroVick to copy the out-of-date transmitter provided as a model. Unsurprisingly, the results were calamitous – the Cossor receivers were too heavy and too insensitive to use, and the MetroVick transmitter two years out-of-date[43]. By fortunate chance, the Pye receiver was available in quantity[44], and even though sometimes of indifferent workmanship[45] acted as a stop-gap, later evolving into a wartime standard.

Once war broke out, security was a lesser issue, and Tizard visited Dundee to instruct that contractors be brought in at an earlier stage, specifically as competition for the Government scientists and over-riding Watson Watt's and Rowe's opposition[46]. This had one positive and one negative result. The positive result was that EMI, the contractor included at Dowding's suggestion[47], employed the outstanding circuit designer Alan Blumlein[48] on the task. His ideas, coupled with EMI's production engineering, created the AI Mark IV, the standard metric-wavelength AI from winter 1940 -1942. The negative result was that Dowding's specification input through Harold Larnder, head of Fighter Command O.R., identified a fundamental design challenge as achieving a minimum range of 300 feet[49]. Though unchallenged by the scientists, this target was mistaken, being a figure for moonless nights. Pre-war trials by RAE had established that, on nights with at least some moonlight, a 1,000ft. range was satisfactory for night visual identification[50], and research by Bowen would later confirm that the night interceptions of 1940-1 were achieved with visual recognition at 1,200 – 1,500 ft[51]. AI IV indeed solved the problem, with a minimum range of 500 ft., by including an extra unit, a "modulator", but as Lovell comments "the introduction of the modulator solved a problem that did not have operational significance"[52]. In fact, as has not previously been observed, the Touch memorandum shows that Bowen tried and discarded the modulator in 1936[53], believing it to contribute unnecessary weight which could be better applied to the transmitter. Time and highly talented resources may therefore have been wasted in 1940 in achieving the AI IV result when what was actually required was a production-engineered version of AI III.

What is undeniable, as Lovell also comments[54], is that there was a skills deficiency among the scientists. The AI team had no circuit designer of the competence of Blumlein. This is perfectly true, but then most of Britain's radio industry had no-one of Blumlein's supreme competence either. Blumlein's talent has subsequently been recognised as of world class[55]. The lessons from this thesis are perhaps that the timing of private industry's involvement is of lesser importance than an accurate and fully-challenged specification of what the contractor is to achieve, and that a primary essential is a skills audit of potential contractors against the requirements of such a specification to identify what each might be capable of achieving. In the context of 1930s radar the questions are why Dixon, who had so successfully written the specification for CH[56], could not have been spared to challenge and validate the "500 ft." minimum range target, enquire whether MetroVick and Cossor had any design capability for airborne equipment, and draw up a detailed specification for an invitation to tender.

A subsidiary aspect of the equipment line of development which merits comment is an extension of Watson Watt's fears on security. Although considerable research was carried out on the foreign ownership and links of potential contractors – so that Marconi were excluded from aerial mast building, despite long experience[57] – there appears to have been insufficient research into the question of components being sourced from potential enemy nations. This led to the curious case of significant components being obtained from Germany, Austria (including after the Anschluss) and Italy, this last continuing to deliver components into 1940[58].

In terms of logistics, the issue most relevant to radar is the question of sustainability, and specifically maintenance. In the case of both ground and airborne radar, this necessity was ignored, and in both cases material problems ensued. Until early 1940, ground radar had but two storemen for the entire Home Chain, and there were neither component reference numbers nor any Stores Vocabulary[59]. The problem of maintaining the Chain on 24-hour watch with this frail support became evident in the earliest days of the war. The Drone Hill downtime recounted in Chapter IV[60] powerfully illustrates the problem. This was one element in Tizard's investigations, and ultimately in Watson Watt's removal from office.

When night interception radar is considered, the over-rapid introduction of AI Marks I, II, III, IIIA, IIIB and IV, all within twelve months, coupled with the lack of any maintenance infrastructure on the airfields whether of tools, testgear, or service technicians, combined with the absence of any production engineering on the early models to give a truly appalling record of serviceability. As has been commented by Hanbury Brown[61], supported by aircrew memoirs such as those of Rawnsley[62], and validated for the first time in this thesis by the unpublished logbook of 219 Squadron[63], airmen became dispirited about the serviceability of the equipment and despairing of any improvement.

Questions of skills and of motivation flow naturally into the area of those three lines of development which are concerned with human resources issues – personnel, organisation, and training. It is relevant here to note that each line of development may itself be considered as a "capability" having its own lines of development, so that, for example, a capability of training requires the infrastructure of training facilities, equipment on which to train people, personnel – trainers – who in turn need to be selected, trained and organised, and so forth. Without over-elaborating this analysis, certain of these sub-elements may conveniently be addressed in examining the human resources lines of development. A second aspect within these human resources areas is that there may be identified at least three distinct groups of individuals to analyse – the scientists; the aircrew; and the RAF ground staff, whether operators, filter room staff, or maintainers.

The personnel line of development embraces the provision of sufficient, capable, motivated people to deliver the outputs. Since the scientists were the first to be involved with radar, that group may conveniently be considered first of all. In terms of number of scientists, there was never a financial constraint. However, the protestations of Watson Watt[64] and of Rowe[65] agree in identifying recruitment of those numbers as a problem. Work on secret, non-publishable research for a low salary was unattractive to scientists and remained so.

Eventually, only the influx of scientists from the Cavendish on the outbreak of war resolved the problem. This it achieved at the cost of demotivation – these newcomers arrived at higher salary grades than many pioneers, and were accompanied by wartime high priorities which were frustrating to those who had struggled under peacetime constraints. As an example, Rowe, already himself promoted over the heads of Bowen and Wilkins and not well-liked by either[66], then appointed W.B. Lewis to be his deputy, rapidly promoting him also to Principal Scientific Officer[67]. This exacerbated the rift between Rowe and Bowen into a chasm, from which Bowen eventually escaped only through his membership of the Tizard Mission to the USA in September 1940[68]. Wilkins, always an undemonstrative man, quietly transferred to Watson Watt's staff in the Air Ministry[69]. How far the rift of Bowen and Rowe slowed the development of AI is difficult to quantify, but the opinion of the scientists is that it certainly did so[70].

The demands on aircrew differed between day and night interceptions. For the day battle, the numbers of single-seat fighter pilots and their role remained much as they had been, though with an emphasis now on following radio instructions rather than "free hunting" for the enemy. It might be noted in passing that, thanks to radar, the obviation of the need to fly standing patrols saved considerable wear and tear upon both fighter pilots and their machines. Indeed, this was one of radar's major contributions. In the night battle, however, the introduction of the radar observer to replace the gunner was a most significant change. The extremely ad hoc nature of the recruitments for this role, exemplified and described by Rawnsley[71], and the difficulties in converting gunners to the role attested by Hanbury Brown[72], contributed significantly to the delay in making AI operational. Eventually, a long-delayed relaxation of physical qualification rules for aircrew, thus allowing many academics to become radar observers, solved the problem[73]. Less remarked is a significant change in the role of the night fighter pilot, who now had to follow the instructions of the radar observer much of the time and so found his role "more that of a taxi driver than a fighter pilot"[74]. The meticulous and quiet "Cat's Eyes" Cunningham became the personification of that role, a world away from the ebullience of a Douglas Bader. Many bomber pilots – Guy Gibson is an example – became excellent night fighter pilots[75].

Many ground staff were also recruited into new roles from previously untapped sources. The most visible were the WAAF operators, whose exemplar is Daphne "Dill" Carne[76]. Recruited with ideally a mathematical or scientific aptitude, they operated the radar equipment throughout the Battle of Britain (CH, CHL) and the Blitz (GCI), including when under attack as at Ventnor, Poling, Rye, Pevensey and Dover. Equally important were the ex-radio and TV servicemen recruited to maintain the hardware. The radio counter measures (RCM) 80 Wing drew upon another source, that of pre-war radio amateurs[77]. In all these cases, the recruitments worked out well, even if never in the numbers actually needed at the time they were needed. However, the motivation of fighting to avoid defeat in the Battle of Britain, or to defend Britain's cities in the Blitz, was a powerful incentive helping to make up for deficiencies in numbers.

Training was a line of development which had been given early consideration, but was permanently under strain given the massive expansion of the use of radar in the early months of the war.

For the scientists, training, if provided, was rudimentary in the extreme. When radar was in its infancy, this was less of a problem – there was little theory or experience to learn and no-one was sure of any answers – but as war approached the problem was more acute. The Cavendish scientists had the benefit of a lecture from Watson Watt, a month on a Chain Home station with perhaps an operating manual to read, and possibly some time with a senior scientist such as Lewis[78]. After this, their learning was "on the job". Most muddled through and grew into their roles, with TRE eventually producing a significant crop of Fellows of the Royal Society who had gained from their experience.

Aircrew training for day interception was a regular feature of Fighter Command after the 1936 Biggin Hill experiments, and with Dowding's insistence on frequent exercises became a continuing part of a fighter pilot's daily life. Training for night interception, described in Chapter VI, did not even begin until August 1939, and because of the unreliability of the equipment was a motivational disaster until the Fighter Interception Unit was established in May 1940. Even at that late date, of course, GCI had not come into use, so that it was not until November 1940 that anything remotely resembling formal training for GCI/AI could begin. Much training, as Rawnsley points out[79], was gained simply by attempting to intercept German raiders.

The training of ground operators and maintainers was at least foreseen well in advance, and for day interception was carried out from 1936 onwards at the Bawdsey Training School under Hart[80]. Chapter IV has illustrated the problems which arose in 1939-40 due to the massive increase in demand, the consequent reduction of the course to two weeks, and the inevitable decline in standards. For the maintainers, by contrast, there were significant increases in training capacity, with the opening of Yatesbury, even though this was delayed because of the appalling winter of 1939-40[81]. The problem in this group was less that of training for technical competence than the poor nature of the Yatesbury facilities – an excellent example of the case where a line of development (infrastructure) supporting a line of development (training) needs forethought and advance planning.

The organisation line of development may conveniently be divided into the changing organisation needed to research, develop and produce radar; the changing RAF organisation needed to operate and maintain it; and the fluctuating boundary between the two.

Organisationally, as was observed in Chapter III, inter-war air defence research was, for 17 of those 21 years, a War Office and not an Air Ministry activity at all[82]. Wimperis had to tread very carefully to ensure that he was enabled to carry out research in this area, and CSSAD was formed originally purely as an Air Ministry activity under the Air Member for Research and Development, Dowding[83]. Only subsequently did it become a sub-Committee of the Air Defence Requirements Committee (ADRC) of the Committee of Imperial Defence, with a remit across all three Services. Its chair, Tizard, was an unpaid adviser to the Air Ministry[84]. The first true radar research establishment, Bawdsey, was a research station under the Director of Scientific Research, Air Ministry (Wimperis, then Pye) until

Pye's proposal to establish the post of Director, Communications Development (DCD), parallel to his own. This he proposed because the post had expanded in terms of responsibilities and had become anomalous in a research function – Watson Watt was then already responsible for major programme implementation as well as research. For comparison, the head of RAE Farnborough carried out research, but built neither aircraft nor airfields. When appointed to this broad role, Watson Watt appeared to make a positive start. However, his lack of attention to specific lines of development led to his downfall in December 1940, when he was moved sideways into the purely advisory role of Scientific Adviser on Telecommunications (SAT)[85]. The title of DCD continued as a programme management role under Sir George Lee, with production management becoming a separate directorate under G/Capt. Leedham.

The Air Ministry, who had set this reorganisation of the role of Watson Watt in train by appointing Air Marshal Joubert to the role of reviewing the organisational problems caused by radar[86], also accepted a second recommendation to establish an RAF Group (60 Group) to take over commissioning and maintenance for the Home Chain[87]. Because of Dowding's resistance, Joubert's third recommendation, for a Command to take over the running of the Chain from Fighter Command, was not implemented.

In May, 1940, the Air Ministry's production and development roles were transferred into the Ministry of Aircraft Production (MAP) established by Churchill and headed by his friend Beaverbrook[88]. The scientists' research establishment, at Worth Matravers, Swanage, thus became MAPRE, and Sir George Lee and G/Capt. Leedham both transferred to MAP. At the Air Ministry, user co-ordination, if not control, was achieved by Joubert's appointment as Assistant Chief of Staff (Radio), or ACAS (R). (The term "Radio" was confusingly used as a cover for Radar in 1940, radio for communication purposes being called "Wireless"). Joubert, an opponent of Dowding, was thus in control of providing all Dowding's radar support functions. Dowding, deprived since June 1940 of the scientific input of Tizard and exhausted by the Battle of Britain, would eventually be transferred from his role of C-in-C Fighter Command in November 1940, to be succeeded by Sholto Douglas.

The above structure and changes were common to both day and night interception radar. Within the RAF, the structure of the air defence system for the day battle was described in Chapter III. it is apparent from the diagram in that chapter that the necessary co-ordination node, the Stanmore Fighter Command HQ Filter Room, could become blocked by heavy traffic in the event of major raids[89]. That it did not completely do so in the Battle of Britain was a result of the work of the Operational Research teams in refining systems, procedures, equipments and organisations. However, towards the end of that battle, the Filter Room was becoming increasingly clogged, leading to demands from the Air Staff to Dowding to decentralise filtering. These demands became more insistent during the night battle, as it was considered that precious time could be saved. Dowding’s initial refusal, and subsequent extremely reluctant implementation of change, became an element in the Air Ministry’s desire to remove him.

For the night battle, the most significant organisational (and equipment) failure of all was the lack of appreciation on the part of both scientists and RAF chiefs that an intermediate radar would be needed between Chain Home and AI for night interception to succeed. This failure is only explicable if it is borne in mind that both scientists and airmen believed that such schemes as Silhouette would work, and that later, if they did not, that Chain Home could direct fighters sufficiently close to their target for AI to acquire it. Given that CH could not be more accurate than 4-5 miles, that AI had a maximum range equal to the aircraft’s altitude, and that most raiders flew between 10,000 and 15,000 ft. (2-3 miles) it is difficult to see why the CH/AI hypothesis was not thoroughly tested before late 1939. GCI radar was developed over December 1939 – October 1940. On its arrival into service, tactics for using it had then to be worked upon, so that the night interception rate began to improve only after January 1941.

The information and communication line of development was an area of triumph for day interception. C4I was not a possibility, given that the computer had yet to be developed, although we may note that the CH Electrical Calculator would quickly develop into a tool speeding the communication of the CH plots to the Fighter Command Filter Room. However, in the field of C3I, the day air defence system, refined by Operational Research, was at the very boundary of what was possible in 1940. Incorporating radar plotting, optical and then electrical automation, dedicated voice lines, radio D/F by "Pipsqueak", IFF, filter rooms, and increasingly VHF ground/air and air/air communications, the system was unique in the world and exceptionally effective in battle as a rapid command, control, communication and information system.

At night, the system was not effective. There was no IFF on GCI or AI frequencies until very late in 1940. "Pipsqueak" cut off intercom between pilot and radar observer for 15 seconds in every minute, necessitating VHF R/T which was in short supply during the Battle of Britain. The fact that GCI radar did not enter service until after October 1940 meant that there still had to be developed the interception routines to match those of the day fighters, and night interception routines differed greatly from those of the day battle. The GCI Controller guided individual, not mass, interceptions, and followed both fighter and bomber on a single data display, the while giving instructions to the fighter of higher accuracy and more frequently than for day interceptions – by day, the eye could see a mass of attackers ten miles away, but at night the need was to detect a single attacker at 1,000 ft range. By May 1941, after many delays, the night interception system had achieved a degree of refinement, unfortunately six months too late to mitigate the effects of the Blitz.

Today's MoD acquisition model has interoperability as its "overarching line of development", and in this area the day interception system was supreme. Radar, IFF, radio D/F, "Y" Service, Observer Corps, filter rooms, fighter controllers at Command, Group and Sector level, and squadron pilots and ground staff engaged in a practised routine which permitted the RAF Signals History to boast that "no major raid was ever missed"[90]. The quotations by Churchill and Galland on the title page of this thesis are proof that in the eyes of both the attacker and the defending national leader, the interoperability of the system was its cardinal virtue. Germany possessed superior radar technology, and had indeed managed successful day interceptions of British bombers; but there existed no comprehensive air defence system grounded upon radar anywhere else in the world in 1940.

For the night battle, the system was fatally flawed. Due to neglect of lines of development, one key piece of equipment, GCI, and its part of the organisation were absent until October, 1940. A second, AI, was unreliable in operation. No trained aircrew or operators existed until too late, no ground organisation had been developed for GCI, and no service engineers were in place for the aircraft equipment.

In summary, it will be apparent at this point that the MoD acquisition model based upon lines of development is indeed validated by the British acquisition of a radar-based defence system in 1935-41. Where lines of development were then respected, considered and planned, that acquisition was successful. Where they were not, it failed in the sense that it did not work, or did not work effectively, or worked but too late to deliver the capability required. Where specific elements of one or other line of development were omitted – as for example the infrastructural case of supplies of seasoned wood for receiver towers in 1937-8 – delay occurred.

VII.4. Beyond Lines of Development.

It is now appropriate to consider whether the study of the acquisition of radar, 1935-41, identifies specific features over and beyond those of the eight lines of development of today's MoD model.

There are, of course, limits to the comparisons which may be drawn when reviewing a 1930s acquisition by application of a modern frame of reference. As was commented in Chapter I, the fact that lines of development are based upon experience rather than a present-day theory argues that examination of the acquisition of radar in terms of lines of development is not anachronistic – indeed, the contemporary RAF Task Plan/ Manning Plan process described by John James[91] employs much of the same methodology. However, any extension of the analysis into detailed comparisons of modern procurement processes and organisations is clearly inappropriate – there was no concept of whole-life plans in 1935, for example – and lessons must be drawn at a higher level.

Such lessons may be considered under four main headings:

- The involvement of private industry;
- The personality and experience of key individuals;
- The key decision points of the acquisition process, and
- The concepts of affordability and trade-off.

Considering first the involvement of private industry, the history of 1930s radar illustrates that merely entering a contract with private industry was not the major Air Ministry challenge. That challenge was, in fact, managing the timely provision of lines of development in order to convert the delivered product into a capability.

Within the process of outsourcing, then accurate specification of the deliverable was the most critical element. Where such specification was provided, as for example by Dixon for ground radar, the outcome was successful. Where it was not, as in the case of AI with MetroVick and Cossor, the result was disastrous. However, even when the task was specified and within the competence of a proven contractor, the result was not always success – the experience with Harland & Wolff, C.F. Elwell and Merryweather on aerial masts are examples.

This leads to a second insight related to the use of outsourcing. The experience of the EMI AI Mk. IV contract has led some[92] to the view that private industry should have been involved earlier in order to bring in a circuit design expert such as Blumlein, there being no electronic engineer within the AI team. As identified in Chapter VI, this is an incorrect conclusion – Blumlein was a world-class expert, but the mere act of contracting-out does not of itself secure world-class experts. Contracting-out the same AI work to MetroVick and Cossor and subsequently to Ekco and Pye, had not been a total success. The correct conclusion to draw is that *both* a specification *and* a human skills inventory were required, both for the Air Ministry interface team and from likely contractors, to be certain that the required skills existed in the private firm proposed, and that they could be effectively managed. The *timing* of the external contractor's involvement was not the critical factor – the *human skills available* were.

Turning to consideration of the personalities and experience of key individuals, it must first be noted that there is likely to be some interaction between an individual's precise role and the personality and experience best suited to that role. Given the observation above, that complete identity of roles between the present MoD model and the 1930s is not realistic, there is therefore a limit to the conclusions which can then be drawn from 1930s personalities and their experience. Nonetheless, certain high-level conclusions may be derived.

For the majority of the timespan of this thesis, Watson Watt performed a role similar to that of today's Integrated Project Team Leader (IPTL). It is greatly tempting to state that Watson Watt's personality – mercurial, verbose, self-important, unstructured, inattentive even to major detail[93] – was in no way suited to such a disciplined role. Such a view contains considerable truth, but omits the necessity in the early stages of a new technology to "sell" its capabilities and motivate its researchers. Both scientists and airmen rated Watson Watt's contribution in 1935-7 highly on these counts[94]. Once rudely shaken by the disaster of the 1936 Air Exercises, and compelled to give up such diversions as his trade union activity, he performed well enough to be promoted DCD in 1938, and made a good start in that role.

The insight to be drawn from his subsequent fall is the need to consider a "lifestage" model of acquisition, wherein distinct behaviours are appropriate at different stages ("lifestages") of today's whole-life acquisition process. If we review this hypothesis against radar acquisition history, the "marketing" style of a Watson Watt might indeed be appropriate at the early stages, to be followed by the measured and meticulous style of a Rowe. As major building and delivery became crucial, then the lifetime experience of GPO programme management of a Sir George Lee became more relevant. Finally in the full flood of radar in 1942-3 there was need for the overarching personality and capabilities of one Sir Robert Renwick, Chairman of the London Electricity Company, who is still seen today as the outstanding "acquisition manager" of radar by both airmen and scientists[95]. The argument would then be to ensure the proper selection and turnover of IPT "lifestage managers" by regular career planning reviews of performance and capabilities against the lifestage of acquisition of the capability. Such visible career planning reviews might also act to motivate IPTLs, for their role is a lonely one, within which it is easy to make powerful enemies.

Not only the role of the IPTL should be considered, however, in terms of personality and experience requirements. In the case of the two most senior 1930s personalities, Tizard and Dowding, today's roles of Senior Responsible Owner (SRO) and of Equipment Capability Customer (ECC) would be most closely comparable. Certainly Tizard as "SRO" was in contact with all the stakeholders and saw it as his responsibility to ensure that lines of development were being considered, at least for day interception. He could not of course spend money or give orders, for his position was that of unpaid adviser. In personality terms, Tizard is described as sociable and good company at all levels, with a fund of WW1 stories[96], but an excellent listener and humble in offering his views. He was also obviously perfectly capable of fighting his corner in Committee, as witness his successful defence when ambushed at the July 1936 ADRC by Lindemann and Churchill[97], formidable opponents who had been secretly briefed by Watson Watt.

Tizard's personality worked well with that of Dowding, who is generally described as aloof, sceptical, territorially sensitive and likely to be persuaded by logic rather than by orders or by ebullience[98]. Dowding, not a "clubbable" man in any way, was disliked by Watson Watt, whom R V Jones records as pleased at Dowding's removal[99], and who explicitly refuses in his memoirs to list Dowding as one of "radar's four supporters"[100], which given the courtesies of 1950s memoirs qualifies as a major insult. Tizard was Dowding's essential intermediary. One potential lesson is that the personalities of SRO and ECC should be compatible, but not such as to create undue dependency – Tizard's acceptance of Silhouette, then of RDF 1.5, and finally that Chain Home would be accurate enough to work with AI to deliver night interception capability perhaps gave Dowding unjustified confidence until too late, and Tizard's departure in June 1940 highlights the danger that the absence of one or other of such "compatible but dependent" partners may leave the other dangerously exposed.

Previous experience may also be as important as personality. Chapter III illustrated that the airmen most involved – Dowding, Freeman, Joubert and Douglas – all had extensive experience of the Air Ministry Task Planning/ Manning Plan process, of managing training, and of significant staff positions[101]. By virtue of his WW1 research experience and of his DSIR secretaryship, so did Tizard[102]. Watson Watt had not – his managerial responsibilities at the Slough laboratories never exceeded 50 people, and he had never procured a major system[103]. This does not argue that such an individual should be debarred from leading a major project, but rather that training in programme management disciplines would then be essential, and in the 1930s such training did not exist. One consequence was that Watson Watt lost control of certain elements of his role, such as planning for sustainability, and this contributed to his removal when the consequences became visible. Joubert, probably by experience the most "human resources minded" of the airmen, devised and implemented the service organisation structure which then coped with the ensuing problems. By this stage, day interception radar was a working entity, albeit with many flaws. Night interception radar, given that the need for GCI had only just been crystallised by Hanbury Brown, was by then beyond being implemented before the Blitz, no matter what the organisation or the experience of the participants.

Review of the key decision points of the 1930s acquisition of radar is also instructive. Some writers[104] have given the impression that radar was an acquisition wherein finance was never allowed to be an obstacle; this was not so, and this history has identified its financial checkpoints which bear comparison with "proof of concept", "initial gate" and "main gate" stages.

At its inception, it was Dowding, Air Member for Research and Development, and so top level budget holder, who insisted upon the "proof of concept" test, the Daventry experiment, before the initial £10,000 for research was granted[105]. After the September 1935 CSSAD, Watson Watt's paper proposing the Home Chain was presented, including staffing estimates for manning the stations[106]. Sir Warren Fisher did then give a £1 million approval on behalf of the Treasury[107] – but it was clear to all parties that this "Initial Gate" approval was simply approval in principle. As stated in Chapter III, defence as a whole carried only modest priority in these early days of radar development. Detailed costings had then to be prepared and properly supported, and after the unsuccessful Air Exercises of 1936, "Main Gate" approval was not given until 1937[108]. (In a reflection of today's experience, not all the costs were fully explored at that time). There followed a series of Air Ministry submissions, Treasury rejoinders and queries, and Air Ministry justifications, throughout the acquisition of Chain Home[109]. At each revision, there was a financial reckoning at high level, and beneath it there was constant challenge and debate on, for example, staff salaries, including Watson Watt's own[110]. Only with the advent of war did this process relax and radar receive an absolute priority, approved first by Chamberlain and again later by Churchill. Pre-war radar acquisition never held a "regardless of cost" status, and possessed a programme cost review structure recognisable today.

Review of finance within the acquisition structure leads naturally to consideration of the question of affordability and trade-off. In this context it should not be forgotten that radar in its early stages was itself a trade-off, being part-funded by the cancellation of the Thames Estuary acoustic mirror scheme[111]. The CSSAD itself acted as a "trade-off" review body from 1935-9, for it considered and resolved upon the feasibility, and if practicable the timescales and cost, of every scheme which presented itself for the air defence of Britain[112]. This did not mean that it necessarily took the correct decisions. The Silhouette scheme is one example of this - the case to the Treasury eventually included statements of the value of the project to the electrification of farms![113] Trade-offs in the field of radar continued throughout the war, although they were often forced by considerations of shortage of components or lack of US supplies than for financial reasons. As an example, the development of the centimetric AA gunnery radar GL Mk. III was delayed for a year by a trade-off[114], Lindemann having calculated that the number of radio valves (then in short supply) required could furnish bombing radars which would cause more damage to Germany than the damage which would be caused to the UK by the number of German planes likely to be shot down with the aid of GL III. In this case, the potential fallibility of trade-off calculations in war was demonstrated by the arrival of the V-1 cruise missile in 1944. Since the V-1 pursued a straight and level course, it was eminently suitable prey for radar-directed AA guns. The British were fortunate to be able to secure sufficient American SCR584 gunnery radars and predictors in time.

VII.5. Insights into Acquisition.

From the present thesis it is now possible to identify a range of insights into the acquisition of military capabilities. These may be categorised under two headings – new insights into existing debates and the existing acquisition model; and novel insights which extend beyond those boundaries.

At least five significant insights into existing models and debates may be distinguished. These may be described as follows:

?? Not only must the acquisition challenge always be initiated as the delivery of a capability, not merely of hardware, but *persistent effort must be devoted to maintaining that capability focus.* The AI team focussed too soon upon airborne hardware delivery, and the need for the necessary ground-based precision radar, GCI, was thus not identified until too late. CSSAD, if no-one else, should have acted to redirect their attention to night interception capability. This in turn illustrates a second point:

?? *"Maintaining a capability focus" in the early phases of acquisition contains a hidden danger of committing resource to simplistic alternatives to novel technologies*, and especially so when the simplistic alternatives involve no new operational concepts, doctrine or tactics. In the case of night interception capability, Silhouette offered a seductive alternative to the "long shot" of radar. It was seductive because it involved no new challenge to the RAF, whether in equipment, tactics or training. The result was that far too much time, thought, faith, resource and attention was devoted to a blind alley, because of the mental commitment given to Silhouette. One can sense in Tizard's previously unreferenced account of his May, 1938 meeting with Dowding[115] the dawning horror of Tizard as he realised the materiality of Dowding's observation that modern monoplane fighters had so large a wing as to block the pilot's downward view, a factor not realised by Tizard as his WW1 experience had been with biplanes where the downward view was far better. Silhouette provided an unjustified level of comfort which slowed attention to the need to test the details of how AI would work in practice.

?? *A consequence of the overarching status of interoperability in the acquisition process is that key interoperabilities must be tested as early as possible.* The assumption of CH/AI interoperability lingered until late 1940. More rigorous early testing would have illustrated its complete impracticability, and so forced the earlier development of GCI.

?? *The management challenge for a Service is not procurement, but managing lines of development: where private industry is to be involved, the Service challenge is "competency based acquisition" - both accurate contract specification and, critically, a skills audit of the contractor.* The experience of 1930s day interception radar shows that where lines of development are respected and the Service readied to receive the capability, then the capability will probably be attained. The experience of night interception radar shows that when lines of development are neglected and the Service is not ready, it will not. The same acquisitions show that the issue is not simply one of using private contractors. Certainly, with a proper specification, satisfactory equipment will be delivered (CH), while without a proper specification, it will not (early AI), but the greater need is for a skills audit. EMI had the genius Alan Blumlein who developed AI Mk IV, but Cossor, also a capable private firm, had no equivalent and produced unusable AI receivers, even though its ground receivers were excellent.

?? *The personality and experience of key participants, SRO and ECC as well as IPTL, are important but complex factors. The need is for "Lifestage" analysis of the acquisition process and identification of suitable personality/experience profiles in a career planning group context, avoiding the creation of personal interdependencies.* In the earliest stages of radar, Watson Watt's enthusiastic personality and radio direction-finding experience were positive, but as the programme grew his inattention to major lines of development almost destroyed attainment of day interception capability. The personalities of Dowding and Tizard worked well together, but this created a significant dependency upon Tizard by Dowding. When Tizard failed to insist upon testing the CH/AI combination, and later when Tizard felt compelled to resign after his disbelief in the German radio-navigational beams was proven wrong, Dowding was left exposed. Today, and for the future, career planning groups positively managing the inevitable turnover of IPTLs, SROs and ECCs, and matching the skills, experience and personality of individuals to each lifestage in the acquisition process, may help to minimise such issues.

Novel insights which extend beyond the boundaries of existing debates and models are twofold, with each such insight interacting with the other:

?? *Mental Visualisation Overstretch.* Even today, when the acquisition model has been codified and computer systems can be developed to underpin its application, the complexities of the linkages and dependencies within the acquisition of a major capability rapidly exceed the capacity of even an intelligent and focussed individual to comprehend. Without such codification and computing aid, the key personalities of the 1930s nevertheless performed astonishingly well. This is particularly praiseworthy when it is remembered that for the two key participants the acquisition was one among many responsibilities.

At the inception of radar, Dowding was AMRD, procuring many other capabilities, and hardware such as the Spitfire and Hurricane. Later, when C-in-C Fighter Command, he was managing and revitalising a major operational command under extreme time pressure, and in 1940, he was directing the Battle of Britain.

Tizard was throughout 1935-40 simultaneously chairing CSSAD and also the equally onerous Aeronautical Research Committee of the CID, where he was, for example, championing the jet engine and new aviation fuels. His paid "day job" was as Rector of Imperial College.

Plainly, one insight would be to allow key individuals to focus full-time on the task in hand – not always easy, for competent individuals are often much in demand. More practically, today, the development of a standard acquisition team structure and related software for each lifestage of an acquisition would assist in the avoidance of information overload.

It might immediately also be noted that, given the point made above that each line of development gives rise in turn to its own subsidiary lines of development – as exemplified in the discussion on training, where infrastructure such as training schools, personnel such as trainers, equipment such as simulators, etc., were identified - the problem of mental visualisation overstretch would again be compounded. However, a further insight identified by this study complicates the issue still further:

?? *Dysfunctional diffusion.* From a technological perspective, radar can be seen as a "metatechnology" – that is, it can be coupled to other technologies to achieve a capability. So, for example, when coupled to an AA gun, it can achieve "kills" of faster aircraft, at night or above cloud. When used in a fighter aircraft, it provides interception capability at night or in foul weather. When used with a ground beacon, it provides navigation.

In the earliest stages of a metatechnology, where all applications remain to be discovered, there is the potential for an explosion of such applications in a very short timeframe. In military applications, with the onset of war, this timeframe will be the more compressed. However, to deliver a capability, each of those potential applications will possess lines of development which, if ignored, will vitiate or delay the achievement of the capability. At the same time, when a metatechnology is embryonic, the number of specialists knowledgeable enough to develop those applications will be small.

Consider now the case of 1930s radar. Once the concept was proven viable, the extension to night interception through airborne radar was a considered move, even if poorly implemented. So also was the War Office's application of radar to AA gunnery. But the further extension of radar to air-to-surface vessel use went beyond the original concept. This was then compounded by ASV radar's use for navigation by Coastal Command's using an IFF set as an improvised beacon, and then further complicated by the adaptation of ASV radar to Naval vessels by Mountbatten, begun as a local initiative.

The consequence was that the AI team, always small, was distracted from the desired capability of night interception by developing ASV for fifteen months in 1937-8 - fifteen months in which the CH/AI ground control system might have been conceived, tested and found wanting. In addition, in late 1939 the AI team were rushing to fit not only 21 AI sets to Blenheims, but also ASV sets to a wide variety of Coastal Command aircraft (Hudsons, Whitleys, Sunderlands, even the Walrus) each model requiring its own unique aerial and cabling systems to be devised.

A second instance is that of the War Office's Coast Defence (CD) radar. When it was discovered to be useful against low-flying aircraft, it became the RAF's Chain Home Low. When optimised for detecting U-boats, it became the Navy's CDU. Further development made it the RAF's Ground Control Interception (GCI) radar. An initial consequence was a demand explosion and scrambled attempts at "crash programmes" of manufacture such as that of Cockroft. The further result was a lack of testgear, manuals, trained operators, overload of communications circuits and a problematic serviceability record. The implementations eventually succeeded, but primarily by over-stretch of the human resource.

Today's emphasis is upon acquiring a capability rather than hardware precisely so as to stimulate novel approaches rather than source hardware replacements. Therefore, novel technologies and metatechnologies may well arise, and fall prey to precisely the same problem of excessively broad and rapid diffusion as radar – "dysfunctional diffusion", in a phrase. It may be timely to employ this study as an opportunity to pause and reflect how acquisition may best cope with this issue, for the historical analogy of AI/ASV radar illustrates an instance where it did not, and the results were material war industry damage and high civilian casualties.

VII.6. Insights into History.

Radar was a technology bred for war, and the present study therefore illuminates a number of areas of military history. Failure in war is likely to lead to harsher insights than success, and so it is in this case – there are aspects of the Battle of Britain which might have worked better, for reasons obvious even at the time, but the preparation for night air defence was so catastrophically deficient that major and systemic lessons may be highlighted.

Considering first the daylight Battle of Britain, it may seem churlish to point out flaws in an air defence system which, whatever its imperfections, worked well enough in summer 1940 to gain a significant victory. Nonetheless, this thesis contends that there are three areas insufficiently emphasised by previous studies – first, that much of the equipment used owed little to Watson Watt's group; second, that certainly on the South Coast, the area of the Battle, the radars were not working effectively, but could have been so with a little earlier thought; and third, that the air defence system was held together by its human links as much as by its technology

It will be apparent from this thesis that Watson Watt's team did **not** develop several significant components even of the radar elements of the day defences – the War Office scientists were responsible for the highly successful Chain Home Low (CHL) radar from which GCI would also develop, for the anti-aircraft gun-laying (GL) radar, and for the Mobile Base (MB) radar which equipped the Advance Chain Home stations in 1938; RAE Farnborough designed "Pipsqueak"; RAF Signals developed the radio D/F system and the "Y" intercept service; and the much-derided RAF Works and Buildings Department designed the aerial masts eventually used by CH after contractors had conspicuously failed to do so. Later, RAF 80 Wing were responsible for developing their own RCM equipment to defeat the German navigational beams. This is not to say that CH was not an outstanding achievement – it was – but that the many other elements which go to create a *capability* have not received their proper share of the credit.

During the Battle of Britain itself, this thesis has identified that the South Coast stations, partly due to defective aerial insulators, were not adequately phased or calibrated so that their bearings were likely to be in error by as much as 17 miles at a 50 mile range. The potential effects of this were mitigated by the combination of their plots with those of other sensors in the filter room, and the application of human judgement there; but there is little doubt that the Home Chain could have been fully operational, phased and calibrated, earlier than was the case, and for reasons which need no hindsight – the issues were apparent in the 1930s. It was questionable, at the least, to leave Watson Watt to spend time on national trade union activities as late as September 1936, and a bizarre misuse of time that he and the scientific staff should have employed themselves on manufacturing aerial feeder. Most inexplicably of all, even though scientists complained about the inflexibility of the RAF stores procedure and lack of test equipment and tools, no-one seems to have made the connection with the fact that the introduction of CH into service would require such problems to have been solved on a much larger scale.

The importance of the human judgement of staff throughout the system, and particularly of those within the Filter Room, the unsung cornerstone of the entire system, has never been properly appreciated. This thesis has emphasised that radar was one, sensor, component of a system, and one among many sensors. Radar was undoubtedly the critical long-range sensor, but it was not without non-trivial faults – as the South Coast experience shows - for which its human operators' judgement had to make amends. This, coupled with the fact that IFF was late in delivery (meaning that friend could not reliably be distinguished from foe), threw extra burden upon such other sensors as the "Y" service and the Observer Corps, and upon the Fighter Command Filter Room to resolve the conflicting plots from the whole, before passing the result to the Operations Room. The "just in time" nature of some key decisions affecting the human resource is exemplified by the fact that the first trained officer filterers arrived for duty just days before the Battle, a late timing which is little short of astonishing. Dowding, as ultimately responsible for the total system and as knowing its failings intimately, was perfectly correct not to consider the decentralisation of this key component of filtering early in 1940 – to have done so would have been to have lost the Battle.

The night battle is a catalogue of acquisition failure, with multiple and inter-related problems. However, it is a contention of this thesis that, possibly because of the bias among published memoirs, historians have focussed attention on an incorrect component in the air defence system. By maintaining a focus upon night interception *capability*, this research has identified that, though it is certain that AI could have been delivered earlier, AI was not at the root of the 1940 night interception problem – GCI was the "missing link" between CH and AI, and is that fundamental problem. If the question then to be posed is whether GCI could have been delivered earlier, two dependencies would have had to have been in place for that to happen; first, the need would have had to be identified, and second, the equipment would have had to be developed. Of the two, the cardinal issue is that of recognition of need. In turn, this could have originated only from testing the interoperability of the CH/AI configuration. Such a test did not need to wait for war - the inhibitors were the continuing development of the Silhouette alternative, the supreme confidence of Watson Watt (and through him, Tizard) that CH could guide night interceptions, and the diversion onto ASV of the AI team, among whom Hanbury Brown, himself a pilot, could have realised the need to test CH/AI. The development of GCI hardware once the need was identified would have been perfectly possible. Bowen had in 1935, and again in 1938, proposed just such hardware (the “radio lighthouse”, as he termed it) but had been told by Rowe that Watson Watt wanted no further work on it, in Bowen’s view because it was “seen as a competitor to RDF1” (Chain Home). Fortunately the Army carried on “beam technique” research, their CD radar becoming CHL and the basis for GCI.

With the insights already discussed, current debates on night interception – the “need” for early involvement of private industry in AI, the “deception” practised by Bowen on Dowding in July 1939 – may be regarded as debates on non-relevant topics. If consideration is given to the whole system and its lines of development (the need for interoperability, for a Service trained and ready to receive the hardware, etc) then the need for GCI to be properly conceptualised and introduced – the fundamental problem - may be seen to originate long before such “1939” debates.

Instead, perhaps because the AI team have produced four books and one significant memorandum of memoirs while the GCI team have been silent, perhaps because it is easier to grasp airborne radar as a concept than the less obvious need for ground control radar, night interception debate has hinged around AI. In particular, it has focussed upon AI’s minimum range requirement, now identified as a “problem with no operational significance”. Brought in earlier, EMI could no doubt have produced the AI IV weeks earlier – but in the absence of GCI, to little operational purpose. By contrast, had EMI and Blumlein been mobilised on GCI development in 1937, major operational results might have been achieved with even the indifferent AI III – at a minimum, the aerial polarisation issue would have been solved. There is in fact a file reference to bringing in private firms to work on “beam technique”, a tantalising prospect which was never implemented. The fact appears to have been that Tizard’s visit to Dundee in December 1939, to insist that private contractors were brought in, caused Rowe and Lewis to attempt “in-house” answers without first challenging any of Fighter Command's requirements – more particularly, Larnder's (head of Fighter Command O.R.) insistence on 300 ft. minimum range. Had they done so, they might have discovered both that the 1,000ft. minimum range was based on RAE experiments, and that Larnder had a record of acting without necessarily consulting Dowding. Air tests might then have resolved the issue, saved unnecessary work on an irrelevant project, and focussed effort on GCI.

Turning to the question of Bowen's "deception" of Dowding at the June 1939 AI trials, Dowding is here supposed to have been so impressed by a claim of a "sensational" advance on the minimum range problem that he sought AI to be produced in numbers, even in an unsatisfactory state. This in turn proved to be self-defeating, diverting Bowen's team to being fitters from research, and introducing to service three Marks of such poorly engineered AI equipment (AI I, II, and III) as to cause aircrew to lose faith in it. There are four arguments against this:

?? Dowding wished only to order 3-4 sets for trials. It was the Air Ministry, advised by Watson watt, who ordered in numbers, and who continued to do so for many months;

?? Dowding was not naïve nor was he easily impressed by scientific claims – he had been Air Member for Supply and Research for five years (1930-5), had demanded the Daventry experiment before giving even research money to radar, and had constantly been sceptical of Watson Watt's claims. He had also seen the calamitous 1936 Air Exercise results;

?? Dowding knew the time it would take to bring equipment into service, and knew how much work remained to produce an interoperable system – with war obviously looming, he would have been ordering AI in any event, and would have been in breach of duty not to do so;

?? It is likely that Bowen's reported "sensational advance" was Touch's technique of "quenching" which did indeed reduce minimum range, but Dowding had more than enough experience to regard such "sensational advances" as gains which might or might not yield the claimed benefits in operational equipment.

He had, after all, had five years experience of Watson Watt's ebullience by this date;

Surviving scientists and engineers who knew Bowen are also quite clear that he would never engage in "deception".

All such questions about AI and its potential early delivery must also be balanced against the key fact that there was no useful RAF platform on which to mount the equipment. The Blenheim had been found by its crews to have been too slow to catch the German bombers; and the Beaufighter was not yet ready in quantity. There would therefore have been limited benefit in an early delivery of effective AI and its installation in too slow a fighter, even supposing there had been some miraculous method of overcoming the other lines of development problems in a matter of weeks – lack of trained aircrew being the most obvious.

However, this objection would not apply to the early delivery of GCI. Ian White's study of night fighting successes[116] at this period has shown that the "Cat's eyes" (non-radar) day fighters, despatched as a measure of desperation in the Blitz, did achieve results better than those of the AI equipped fighters until almost the end of this period. Had "Cat's eyes" fighters been directed by an effective GCI from September 1940 – only three months before GCI was available in numbers – operating with the knowledge then available of where the German navigational beams were set each night, then very positive results might have been achieved. Such a defence would have required far less in the way of lines of development than AI, and could have been carried out without diverting any resources from AI's introduction.

The military debate, this thesis argues, should centre upon a new contention, the failure to make an early test of a key interoperability and so identify GCI as critical. Bowen is guiltless of any part in this failure – he had proposed the "radar lighthouse" in 1935 and again in 1938, and been instructed that no work was to be carried out on it. The failure rests above his level; it must be laid at the doors of Watson Watt, Tizard and Dowding. Watson

Watt was possessed of the view that CH was capable of guiding interceptions, and plainly did not feel disposed to test this. Tizard had already tested the key interoperabilities of day interception radar, and yet inexplicably did not test those for night interception radar with the same rigour – he was committed to Silhouette. Dowding, who had participated in the Biggin Hill experiments and so had a template for what tests might be needed for night interceptions, did eventually carry out the necessary CH/AI tests, but too late – in late 1939 – and on too small a scale, allowing hopes of CH/AI to linger von until October, 1940, supported by Watson Watt.

Seen in this light, the tragedy is truly Grecian. Throughout 1937-8, Tizard, an unpaid adviser for all this work, and attempting to hold down three jobs, carried out day interception tests but, probably relying on Watson Watt's judgement, did not carry out those for night interception. Tizard was pursuing Silhouette during this time, and night interception seemed adequately covered. Dowding relied upon Tizard's judgement, and did not carry out independent tests – he was at this point focussing on bringing the Hurricane and Spitfire into service, and making day interception a reality. Bowen meanwhile was concentrating on ASV radar – successfully, certainly, but a diversion from considering problems of how night interception would actually be achieved. Watson Watt was concerned with driving forward day interception radar to meet ever faster programmes; night radar, he believed, would be taken care of by CH and AI. When the realisation began to dawn in November 1939, with Hanbury Brown's report and Tester's experiments, Rowe and Lewis commissioned work on the PPI display through Dummer, but this would take months to yield results. In May, believing that AI was the key if only Dowding's demands on the minimum range problem could be met, and uncertain of their own solution, they mobilised EMI and their leading British circuit genius, Blumlein, onto the problem. The result was an outstanding solution to a problem of little operational significance. By then, Dowding knew through Tester's experiments that the CH/AI solution was wanting, but he knew also that the GCI solution would take months, and he knew the problems of introducing AI. He was at that point deprived of his scientific adviser, Tizard, who resigned over the German beams. Dowding had thus simultaneously to oversee the Battle of Britain and to develop the night interception capability. The remaining senior radar experts, Joubert for the RAF and Watson Watt for the scientists, were both opposed to him. Only the Air Ministry, whom Dowding saw as his opponents, achieved a success, for it was their Signals team who detected and countered the German radio-navigational beams. Rowe's scientists worked hard throughout the Battle of Britain to produce GCI, but it was not ready until too late. In EMI, Blumlein's genius had focussed on the AI minimum range challenge – an irrelevant problem. At the start of the Blitz, Dowding could only offer the option of persisting with AI. Because the need for GCI had not been identified earlier, he had no other option for guiding "cat's eye" day fighters. The very success of day interception radar in the Battle of Britain caused civilians to question why night air defence was not more effective. Radar was still a secret, and so Churchill could give the public no answers. Dowding's refusal even to consider any other option eventually caused Churchill to withdraw support, and Dowding was transferred against his will from his command. Only after GCI was in place could the lines of development be worked through, and it was as late as spring 1941, with the combined introduction of the fast Beaufighter, of AI Mk IV, of GCI, of understood tactics and of training for aircrew, that night interception capability was achieved. By then, the Luftwaffe was already moving to prepare for Barbarossa, the invasion of Russia; by then also, the war industry damage and the civilian casualties had been sustained. The long shadow of the Silhouette alternative, and then the failure to test one assumption, of interoperability, and to develop one item of equipment, GCI, had had major consequences of civilian deaths and damage to war industries.

VII.7. Further Work.

This thesis has tested the current MoD acquisition model against the 1935-41 acquisitions of the day and night air defence capabilities provided by the then-novel technology of radar. It has confirmed the validity of that model from the history of those two parallel acquisitions, one successful (day interception radar) and one less so (night interception radar). Specific insights have also been identified from this research which may extend the applicability of the MoD model both for today's acquisitions and as a tool of historical analysis.

One paper arising from this research and illustrating the application of modern acquisition theory to the specific case of Bowen and the "deception" controversy, was presented as the 2007 Spring Lecture of the Defence Electronics History Society at DCMT Shrivenham. There was considerable interest in both the approach and the conclusions, and a desire for further work on this basis.

In continuation of this approach, therefore, one topic of considerable current interest is the examination of personality factors most appropriate for the holders of key posts in the defence acquisition process – for example, whether specific leadership qualities are required by an Integrated Project Team Leader. Historical research offers the opportunity for examination of such topics without the complex difficulties of researching individuals currently holding such posts. Accordingly, three papers are in preparation for presentation to the Bawdsey Radar Trust, and these analyse the personalities and roles in radar acquisition of:

- Churchill, Tizard and Lindemann;
- Tizard, Dowding and Watson Watt;
- Watson Watt, Rowe and Bowen.

The presence of a common personality to each pair of talks provides a deliberate linkage to the examination of the process from different levels.

Preliminary work has identified many further possibilities for research arising from the potential of applying the MoD acquisition model, ranging in scale from research into individual details of research note length, to specific topics for papers, to more general theses. To gain the benefit of a structured approach and maintain the validity of such continuing research, it is desirable to progress by analysing situations where, initially, as few of the characteristics as possible are changed, and then proceed gradually to situations of significantly different characteristics. Such characteristics include timeframe, technology, capability, process and international dimensions. Two examples of such more general theses have been the subject of feasibility examination:

- ?? The development of radar acquisition 1941-5;
- ?? The industrialisation of intelligence 1939-45.

The development of radar acquisition 1941-5 would extend the scope of the existing thesis throughout World War 2, and involve analysis of the developing characteristics of:

- ?? Capability, for radar is then applied to offensive purposes such as bombing in addition to defence;
- ?? Technology, as microwave radar succeeds metric radar for many purposes;
- ?? International dimensions, since US acquisition, manufacture and supply to the UK become highly significant;
- ?? Process, since all three Armed Services are now fully involved.

During this period, significant process developments take place as the scale of radar acquisition becomes massive and the technology becomes mature.

The "industrialisation of intelligence" refers to the establishment of the large-scale SIGINT and code-breaking activity centred upon Bletchley Park and the German Enigma and Fish codes, whose decrypts were known as ULTRA. The electrical and electronic technology to achieve this has been studied and published, as have the uses to which the decrypts were put and the biographies of certain key personalities such as Turing. The area which has not, so far, received academic attention has been the creation of a 10,000 person organisation built around electronic technology, including arguably the first electronic computer, to provide the Allies with a volume intelligence capability. Interestingly also, a number of radar personalities moved into this area after 1941. The applicability of the MoD acquisition model and lines of development to the acquisition of this capability offer the opportunity for significant insights into this proto-computer-based acquisition.

Today's acquisitions are of course highly desirable as subjects for analysis, but a number of practical questions such as security clearance, ability to publish and commercial sensitivity arise. An approach to present acquisitions is likely to be a time-consuming process which will be addressed after concluding work on the existing thesis.

VII.8. In Conclusion.

The Battle of Britain and the Blitz are both now passing into the state of legend and myth. The first comprehensive examination of that developing mythology was carried out by Angus Calder as long ago as 1991[117], and during his review he makes several pertinent observations about the 1952 film *Angels One-Five*:

> "There is no suggestion that this battle belongs solely, or even chiefly, to the young Knights of the Air. What is foregrounded is the brilliance of British Method, based on "radiolocation" (radar). … There are only brief … episodes in the air: we see much more of the Ops Room, and stress is laid on the strain felt by Squadron leader Clinton in charge of that, rather than any weariness among the pilots. The Ops Room girls plot accurately the course of battle. The Ops Room guides pilots intelligently to their targets. Out numbered six to one … the RAF family are seen to be defeating "him" by superior discipline and method.".

Most interestingly, and a point missed by Calder, the shooting down of the central pilot figure takes place when the radar plot used to guide him suddenly "jumps" ten miles leaving him, from a position in which he could attack, in a position where he will be attacked; the Controller gives the impression that this is not uncommon. The pilot is duly shot up, but attempts to regain his airfield, In the best tragic tradition there is no dramatic on-screen violence; his radio messages as received in the Ops Room simply fall silent. The system thus takes over even the recording of its human components' deaths, even as it ensures their victory. The film acts as a depiction of the overall capability of the system – a depiction including its faults and their consequences – and as a result, as Calder comments, "its modesty now seems excessive". It is unique to see an acquired capability, with flaws, as opposed to some lionised personality, becoming mythologised, and it therefore forms an apposite conclusion to this thesis.

VII.8.

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II.6. TV Programmes, Video and DVD

The Secret War, a documentary originally made for BBC TV (BBC TV Enterprises, 1988) Producer Brian Johnson. Vol. 1 (of 4) covers radar, German navigational beams and British countermeasures.

The Watson-Watt Centenary, a video version of the lecture by Professor R. Hanbury Brown, FRS, delivered at the Institution of Electrical Engineers on 22.2.93 (Robert Fisher, Brantham, Manningtree, Essex).

Weren't those Great Days?!, a compilation of original Telecommunications Research Establishment WW2 films taken and restored by Douglas Fisher, one of TRE's wartime photographers (Robert Fisher, Brantham, Manningtree, Essex).

II.7. Internet

As explained in Chapter II, the bulk of internet sites mentioning radar history are derivative from material already published in the references cited; those (disappointingly few) offering original material used in this research are cited below.

Professor Hartley's paper on 'The Economics of UK Procurement Policy' cited above was accessed from www.rmc.ca/academic/poli-econ/idrm/papers/Hartley-2.pdf on 7 November 2007.

The Hulsmeyer study by Arthur Bauer in www.cdvandt.org, previously www.xs4all.nl/ was accessed on 14 February 2007.

Silhouette sites in Essex were downloaded from www.unlockingessex.essexcc.gov.uk/, the Essex County Council Sites and Monuments Record, where the sites are mis-identified as "floodlights"; the site was accessed on 18 August 2006.

The papers by Russell Burns listed above were accessed from www.newcomen.org on 14 November 2006.

Staff lists of the Telecommunications Research Establishment were accessed from the Penley Radar Pages, www.penleyradararchives.org.uk, on 3 November 2005.

APPENDIX A
THE UK MINISTRY OF DEFENCE ACQUISITION MODEL

A.1. Introduction

The objective of this Appendix is to introduce the non-acquisition specialist to the acquisition model developed since 1997 by the UK Ministry of Defence (MoD), and to introduce those concepts and technical terms related to that acquisition process which are discussed in the body of the present thesis.

In 1997-8 the then newly-elected UK Labour Government conducted a Strategic Defence Review[1] and introduced therein a "Smart Procurement Initiative". The MoD defined the term "Smart Procurement" in 1999[2] to mean

> "a better way for the Ministry of Defence to decide what equipment is needed to carry out the defence tasks required of it, and how the equipment or service should be procured, supported and improved while in service, and safely disposed of at the end of its life".

It was explicit in the same document[3] that one driver behind Smart Procurement was time and cost over-runs as identified in National Audit Office reports[4]; three other drivers were also listed. The first of these three was the changing nature of the threat to the UK following the end of the Cold War. The UK was felt now to be facing less predictable threats, and its military a broader range of tasks, including aid to civil powers, famine relief etc, so that new solutions and new technology needed to be deployed more quickly. The second driver lay in the increased complexity and diversity of defence equipment, necessitating greater flexibility and responsiveness in defence acquisition. Finally, mergers and alliances within the defence industries themselves necessitated new relationships with industry.

Three elements within the Smart Procurement Initiative are referred to within the present thesis. These are the emphasis on “Capability”, the concept of “Lines of Development”, and the process and organisation relating to “Through-Life Capability Management”. Each is now separately considered.

A.2. Capability.

Smart Procurement laid great stress on the need to think primarily in terms of acquiring a capability, and then secondarily of the equipment required. To take a trivial example, if the military challenge is to cross rivers, then the military capability needed is that of moving troops and their kit across stretches of water, but the equipment needed could vary from aircraft for a parachute drop, through helicopters, landing craft, transportable boats or amphibious vehicles, to portable bridging equipment or indeed teaching troops to swim. This last of course would require no equipment at all, but would not cover how equipment might be moved across water.

Three lines of argument leading to the “capability emphasis” may be discerned. The first was the increasing move to actual warfighting for UK Armed Forces, whose role during the Cold War had often been deterrent, enlivened by occasional expeditions such as the Falklands or counter-insurgency operations as in Northern Ireland or Belize. However, even by the time the Strategic Defence Review was published, UK forces had already been actively engaged both in the Balkans and the Gulf, and those operations underlined the need for increasingly broad and effective capabilities to be developed for the unexpected and the unforgiving environment of warfighting.

In parallel with this, the increasing rapidity of technological change, most apparent in information/communications/computing technologies and their enthusiastically swift adoption in the civilian sector, appeared to offer the MoD innovative solutions. One example was, and continues to be, the prospective use of Unmanned Aerial Vehicles (UAVs, “drones” such as the UK’s Phoenix) both for surveillance and indeed for strike missions deep into hostile airspace without risk to expensive aircrew or even expensive aircraft.

A final but significant driver was cost escalation. The most physically obvious items of military hardware – warships, aircraft, tanks, missiles - were displaying significant cost increases with each new generation of equipment. Simply replacing existing equipment on a “1 for 1” basis was becoming excessively expensive, and the Treasury were eager to identify novel solutions which might reduce costs.

In line with this emphasis, the UK MoD developed its organisation to specify military requirements in terms of capabilities, and to set down the results in priority rankings in a rolling 10-year plan which had to be affordable. The pivot of that new organisation was titled the “Equipment Capability Customer” (ECC), which was intended to work through Capability Working Groups of relevant stakeholders. The emphasis of the work of these groups was made explicit:

> “Many procurements proceed on the basis of an assumed solution, resulting in concentration on equipment performance rather than system and user needs. Smart requirements moves that focus to the needs of the users by defining “what the users of a particular future system will need”[5].

The ECC, therefore, was as “customer” to think primarily of capabilities; the Defence Procurement Agency (DPA), successor to the Defence Procurement Executive, was to act as the “supplier”, placing orders with industry for equipment to provide the specified capabilities.

The ECC can be seen as the successor to the pre-existing MoD Systems area, and was headed by the Deputy Chief of the Defence Staff (Equipment Capability) with four two-star

Capability Managers (for Manoeuvre, Deployment, Strike, C4I/ISTAR), reduced by 2004 to three (Precision Attack, Battlespace Manoeuvre and Information Superiority).

Within the DPA "supplier" area, there was after 1998 established a classical form of project team, the Integrated Project Team (IPT), headed by an Integrated Project Team Leader (IPTL). The IPT was originally conceived as managing the acquisition process from beginning to end; however, in reality, once the equipment entered service, it was conventionally passed from the DPA to the Defence Logistics Organisation, which operated a distinct IPT structure. The process followed today is further discussed below; the concept of "Lines of Development" is now addressed.

A.3. Defence Lines of Development.

In the early stages of Smart Procurement, the MoD emphasis continued to be that equipment was the central component of acquiring a military capability. Certainly, it was recognised that equipment demanded maintenance, repair when broken, upgrades over time, and support; however, the early procurement emphasis was still on the equipment itself and upon the specification of such equipment considerations as "Technical Readiness Level", designed to highlight the technical risk of acquiring a new capability, and self-evidently applicable primarily to equipment.

Nevertheless, even at this stage, representatives from such areas as Doctrine and Personnel were members of the Capability Working Groups. As experience developed – and perhaps as there became public such unwelcome experiences as the problematic introduction of the Apache Helicopter[6] in which personnel and training factors were materially involved – then it became increasingly apparent that the MoD would have to think rigorously about *non-equipment* elements which had a direct linkage to equipment ordered by the MoD and supplied by industry.

It is relevant at this point to observe that the importance of human-resource related factors (personnel, organisation and training) had been incorporated in, for example, RAF planning since the 1930s[7]. At that time, the RAF operated a Task Chart/Manning Plan system whereby, if for example a new aircraft type was to be introduced, a process of working backwards from the effective (in-service) date through all the tasks necessary to achieve this (e.g. training pilots, ground crew and maintainers) flowed through to a level of detail whereby, as an example, the need for qualified surveyors to investigate sites for training schools for ground crew was quantified, and timescales for recruiting them established.

A second relevant observation is that management tools already in use by the MoD at this time, in particular the PRINCE 2 methodology[8], reinforced the need to address these non-equipment factors. PRINCE 2 was itself based on PROMPT II[9], a methodology adopted by the Government's Central Computing and Telecommunications Agency in 1979 for all Government information systems projects. PRINCE succeeded PROMPT II in 1989, with PRINCE 2 being launched in 1996, shortly before the Strategic Defence Review.

There was, therefore, both a lengthy history and a developing pressure which caused attention now to be focussed upon a series of factors beyond Equipment and those elements immediately associated with it, such as Logistics and Infrastructure.

There were, however, countervailing pressures within the MoD[10]. Each of the three Services had long traditions of autonomy; but the Equipment Capability Customer created in 1999 demanded that this be set aside, the military leaders being obliged to think in terms of what was good for defence, not necessarily what was good for their Service. That same ECC organisation controlled not only requirements specification, but also, and critically, finance, giving it the power to decide what would be done immediately, what might be done later, and what would never be done. Any tendency to move towards an ECC additionally controlling human resource aspects – personnel, staffing and training – was successfully resisted by the Services in 1998-9, the ECC being constrained to the equipment domain.

However, the exposure to public scrutiny of the problems involved in introducing the Apache Attack Helicopter[11] stimulated yet further thought. Historically, pilots in the Army were essentially involved in transport; the Apache Attack Helicopter by contrast demanded attributes more akin to those of RAF ground attack pilots. As a result, selection and training would take far longer (as also they would for the maintainers, faced with more complex equipment) - but the MoD acquisition team decided they could achieve a better financial deal if training provision was tendered separately from procurement of the helicopters. The result was that timescales for building the helicopters proved far shorter than the timescales for training the pilots: the helicopters remained embarrassingly in storage for many months, visibly useless, until the trained pilots and maintainers were ready.

Against this background, by January 2004 the MoD Smart Acquisition Handbook[12] listed six “lines of development” which were necessary for delivery of a defence capability:

?? Equipment;

?? Infrastructure;

?? Logistics;

?? Personnel

?? Training;

?? Doctrine and Concepts.

Within two years, this list had been expanded to eight by the inclusion of Organisation and of Information, and was in October 2005[13] codified as:

?? **“Training**: the provision of the means to practise, deliver and validate, within constraints, the practical application of a common military doctrine to deliver a military capability;

?? **Equipment**: the provision of military platforms, systems and weapons, expendable and non-expendable (including updates to legacy systems), needed to outfit/equip an individual, group or organisation;

?? **Personnel**: the timely provision of sufficient, capable and motivated personnel to deliver Defence outputs both now and in the future;

?? **Information**; the provision of a coherent development of data, information and knowledge requirements for capabilities and all processes designed to gather and handle data, information and knowledge. Data is defined as raw facts, without inherent meaning, used by humans and systems. Information is defined as data placed in context. Knowledge is information applied to a particular situation.

?? **Concepts and Doctrine**; a concept is an expression of the capabilities that are likely to be used to accomplish an activity in the future. Doctrine is an expression of the principles by which military forces guide their actions and is a codification of how activity is conducted today. It is authoritative, but requires judgement in application.

?? **Organisation**: relates to the operational and non-operational relationships of people. It typically includes military force structures, MoD civilian organisation structures and defence contractors providing support.

?? **Infrastructure**; the acquisition, development, management and disposal of all fixed, permanent buildings and structures, land, utilities and facility management services (both hard and soft facility management (FM)) in support of Defence capabilities. It includes estate development and structures that support military and civilian personnel.

?? **Logistics**: the science of planning and carrying out the operational movement and maintenance of forces. In its most comprehensive sense, it relates to the aspects of military operations which deal with: the design, development, acquisition, storage, transport, distribution, maintenance, evacuation and disposition of materiel; the transport of personnel; the acquisition, construction, maintenance, operation and disposition of facilities; the acquisition or furnishing of services, medical and health service support."

It is this structure of Lines of Development which is utilised in this thesis, as being that which was current when the present research began in 2005.

A final element was also incorporated in the MoD model at that time, this being the overarching concept of interoperability[14], which was defined as:

> "the ability of UK Forces … to train, exercise and operate effectively together in the execution of assigned missions and tasks …".

This element is of especial relevance within this thesis as radar was one component, a sensor, within a comprehensive system of many components which contributed to the capability of air defence. Radar, on its own, was of limited value, and the short time available to achieve air interception both by day and by night meant that radar had to interoperate seamlessly with all other components and Forces making up the air defence system, such as the Observer Corps, SIGINT, radio direction finding, Identification Friend or Foe technology, Filter Rooms and ground/air communications among others.

Up to this point, it is not anachronistic to use the MoD model as a tool for analysis of the events of the 1930s; as has been seen, this present-day model builds on best practice over many years, and indeed on mechanisms which were present, for example, in the 1930s RAF. By contrast, the detailed organisation structure by which Acquisition and Lines of Development are managed within today's MoD was not a feature of the 1930s. The ECCs Capability Working Groups and IPTs have been described above: one final component is now considered so that certain lessons for today identified in this thesis may be appreciated in their present context.

It will be apparent that a military capability is more likely to be achieved if both equipment and all other lines of development mature synchronously with the delivery of the equipment. The more likely event is that one or other line of development will be delayed, and there is therefore need for a person to act to ensure maximum contact with all relevant stakeholders and to balance across lines of development to ensure the optimal outcome. It is important to note in passing that there is current debate on whether the dominant task of the MoD is either to act to ensure balance achievement across all lines of development, or to contract with industry for equipment[15].

In consequence, the MoD has defined a role titled “Senior Responsible Owner” (SRO) for many new equipment projects, with the task of ensuring and validating that the appropriate lines of development are ready when called upon, and are pursuing a plan to achieve that end. Most SROs, excepting only that for the especially large and multi-facetted future carrier programme, were positioned in the Equipment Capability Customer organisation, and the role is still evolving.

A.4. Through-Life Management, and Approval Gates.

The third element of the MoD Acquisition concept referred to in the present thesis is that of “Through-Life Management” (TLM) crystallised into a Through-Life Management Plan (TLMP).

Through-Life Management envisions and acts upon all stages of the acquisition of a capability, from beginning to end, and identifies six such stages. The nomenclatures of two of these six, and the timing within the process of the decision/approval points (“gates”), vary according to whether a conventional item of equipment is being acquired, or whether the acquisition is of a service or a public/private partnership (PPP) funded item of equipment. In the first instance, the six stages are seen as:

?? **Concept –** considering required outputs, identifying options and initiating a TLMP;

?? **Assessment –** producing a System Requirements Document, identifying the optimal solution and risk-managing this;

?? **Demonstration –** demonstrating the ability to produce the required capability, and placing contracts;

?? **Manufacture –** delivering the solution to specification, cost and time;

?? **In-Service –** using the equipment, supporting and upgrading it as need be:

?? **Disposal –** safe, efficient and effective disposal.

This cycle is known by its acronym as the “CADMID” cycle.

The key approval decisions to be taken are titled "**Initial Gate**" and "**Main Gate**". Taken at the end of the Concept phase, Initial Gate approves the Assessment phase and identifies the time/cost/performance parameters for the total project throughout its life, although necessarily with margins for error, since knowledge is at this point incomplete. Main Gate, taken at the end of the Assessment stage, establishes a full business case on whether to proceed, including tightly defined time/cost/performance parameters.

In the parallel cycle for the acquisition of services and of PPP funded equipment, "Manufacture" becomes "Migration" to new services or assets (since equipment may or may not be a significant component of the whole), and "Disposal" is replaced by "Termination" for similar reasons. Initial Gate is now placed after the Assessment stage, and the Main Gate after the Demonstration stage, since the Demonstration stage now incorporates issuing Invitations to Tender (ITTs) or Invitations to Negotiate (ITNs) and recommending a bidder. This process is known by its acronym as the "CADMIT" cycle.

Because the idea of "Through-Life Management" was not conceptualised in the 1930s – although there are many instances of the cost-effective re-use of obsolescent radar equipment - it would be anachronistic to apply the concept rigorously to the period, but observations are made within the thesis on the timing of the key 1930s decisions to proceed with radar. These approximate to the Initial Gate and Main Gate decisions of the CADMID cycle, and interestingly almost exactly parallel the positioning of those Gates in the present-day acquisition process.

It might be observed that the current broad target is to spend 15% of the development and production cost before Main Gate, in order to de-risk the project by building knowledge. Nonetheless, the House of Commons Defence Committee was advised on 12 May 2004[16] by Sir Peter Spencer, incoming Chief of Defence Procurement, that the historic figure was as little as 2% and the then-current figure 4.4%, the MoD having often pressed projects through Main Gate without committing sufficient time or money to de-risk those projects. The 1930s air defence radar programme to fight the day Battle of Britain passed the equivalent of Initial Gate with under 0.5% committed, but around 15% was committed by the equivalent of Main Gate, due in part to correcting certain major problems described in this thesis. Radar for that day battle would not, therefore, be regarded as an "out-of-control" project by today's standards, and the 1930s Treasury acted to ensure that proper tendering and financial control were exercised, including interestingly trading across projects and across lines of development:

?? Closing previous attempts to develop (War Office) sensors such as sound locators, and offsetting the saving against the cost of (RAF) early-warning radar;

?? Suggesting the employment of untapped reservoirs of education and skill within the Services, in this case, the women of the WAAF, as radar operators (the scientists would have preferred civilians);

?? Ensuring alternative, and indeed non-military, uses for equipment if one concept failed – for example, the use of the electrical generators powering the Silhouette floodlighting system discussed in Chapter V, for the electrification of farms.

Radar to fight the night Blitz, by contrast, had an insignificant proportion of its cost expended by the time it had its "Main Gate" equivalent; this thesis will show that almost no knowledge on how to achieve effective night interception had been built up by that time, and that much resource was expended on acquiring that knowledge, inefficiently and by trial and error, only after the project was approved.

A.5. References.

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7. John James, *The Paladins*, London: Macdonald, 1990, Chapter 11.
8. Office of Government Commerce, *Managing Successful Projects with PRINCE2*, TSO: London, 2005.
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10. Professor Trevor Taylor, *The Evolution of Smart Acquisition in the UK*, unpublished paper, November 2006; I am grateful to Professor Taylor for access to this study.
11. National Audit Office, *Building an Air Manoeuvre Capability: the Introduction of the Apache Helicopter*, London, HC1246, Session 2001-2, 31 October 2002.
12. Ministry of Defence, *The Smart Acquisition Handbook*, 5th edition, MoD: London, January 2004.
13. Ministry of Defence, *The Acquisition Handbook*, 6th edition, MoD: London, October 2005.
14. Ibid, p.11.
15. T. Taylor and D. Neal, The Delineation of Defense Equipment Projects in the UK Ministry of Defence, *Defense and Security Analysis*, Vol. 20, No. 2, June 2004, pp. 165 - 178.
16. Evidence to the House of Commons Defence Committee on 12 May 2004, at http://www.publications.parliament.uk/pa/cm200304/cmselect/cmdfence/572/4051204.htm

APPENDIX B.

FLOODLIGHT AND BEAM RADARS.

In January and February 1935, Watson Watt proposed the design for a radar system against a user requirement for the early warning of the approach of aircraft.

There are two possible approaches to satisfying that requirement. The first, and the choice most used today, is for the radar to have a rotating aerial which will project a narrow beam of energy over the area to be searched, with a linked data display representing a map, most usually with the radar at its centre. This is referred to as "beam" radar, and its display as the "Plan Position Indicator", described in Chapter V and illustrated in Figs. 55 and 69. To use such an approach to cover a wide area, a rotatable or steerable aerial is necessary.

However, for the long range needed for early warning, it is necessary to project considerable radio frequency energy from the transmitter. When Watson Watt wrote his proposal, such high power could be generated at frequencies not significantly greater than 6 MHz (a wavelength of 50 metres). In turn, effective aerials for such frequencies would be physically very large – in excess of 200 feet tall (Figs. 23, 26). It was plainly impractical to construct an aerial array of such dimensions which could physically rotate, and instead Watson Watt chose a second approach, "floodlight" radar, which uses an aerial design projecting the transmitter's energy over a broad area in front of the transmitter, to either side of an axis called the "line of shoot". A considerable merit of this "floodlight" approach, from an early warning point of view, was that every aircraft within that "illuminated" area would appear on the screen – there would be no chance of losing an aircraft as might be the case with a rotating display. Fig. 104 below, from a contemporary instruction booklet, illustrates the area "illuminated" by a Chain Home "floodlight" radar.

The contrast with "beam" radar is shown in Fig. 105 below, from the same contemporary publication, and this illustrates the area "illuminated" by a Chain Home Low "beam" installation. Chain Home Low, designed several years after Chain Home, took advantage of improvements in short-wave transmitter valves which could generate high power at much shorter wavelengths than Chain Home. Use of these shorter wavelengths meant that Chain Home Low could have an aerial system which, while large, could rotate (Fig. 38), although initially over the semi-circle shown in Fig. 105 rather than through 360 degrees. Chain Home Low did not generate the power of Chain Home, and so had a shorter range; but because the Battle of Britain was fought over the short ranges of the Channel rather than the anticipated long ranges over the North Sea facing Germany, Chain Home Low formed a useful second early warning radar.

German radar was developed originally for Naval gunnery purposes and concentrated on "beam" technique. The German "Freya" radar (Fig. 42) is a "beam" radar.

FIGURES.

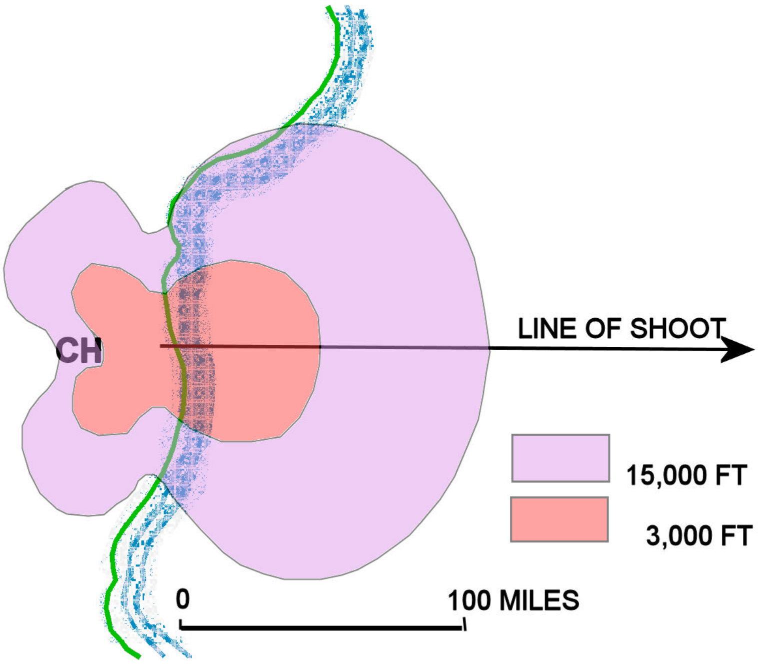

Fig. 105. Area "illuminated" by a Chain Home "floodlight" radar. (TNA/PRO AIR 10/3758 p.5).

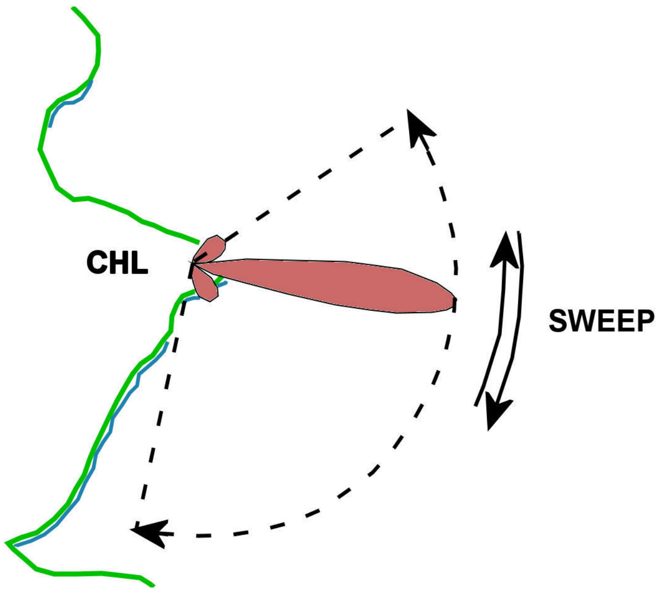

Fig. 106. Area illuminated by a Chain Home Low "beam" radar (Ibid, p. 6).