CRANFIELD UNIVERSITY

Y. PORTILLO

PRE-TACTICAL TRAJECTORY COMPATIBILITY DETERMINATION TO REDUCE AIR TRAFFIC CONTROLLERS' TACTICAL WORKLOAD

SCHOOL OF ENGINEERING

MSc by Research
Academic year: 2011-1012

Supervisors: R. Fewings /Z. Lei
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ABSTRACT

The current Air Traffic Management (ATM) system, based on principles established more than 50 years ago, is starting to show clear signs of saturation. This fact. joined to increasingly environmental awareness, leads to a paradigm shift from the current sector-based ATM system, to a future trajectory-based ATM system.

Within this research, factors and processes affecting trajectory-based operations are analysed, and the main factors hindering an accurate trajectory definition identified, in order to establish the criteria under which two aircraft trajectories could be declared as compatible in a pre-tactical management stage. Trajectory compatibility determination will endeavour to reduce the real-time Air Traffic Controller's (ATCO's) workload in the tactical stage, currently identified as one of the main bottlenecks in the existing ATM system.

The obtained results are based on a trade-off between the system capacity, understood as the number of ATCO tactical interventions, versus the system predictability, as the number of misdetections or probability of conflict to be assumed in a pre-tactical timeframe. A criterion to identify when two trajectories are compatible is presented, firstly considering the movement as horizontal only, then including the vertical components when one or both aircraft are climbing or descending.

The research initial results were presented in a Paper in the first SESAR Innovation Days which took place at Toulouse from the 29th of November 2011 to the 1st of December 2011 (Paper included as Annex V).

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Finally, and most important, I am deeply grateful to my husband, Professor Francisco Saez, whose effort, support, ideas and love have made this Research possible.

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ACRONYMS

4DT	4 Dimensional Trajectory
ANSP	Air Navigation Service Provider
ATC	Air Traffic Control
ATCO	Air Traffic Controller
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
BT	Business Trajectory
CPA	Closest Point of Approach
CFMU	Central Flow Management Unit
CTOT	Calculated Take off Time
DST	Decision Support Tools
EUROCAE	European Organisation for Civil Aviation Equipment
EUROCONTROL	European Organisation for the Safety of Air Navigation
FAA	Federal Aviation Administration
FTE	Flight Technical Error
FL	Flight Level
ICAO	International Civil Aviation Organisation
JPDO	Joint Planning and Development Office
MATLAB	MathWorks Mathematical Software
MITRE	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NM	Nautical Mile
NOAA	National Oceanic and Atmospheric Administration
NSE	Navigation System Error
PBN	Performance Based Navigation
PDE	Path Definition Error
PEE	Position Estimation Error
RBT	Reference Business Trajectory
RMS	Root Mean Square

RNP	Required Navigation Performance
RTA	Required Time of Arrival
RTCA	Radio Technical Commission for Aeronautics
SBT	Shared Business Trajectory
SESAR	Single European Sky ATM Research
TBO	Trajectory Based Operations
TCAS	Traffic Collision Avoidance System
TCU	Towering Cumulus (or Cumulus congestus clouds are characteristic of unstable areas of the atmosphere which are undergoing convection.)
TP	Trajectory Predictor
TSE	Total System Error
UPM	Universidad Politecnica de Madrid
WP	Way Point

1. INTRODUCTION

1.1 Background

In spite of the fact that airspace could be considered initially as an unlimited resource, this is not a true statement. For Air Traffic Management (ATM) purposes, airspace is currently divided into different volumes, called Air Traffic Control (ATC) sectors, each of them controlled by an Air Traffic Controller (ATCO). The capacity of the ATM system is limited by the amount of simultaneous traffic inside each ATC sector that an ATCO is able to handle. This amount of traffic depends on a number of factors, including the physical pattern of air routes and airports, the traffic demand distribution (both geographic and temporal), the physical volume of the sector and the ATC working procedures designed to maximise the traffic throughput. As a result, airlines often cannot fly an optimal route, but an available route which permits the balance between demand and capacity for that specific time.

The continuous increase in air traffic has led to a certain degree of saturation in both Europe and the US, especially in high density traffic areas, where the limiting factor on capacity is, apart from airport capacity, the controller tactical workload in the ATC sectors. Tactical actions, taken by controllers, to avoid conflicts between aircraft, have been agreed as the main bottleneck for today's ATM system. These actions grow rapidly with traffic density, limiting the number of aircraft that can be safely attended. As an example, the proportion of ATFM delay in July 2011 (see Figure 1.1) shows that 61.3% (46.4% en route capacity plus 14.9% en route ATC staffing) of the delay is due to a lack of en route capacity.

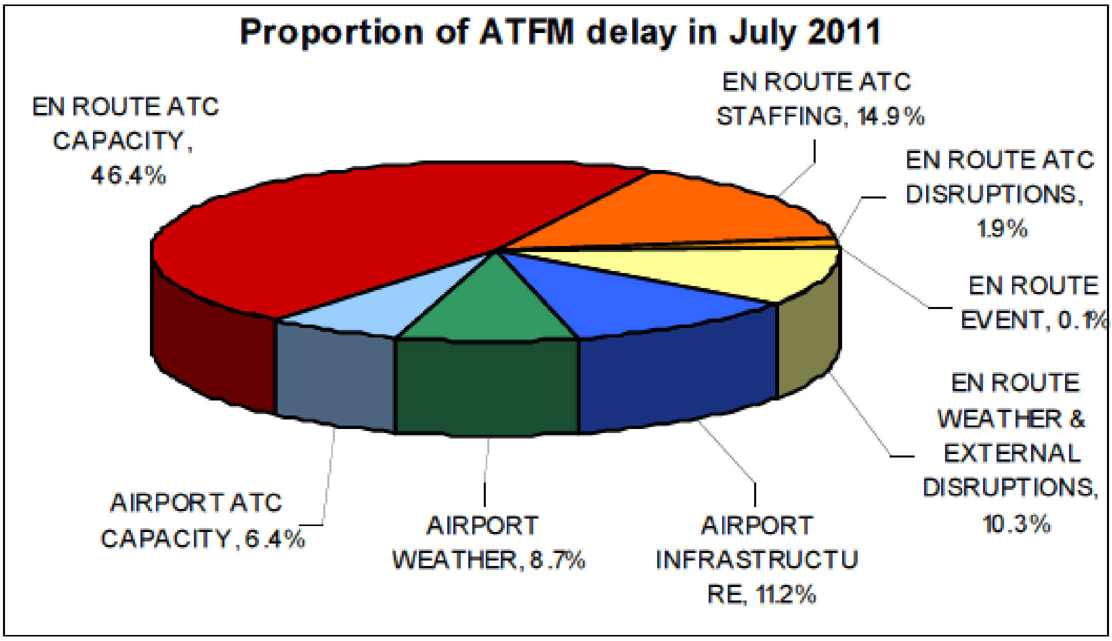


Figure 1.1 Proportion of ATFM delays as reported by Network Operations Report July 2011. EUROCONTROL

1.2 Aim and objectives

The research aim is to analyse when two aircraft trajectories can be declared as compatible in a pre-tactical stage of the operation, in order to provide a Decision Support Tool (DST) in the new paradigm shift from current ATM based on sector management, to future ATM based on trajectory management.

The research will be devoted to clearly reduce the ATCO workload due to tactical interventions, increasing airspace capacity and improving safety performance. Even though it is not possible to reduce the post-resolution conflict probability to zero when the time to the predicted conflict is larger than a few minutes, the intent is to reduce ATCO workload, although they will continue to have ultimate responsibility for ensuring proper separation at all times.

To this end, the research objectives include:

- Analysis of the new paradigm shift from sector management to trajectory management

- Analysis and estimation of the main uncertainties affecting the trajectory definition
- Revisit existing trajectory models and identify their possible enhancements
- Establish the criteria for trajectory compatibility
- Show conclusions to improve Trajectory Based Operations
- Identify further work to cover the limitations noted on completion of the research

1.3 Thesis Structure

The Thesis is made up of six Chapters describing the work conducted during the research.

The first Chapter deals with the introduction, including the background, aim and objectives. The second Chapter is concerned with the literature review. From these Chapters, the aim and the methodology of this research are set up from the analysis of the future ATM system definition, the description of Trajectory Based Operations, analysis of the factors affecting the trajectory definition and the study of the existing trajectory compatibility models.

The methodology and conceptual definition will be presented in the third Chapter. It includes the analysis of an existing 3D Model, the identification of possible enhancements, the new developed model limitations, the research mathematical calculations, and the determination of the trajectories compatibility made as a trade-off between capacity and predictability. An initial approach to the vertical movement analysis is also presented in this Chapter.

Chapter four presents the analysis including the minimum distance obtained to declare two trajectories as compatible, and the definition of the time intervals to analyse the vertical movement.

Chapter five presents the discussion as a summary of the key findings and an assessment of the implications of the results, and Chapter six includes the conclusions obtained. Linking back to Chapter one, the initial research aims and objectives are discussed and the limitations and further work identified.

The Annexes present a detailed description of the existing model, some of the mathematical calculations and the MATLAB programmes developed. Annex V includes the initial research results presented in a Paper in the first SESAR Innovation Days (Toulouse, 29th of November 2011 to 1st of December 2011) and Annex VI presents the questionnaire delivered to Air Traffic Controllers in Madrid Air Traffic Control Centre.

2. LITERATURE REVIEW

The literature review has focussed on the following aspects:

1 The future of ATM: in order to define the scope of the research, the triggers, the objectives and the limitations.

2 Trajectory Based Operations: to identify the existing definitions of a trajectory and its different planning layers.

3 Trajectory uncertainties: to analyse the main uncertainties associated with the predicted trajectory.

4 Existing trajectory compatibility models analysis: to identify the limitations of current models and possible enhancements.

2.1 Future ATM system definition

Although in the past decade ANSPs, Airline Operators, Airports and the CFMU have managed to cope with a significant traffic growth in an acceptably safe and expeditious manner (with delays being historically low at 1.9 mins/flight), the current ATM system shows clear signs of saturation. In addition, an increased environmental awareness calls for more efficient operations and better supporting technology. Moreover, in the light of the current economic crisis, extra requirements are placed on the European ATM system to reduce cost (e.g., ATM costs are estimated to average 1070 EUR/flight[1]), and increase safety.

Today's ATM processes are based on principles introduced more than 50 years ago and they are in high density areas, as Europe, neither sufficiently geared nor flexible enough to adhere to the schedules of the commercial airspace users. Shifting to advanced airspace environments will require fundamental changes to air traffic management methodology. The FAA's Next Generation Air Transportation System (NextGen), and Europe's Single European Sky ATM Research (SESAR) are two initiatives launched towards completing these changes.

NextGen[2] is a comprehensive overhaul of the USA National Airspace System to make air travel more convenient and dependable, while ensuring the flight is as safe, secure and hassle-free as possible. The FAA is building the capability to guide and track air traffic more precisely and efficiently to save fuel and reduce noise and pollution. For that NextGen will:

- help travel to be more predictable,
- reduce aviation’s impact on the environment,
- help the system to be even more proactive about preventing accidents,
- get the right information to the right person at the right time,
- continually improve and accommodate future needs of air travel while strengthening the economy with one seamless global sky,
- help communities make better use of their airports,
- help to meet the increasing national security needs and ensure that travelers benefit from the highest levels of safety.

On the other hand, stakeholders of the European aviation community, comprising the aeronautics industry, air traffic management, airports, airlines, energy providers and the research community, were invited to share their ideas to develop a vision for Europe’s aviation system and industry by 2050[3]. The resulting document focuses on the necessity of meeting the needs of citizens and the market through research, technology and innovation, reducing aviation’s impact on the environment.

The European air traffic management (ATM) system currently handles around 26,000 flights daily. Forecasts indicate air traffic levels are likely to double by 2020. Moreover, European ATM costs are higher compared to other similar systems in the world. How will the European airspace accommodate the increasing air traffic flows, whilst cutting costs and improving its performance? The answer came with the initiative of organising airspace into functional blocks, according to traffic flows rather than to national borders. Such a project was not possible without common rules and procedures at European level.

The Single European Sky (SES), launched by the European Commission in 1999, was born to meet future capacity and safety needs through legislation establishing targets in key areas of safety, network capacity, effectiveness and environmental impact. The Single European Sky drove the transformation of the role of EUROCONTROL, which has become the Network Manager of the European ATM network.

On the technology side, SES is supported by the Single European Sky ATM Research (SESAR) Programme, which will provide advanced technologies and procedures with a view to modernising and optimising the future European ATM network.

For that, the SESAR Joint Undertaking (SJU) was created under European Community law on 27 February 2007, with EUROCONTROL and the European Community as founding members, in order to ensure the modernisation of the European air traffic management system by coordinating and concentrating all relevant research and development efforts in the Community.

The main drivers to design the new SESAR concept of operations are (taking into account a 3 fold increase in demand): [4]

- 3 fold increase in capacity
- 10 fold increase in safety
- 50 % reduction in users costs per flight
- 10% reduction in the environmental impact per flight

For that, the SESAR concept of operations implies the following paradigms:

- Trajectory based operations respecting the airspace user's individual business cases.
- Improved conflict management:
  - Shifting from tactical intervention to strategic de-confliction
  - Redistribution of tasks between ATM partners
  - Improved system automation support
  - The human being continues to be the most flexible and creative element to:
    - achieve the performance of the overall ATM System
    - manage the threats, errors and unpredictable events

The two pillars on which the system is based on are trajectory management and conflict management.

The Trajectory Management concept:

- Entails the systematic exchange of common aircraft trajectory data between various participants in the ATM process
- Ensures that all participants share a common view of a flight and have access to the most accurate data available to perform their tasks
- Supports a degree of pre-deconfliction traffic flows resulting in fewer tactical interventions during flight execution.

From the Research's aim and objectives the following aspects have been extracted, linking back with the above highlighted areas in order to place the Research within the SESAR context:

- The research aim is to analyse when two trajectories can be declared as compatible in a pre-tactical stage of the operation; this would clearly help in the shifting from tactical intervention to strategic de-confliction.
- The research aims to clearly reduce the ATCO workload; assisting in the redistribution of tasks between ATM partners
- The objective is to provide a decision support tool in the new shift; aiding the system automation support.
- The intent is to reduce ATCO workload although they will continue to have ultimate responsibility for ensuring proper separation at all times; human continues to be the most flexible element under the Research's scope.

On the other hand, the conflict management concept includes[4] high complexity operations (those within TMAs and high density en route airspace) and medium complexity operations (those within en route airspace above FL200). It is assumed that some constraints exist in the Reference Business Trajectory construction for high complexity operations, whereas in medium complexity scenarios the priority is to allow flights to operate as near as possible to their business trajectories whilst eliminating all en route capacity constraints. The Research could be used to allow any of the approaches, as the pre-tactical de-confliction tool is in any case useful to reduce the tactical ATC interventions in both high density and medium density en route scenarios.

When considering the business trajectory cycle, the proposed decision support tool would be placed any time hours before the operation takes place, helping to decide in which cases the Shared Business Trajectory becomes the Reference Business Trajectory. As tactical actions can modify the trajectory in any stage of the cycle, the tool could be continuously used to reclose the loop introducing this feedback into the system. The Trajectory Based Operations concept will be revisited in the next sections of the document.

The European ATM Master Plan[5] provides the roadmap for the development and deployment phases of the SESAR programme which constitutes the technological pillar of the Single European Sky policy. SESAR aims to develop the new generation air traffic management system capable of ensuring safety and efficiency of air transport throughout Europe over the next 30 years.

At the highest level, the SESAR Master Plan defines how to develop and deploy the new ATM system supporting the new ATM concept required to significantly contribute to the overall Single European Sky policy objectives.

In order to support the air navigation community in executing the European ATM Master Plan, EUROCONTROL has published strategic guidance describing how EUROCONTROL, through its activities, will reach the targets set out in the Master Plan.[6]

In both documents the following key features are considered:

- Optimal trajectory management, reducing the constraints of airspace organisation, introducing the Business Trajectory concept.
- Collaborative planning reflected in the Network Operations Plan.
- Full integration of Airport operations, as part of ATM and planning process.
- New separation models, to allow both safety and capacity to be increased.

- System Wide Information Management, integrating all ATM-related data, to exploit the power of shared information.

The design of airspace to match the trajectory-based management approach is established as crucial. The controller tactical intervention reduction, as one of the main factors affecting capacity limitations, will be achieved by providing strategic DST.

In order to go further than SESAR and NextGen, a paradigm shift is required in ATM Automation[7]. As an aircraft moves, within the atmosphere, and the aircraft mission begins and ends at an airport, the limitations of ATM will be the atmospheric behaviour and airport capacity constraints. On the other hand, the goals of the ATM are both to provide the required separation between aircraft maintaining the safety standards applied for the air transport, and to maintain the competitiveness of the air transport mode by providing the required efficiency and being environmentally friendly. The automation role should be based on overall system performance, taking these invariants as a starting point. Operational changes will be supported by new roles in managing aircraft trajectories, separation provision and trajectory de-confliction.

2.2 Trajectory Based Operations (TBO)

Current ATC sector capacity[8, 9] is defined as the number of aircraft permitted within a sector in a time unit, usually an hour. As an example, capacity values in Madrid Air Traffic Control Centre are in a range between 35 and 50 aircraft per hour, depending on sector complexity.

A “pure en route sector”, in which most aircraft are established at a defined flight level and no level change is expected, is able to “absorb” more traffic than a more complex sector and, consequently, the assigned capacity can be higher. On the other hand, collateral sectors to terminal areas, in which aircraft are climbing or descending to/from their cruise level, would normally involve a higher complexity and a lower assigned capacity. Similarly, sectors in which level flight traffic interacts with non-level flights would have lower assigned capacity values. Finally, integrating sectors never results in a sector capacity which is the addition of the capacities of the former sectors, but a particular capacity value calculated considering the overall new sector complexity.

In order to compare traffic demand with available ATC sector capacity during a period of time, the starting time must be defined, and from it, the number of aircraft entering the sector is counted during this period (usually sixty minutes). A total number of aircraft will be obtained, no matter the traffic distribution during these 60 minutes. For instance, considering a total traffic demand of 45 movements/hour, the same value will be obtained whether 25 aircraft enter the sector in the first fifteen minutes or the 45 aircraft are equally distributed throughout the whole hour. New parameters measuring the sector capacity are being used nowadays by the Air Traffic Management units as the above defined capacity value does not provide a real idea of the traffic density through the sector.

On the other hand, some feedback of the traffic complexity should be added to these calculations. Not only the amount of simultaneous traffic within a sector (named occupancy) but also the type of traffic, is important to better evaluate sector performance. Any ATCO would be very comfortable dealing with 15 simultaneous aircraft established at non-conflicted levels, whereas a totally different result would be obtained when the same amount of aircraft established at the same flight level are compared with climbing/descending aircraft with interacting trajectory courses.

When analysing the factors affecting the traffic demand complexity, different aspects should be included. Simultaneous traffic provides a good measure of the sector complexity, and the number of peaks in demand and their duration could be a good way of predicting sector complexity. However, the characteristics of traffic demand should be included in the analysis. The predicted conflict density should be taken into consideration when evaluating the future demand, the foreseen workload and the possible overloads.

The trigger to deliver a regulation should be an expected number of conflicts exceeding a pre-determined value that should be initially settled. Nowadays regulations are imposed on those aircraft overflying sectors for which nominal capacity is foreseen to have been already reached, no matter the number of existing conflicts. If conflict hotspots could be identified in advanced and avoided, the air traffic demand could be increased overall.

Trajectory de-confliction has an important role in conflict hotspot identification. If trajectories could be de-conflicted in a pre-tactical stage of the operation, the amount of possible conflicts downstream would be radically reduced. Those areas in which the number of foreseen conflicts are over a pre-defined value, would be declared as hotspots, and alternative trajectories should be provided to avoid them.

Trajectory compatibility could be determined as a trade-off between overall capacity and probability of conflict. If trajectories could be de-conflicted in a pre-tactical stage of the operation (hours in advance) the number of tactical conflicts to be solved would be radically reduced and overall system capacity would be increased. The Air Traffic Management way of operation would be conceptually based on trajectory analysis and de-confliction, and not on number of operations irrespective of their complexity.

The Research's aim is to define when two trajectories can be defined as compatible, taking into account the probability of conflict and the overall system capacity. For that, the longitudinal uncertainties in the trajectory definition will be considered as the most important factor hindering Trajectory Based Operations (TBO). Wind estimation error will be introduced in the calculations as the main factor for trajectory uncertainty, although other aspects such us changes in the Estimated Departure Time should be included in a further step.

A critical enabler for TBO is the availability of an accurate, planned trajectory providing valuable information to allow more effective use of airspace. However, there are many definitions of a trajectory. The framework developed by the FAA/EUROCONTROL R&D Action Plan includes definitions of "trajectory" and "trajectory predictor" (TP)[10]: "the Predicted Trajectory describes the estimated path that a moving aircraft will follow through airspace. The Trajectory can be described mathematically by a time-ordered set of Trajectory Vectors".

The International Civil Aviation Organization (ICAO) defines the trajectory as "a description of the movement of an aircraft, both in the air and on the ground, including position, time and, at least via calculation, speed and acceleration"[11] .

The RTCA Special Committee-214 in combination with EUROCAE Working Group 78 adds additional detail defining the 4-Dimensional Trajectory as “a precise description of an aircraft path in space and time: the “centreline” of a path plus the position uncertainty, using waypoints to describe specific steps along the path”[12] .

The RTCA Concept of Use for Trajectory Operations also recognizes that there must be some flexibility in the actual data contained in a trajectory: “An aircraft trajectory is a representation of the planned or actual flown route in 4 dimensions (latitude, longitude, altitude, and time), with discrete points defined along that route. The granularity of the representation of the flight trajectory depends on the intended use of that information, and may not necessarily include all 4 dimensions”[13].

Trajectory based operations are a key component of both the US’s NextGen and Europe’s SESAR. Furthermore, the concept of trajectory negotiation is not new. In the 1990’s EUROCONTROL described the aircraft operator’s desire to negotiate “the most optimal or preferred trajectory, whereas the responsibility of the 'ground' or ATC sub-system is to ensure the safe separation of the aircraft flying the trajectories and the optimal sequencing, from the system viewpoint, of those aircraft that are departures and arrivals”[14].

Around the same time, NASA described a trajectory negotiation concept in which airspace users could submit trajectory preferences to resolve conflicts, in the form of a 4D trajectory itself or route, altitude and speed preferences[15].

The NextGen Concept of Operations describes the use of 4DTs in a TBO environment, where “air traffic services are provided through the generation, negotiation, communication, and management of both individual 4DTs and aggregate flows representing the trajectories of many aircraft.” User preferences are addressed through this negotiation where users “achieve their business and operational objectives through access to reliable real time information relevant to their proposed operation, to understand the impact of their decisions related to their operations, and to negotiate with the ANSP to achieve their objectives”[16].

SESAR describes a negotiation process where “airspace users will agree with ANSPs and airport operators, from early planning to the day of operations the airspace user’s preferred trajectory for the flight in four dimensions (three spatial dimensions, plus time), where the various constraints of airspace and airport capacity have been fully taken into account” [17].

In the Mid-Term Concept of Operations, the FAA has recognised “Automated Support for Trajectory Negotiation” as a key TBO “Operational Improvement,” where “Trajectory management is enhanced by automated assistance to negotiate pilot trajectory change requests with properly equipped aircraft operators. 4-D trajectories are negotiated between the pilot/aircraft operator and the ANSP, using ground-based automation to provide trial planning using intent data in en route TBO”[18]. The exchange of 4DT information and airspace constraints are described as the foundation of trajectory negotiations, where “ANSP automation provides feedback in terms of required aircraft performance and sets conformance bounds or windows for trajectories or portions of the 4DT, as needed. Users can change plans to minimize the impact of anticipated constraints, and revise flight plans accordingly. Throughout the flight planning/feedback process, users negotiate trajectories with the ANSP electronically from multiple locations with multiple service providers. Once trajectory negotiation is complete, the agreed upon trajectory is used by the system to generate the initial flight plan with appropriate time constraints along the route.” These negotiations rely on decision support tools, the Required Time of Arrival (RTA) and speed adjustment functionality[14].

It is very important to reduce the uncertainty associated with the prediction of an aircraft’s future location through the use of an accurate 4DT in space (latitude, longitude, altitude) and time. The NextGen Concept of Operations states that the “use of precise 4DTs dramatically reduces the uncertainty of an aircraft’s future flight path, in terms of predicted spatial position (latitude, longitude, and altitude) and time along points in its path” [13].

It is necessary to highlight that although nowadays there are different definitions for aircraft trajectory and a common view sometimes referred to as "flight object" is required, any trajectory definition will be able to support the "trajectory compatibility" concept aimed in this Research. No matter the way the trajectory is defined, it could be transformed into a limited set of segments to fit into the model proposed under the Research.

As trajectory management is one of the key concepts for the development of the future ATM System, EUROCONTROL has prepared a set of documents to enable a common understanding and to permit all the parties to focus their research and development activities.[19]

In particular, the definition of all the terminology and common Trajectory Prediction Structure is provided in a specific white paper[20] in which the Business Trajectory, as the representation of an airpace's user's intention with respect to a given flight guaranteeing the best outcome for this flight, is defined (see Figure 2.1).

As defined[16] the Business Trajectory (BT) is the representation of an airspace user's intention with respect to a given flight, guaranteeing the best outcome for this flight (as seen from the airspace user's perspective) respecting momentary and permanent constraints.

The Trajectory originated as a Business Trajectory is a planned flight known only to the Aircraft Operator and potentially consisting of no further detail than the departure and destination aerodromes. It may originate several months, or only hours before the intended departure time, depending on the business model of the operator. Once the corporate plans are sufficiently mature, the Aircraft Operator "shares" the Business Trajectory with the wider aviation community, and then the Business Trajectory becomes the Shared Business Trajectory (SBT).

The ATM System evaluates each proposed trajectory as it is received, identifying possible capacity imbalances, the proximity of the proposed flight to planned airspace reservations and adding the proposed flight to the demand/capacity equations along the proposed route of flight.

At some point in the hours prior to departure, the Aircraft Operator and the Service Provider agree on the trajectory details and the SBT is published as the Reference Business Trajectory (RBT), defined as the trajectory that the Airspace User agrees to fly and that the ANSP and Airport agree to facilitate.

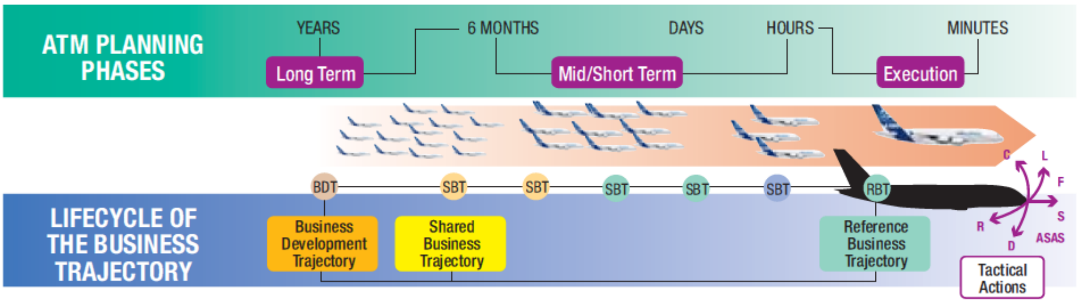


Figure 2.1. Business trajectory lifecycle
(SESAR Consortium. The ATM target concept. D3. Sept 2007)

Trajectory management arises as having two different sequential steps:

- Trajectory planning: what is planned to happen with the trajectory (planned or reference state),
- Trajectory execution: what is actually happening with each flight compared with its planned trajectory (flown trajectory).

Conformance monitoring between both "trajectories" (planned and flown) will drive any renegotiation process[6]. The better the trajectory planning process works, the smaller the number of necessary renegotiations becomes. This leads to the final result of fewer short term interventions and a more strategic environment. This is only feasible if the information used for trajectory prediction is accurate enough, and this requires a good knowledge, within the planning timeframe, of at least:

- The atmosphere's kinetic and thermodynamic characteristics at any time,
- Performance of all aircraft that plan to use the airspace,
- System (airspace and airports) existing constrains,

- Any unpredictable event, in real time, that could change all previous information,
- The true flights starting times.

Any distortion of SBT, however necessary, will inevitably result in a smaller or bigger change in the cost-effectiveness of the operation. This is a vitally important consideration for the air traffic management services to keep in mind at all times and strive to keep the overall business trajectory intact as much as possible. Any choice of a solution to ensure separation must keep this in mind, right after the safety consideration. It is obvious that as we are dealing with the complete aircraft trajectory, choices made must consider the overall effects beyond a control sector or even a control centre.

Keeping in mind its possible utilisation, at this first stage, the tool developed should try to identify potential conflicts before the operation takes place. Considering the different planning layers in the transition to a TBO environment the tool will be used to obtain the RBT from the SBT introduced within the system. Only those trajectories considered as de-conflicted should be admitted into the system, and the rest of them should be accordingly modified. Different choices could be presented to the user taking into consideration that the initial SBT should be keep as intact as possible. However, how to determine these new options is not a matter of the Research.

As the real operation takes place, intervention upon the initially “allowed RBT” will happen on a real-time basis, in full knowledge of the downstream conditions in every instant. In most circumstances, ATC will issue constraints to be met and the airspace users will decide what the most economical way to meet that constraint is. Again, in this later stage, the proposed tool will help to calculate trajectories’ compatibility and to choose the option causing the least distortion.

As the TBO is a living concept applicable for the whole operation, the tool presented in the Research could be used at the different stages of the process guaranteeing trajectory compatibility in every instant and helping to find the optimal solutions.

There are many different stakeholders in the transition to a TBO environment, and there are many different timeframes over which TBO may operate; from strategic capacity management operating from the timeframe of years to short-term collision avoidance, operating up to a fraction of a minute. Therefore, it is very important to reduce the uncertainty associated with the prediction of an aircraft's future location through use of an accurate 4D Trajectory in space (latitude, longitude, altitude and time).

As stated by Kuchar[21] the intent information plays a critical role in reducing controllers' workload by predicting the future traffic situation. His studies outline some of the fundamental issues that arise in problems involving intent, and provide an initial approach to modelling the decision trade-offs. It is also stated that it is necessary to estimate the level of confidence that can be placed on different types of intent information under different situations, requiring quantitative models to aid in design analysis and operation.

One of these methods to compute the probability of conflict including intent information and trajectory uncertainty[22] has been developed, using a set of probability functions that describe potential trajectory errors into a series of Monte Carlo real-time simulations. These simulations are used to estimate the probability of conflict in traffic encounters and suggest that similar approaches could be used in real-time conflict detection systems. Intent information is included in the model, as a series of waypoints, heading or track holds, target altitudes or manoeuvring limitations.

NASA Langley Research Centre has developed onboard decision support tools that provide airborne conflict management and strategic flight planning support.[23] As a reliable trajectory prediction is a key factor, the trajectory uncertainties due to environmental effects and aircraft performance error have been accommodated using cross-track, vertical and along track buffers based on prediction errors detected in simulations.

The main factors influencing trajectories under specific operation conditions were identified by a joint team of FAA-MITRE and NASA engineers.[24] Trajectory prediction accuracy is affected by a collection of these factors, among which are included the speed uncertainty, the aircraft performance and weight, and wind.

2.3 Main uncertainties in a trajectory definition

Within the trajectory management process, the first step in the trajectory planning process shows two main questions that should be deeply analysed[6]:

- What is the flexibility in the trajectory horizontal and vertical profiles definition available for an aircraft?
- When should a given set of trajectories be declared as compatible?

It must be stressed that "intent flight paths" are not static concepts. Once the origin and destination positions have been settled, navigation is a procedure which requires three interrelated actions:

- Route definition.
- Positioning within the previously defined route.
- Guidance, that is to correct the position if necessary when comparing the real position with the expected one.

When executing the above defined actions, the following errors could be committed:

- Path Definition Error, PDE: Errors in the navigation database, such as waypoint location, or coordinate-entering failures, can mislead the Flight Crew.
- Flight Technical Error, FTE: the flight control system, manual or automatic, could cause the aircraft to deviate from its intended track.
- Position Estimation Error, PEE: the position estimated via any navigation aid mean, could include different errors that must be taken into consideration.

The three errors together compose the Total System Error (TSE) or deviation between the desired and the real position.

Considering the intended route defined in the flight plan, the aircraft could have a lateral deviation, a vertical deviation or a longitudinal deviation from it. As the route is defined as a time set of segments, the deviation of the aircraft position in the lateral, vertical and longitudinal dimension allows the establishment of the 4D Navigation (see Figure 2.2).

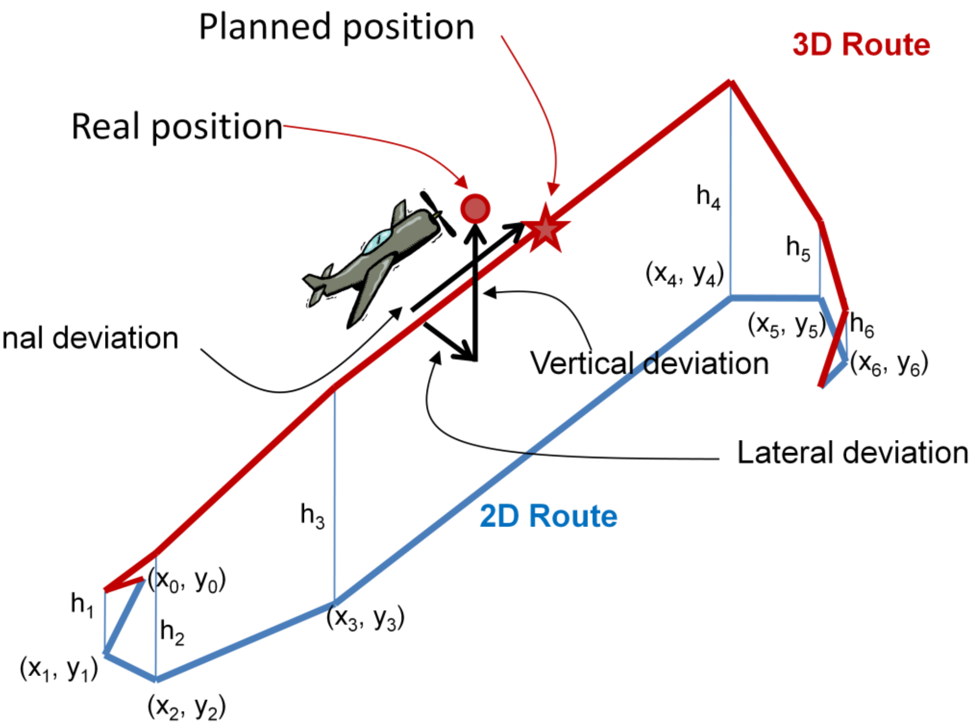


Figure 2.2. 4D Navigation

When analysing the lateral uncertainties, the TSE, for some specific aircraft navigation system requirements, operating in a particular airspace, supported by the appropriate navigation infrastructure, is settled within the Performance Based Navigation (PBN) Manual of ICAO[25]. As an example, during operations in airspace or on routes designated as RNP-1, the lateral system error must be within ±1NM for at least 95% of the total flight time (2σ).

The current vertical profile of the aircraft trajectories, as it is shown in Figure 2.3, only exhibits a given performance for vertical deviations when the aircraft is flying following a precision approach and also when it is in level flight. Other descent and climbing phases are flown without a reference line, using different profiles based on efficiency criteria such as the Cost Index[26] and some restrictions or limits (upper and/or lower), given usually by ATC, or established by the operational navigation procedure.

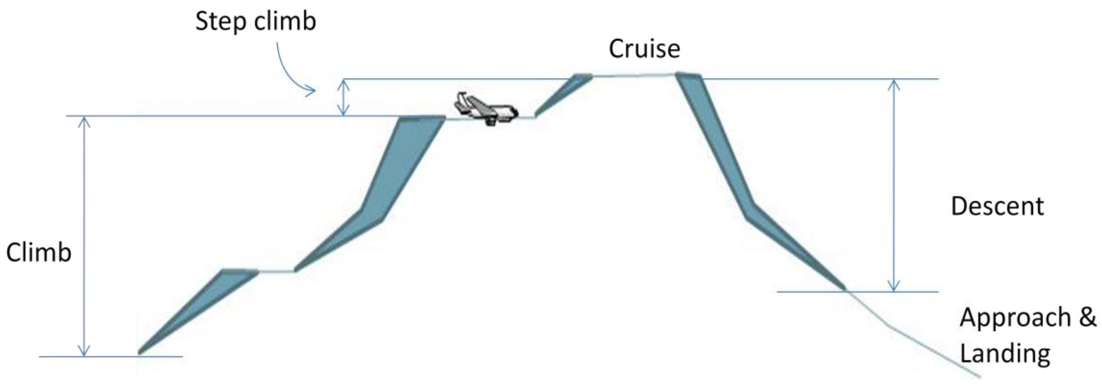


Figure 2.3. Current vertical profile and its uncertainties

Taking this into account, in order to analyse the vertical uncertainties, two different cases should be brought into consideration. When the aircraft is established at a defined flight level a total vertical error can be determined, as for the operations in Reduced Vertical Separation Minimum (RVSM) is defined a total vertical error of 200ft (accuracy requirements 3σ, that is about the 99% of the total flight time)[27]. On the other hand, when aircraft are climbing or descending vertical uncertainties are much greater as climbing rate varies with aircraft performance and the atmospheric temperature and density.

When analysing longitudinal uncertainties, it must be considered that aircraft fly most of the time at a constant Mach Number airspeed rather than at a constant ground speed and, as a consequence, the effects of wind modelling and prediction errors accumulate with time. Airlines use wind estimation to minimise flight costs by appropriate choice of a route, cruise level and by loading the minimum necessary fuel on board.

As an example, the NOAA's National Weather Service provides hourly wind forecast information for different flight levels and the entire USA airspace (see Figure 2.4).

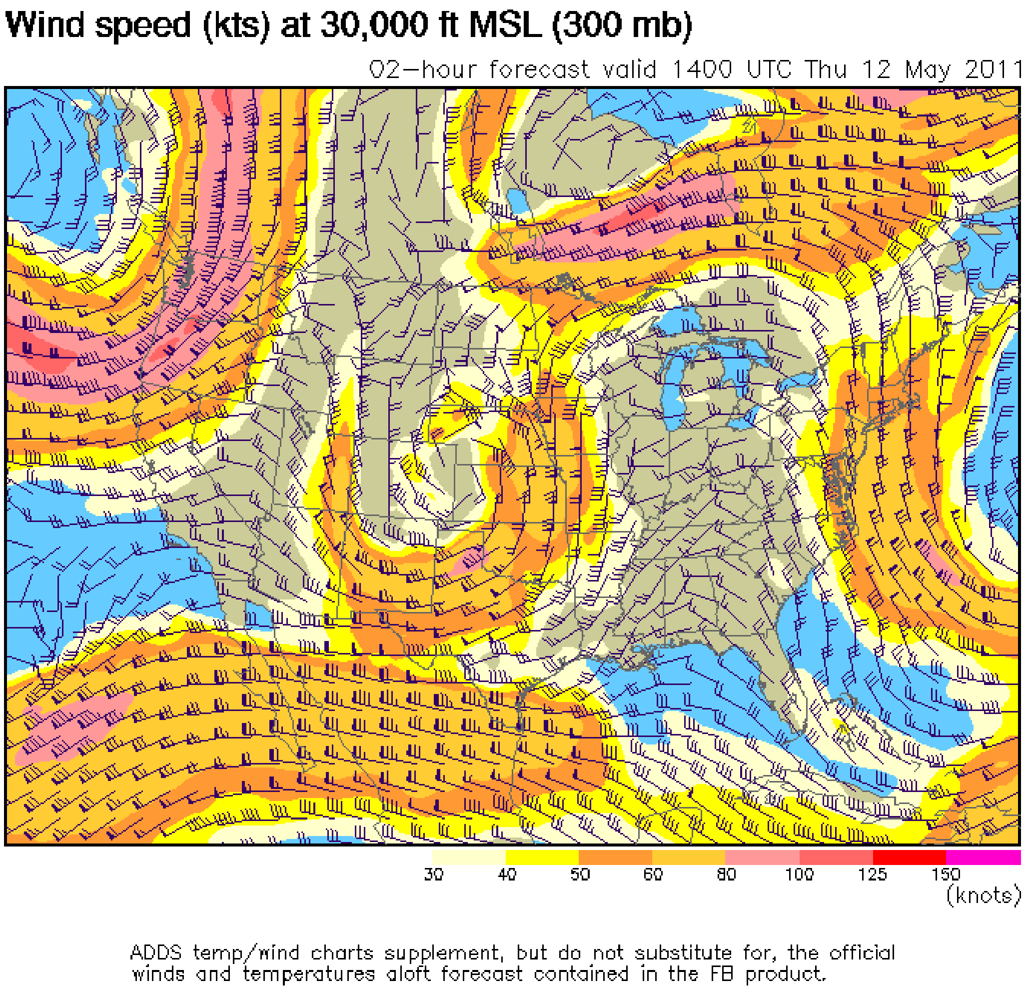


Figure 2.4. NOAA. Wind information at FL300. 12/05/2011 14 UTC

Wind prediction errors may represent the largest source of trajectory prediction error. Some studies have been conducted in order to validate trajectory prediction accuracy, and identify and measure major sources of trajectory prediction error. A key finding of these tests was that wind prediction error was the greatest source of error for trajectory predictions of the order of 20 minutes time horizon.[28].

The performance of ATM decision support tools depends in a large part on the accuracy of the supporting 4D trajectory predictors, being particularly relevant to conflict prediction. Different studies have tried to better understand the wind-prediction errors, to establish metrics for quantifying large errors and to validate different approaches to improved wind prediction accuracy.[29]

Several attempts have been made to improve the trajectory prediction by estimating wind [30] [31] [32], however all of them try to provide real-time information to the ATC, and do not consider a pre-tactical timeframe.

A year-long study of the Denver Centre airspace was conducted by the Massachusetts Institute of Technology Lincoln Laboratory [33] to understand the magnitude and source of these errors, and to establish metrics for quantifying large errors that may be critical to ATM decision support tools. The test conducted included a cruise segment (FL350 or FL330), a descent segment (to FL170 or FL180) and a region over the western and central United States from 100 to 200NM.

It was found that RMS (Root Mean Square) vector differences between observations and forecasts increased as wind speed increased, and also as altitude increased and in winter months (both associated with higher wind speed). On the other hand, RMS vector differences are also computed in the presence or absence of precipitation, thunder and wave clouds, appearing that the differences between forecasts and observations were greatest during convective weather events (thunder, TCU), showing an overall RMS vector difference between both situations of up to 1 m/s.

The rest of the metrics found are summarised as follows:

- The study shows a predominant daily value for RMS vector difference of 4.5-5.5 m/s range, accounting for about 164 of the 395 days (13 month period).

- The forecast errors grow with the length of the forecast projection, for example, the RMS vector difference values increase by about 1.5 m/s from 1 to 6 hours.

- For ATM applications the peak error periods for wind forecasts are critical. If it is taken into account that the standard for en route radar separation is 5NM, a

15kt (7.5 m/s) mean error in along track wind component over a 20 min trajectory prediction for an aircraft will result in a 5NM position error. Therefore, the peak error events included are considered to be at least 10 m/s.

2.4 Existing trajectory compatibility models

Collision risk estimation in airspace and mathematical modelling of mid-air collisions has been carried out for over more than 40 years [34]. During this period, mathematical models of processes leading to possible collisions of aircraft flying nearby have been developed in order to estimate the risk of collision.

B. L. Marks [35] of the Royal Aircraft Establishment developed the principles on which a collision risk model could be developed in the early 1960s. Marks' work was modified and enhanced by P. Reich[36] and that model, later called the Reich model, has been the basis for many of the important developments in this field.

The Reich model uses information relating to the probabilistic distributions of aircraft's lateral and vertical position, traffic flows on the routes, aircraft's relative velocities and aircraft dimensions to generate estimates of collision risk. Unfortunately, this model does not adequately cover situations where ground controllers monitor the air traffic through radar surveillance and provide tactical instructions to the aircraft crews. Furthermore, the problem of collision risk modelling in the analysis of "high traffic density" ATC scenarios is different to that of "procedural scenarios", which have been developed by Reich[37] and Brooker[38], amongst others. This is mainly due to the active role of Controllers in the first case. Here positive control is used extensively to modify the planned aircraft route. This requires the inclusion in the model of "human factor response" behaviour.

Taking into account that in most high density scenarios, recorded data of tracks can be obtained for all aircraft flying in it, and that this indirect information is closely related to the "human factor response", a detailed mathematical model for probability of collision in a radar ATC environment has been developed[39].

This work has been latterly enhanced by providing an individual probability of potential collision (severity) for each individual encounter, based on the kinematics of the encounter and the minimum lateral and vertical separation at the Closest Point of Approach (CPA)[40].

The formulation presented allows, not only the estimation of the severity for each individual potential aircraft's encounter, but also the expected probability of collision for all aircraft pairs who have potentially violated the separation standards. The obtained results are applied to the stored aircraft's tracks that have flown in it within a given time frame.

Within the EUROCONTROL Concept Paper for Separation Safety Modelling[41] a number of areas related to modelling the effects on aviation safety of reducing the aircraft separation minima standards are addressed. It establishes the necessity to concentrate primarily in en route airspace, as the collision risk will be simpler to model than in terminal airspace, as well as the need to develop a model that can include various geometries of aircraft trajectories as well as changes in those geometries. It compares the so called "probabilistic models" versus "analytical models" and concentrates on models for midair collisions applicable to airspace where radar separation is provided, and the question of how reducing horizontal separation minima would affect collision risk.

Trajectory Predictors[42, 43, 44] assume that any deviation from predicted trajectory can be split into different dimensions having different levels of accuracy or limits in their uncertainty containment. Therefore, when a trajectory has been established as 2D, trajectory predictors consider a lateral deviation containment criteria following Performance Based Navigation, whereas 3D trajectory predictors also include a vertical deviation containment criteria based on RVSM for level flight aircraft.

Furthermore, if the trajectory is defined as 4D, trajectory predictors shall include longitudinal uncertainties containment criteria. However, this last goal has not been fulfilled so far. Similarly, the containment region including vertical uncertainties when aircraft are climbing or descending will impose very large altitude buffers for conflict avoidance. This fact would reduce the effective airspace availability and would hinder operational efficiency in high traffic density regions where there is an important percentage of evolving traffic.

No matter what type of aircraft trajectory has been established, it will always be possible to use a simple model in which trajectories can be considered as an ordered sequence of segments. Thus, the model could take this information from any Trajectory Predictor. A segmented trajectory composed of a set of segments representing the aircraft's uniform movement is the basis of the Research, whose main purpose is not to determine how to predict a trajectory or to find the best possible prediction for it, but to establish the criteria to define two trajectories as compatible as a trade-off between probabilities of conflict and number of foreseen air traffic controller interventions.

This approach will assume that the involved aircraft are able to follow these segments, with minimum lateral separations based on RNPs, and minimum vertical separations based on RVSM. In other words, our scenario should fulfil PBN requirements.

The segmentation used is based on trajectories defined through waypoints, any segment of them being considered as "accurate" and trajectory compatibility determination being done through a simple mathematical approach. "Reich-based" models make a similar assumption. Omitting the remaining uncertainties, the longitudinal ones, caused by the wind can easily be included in the form of wind error standard deviation.

Similarly, different models include the wind error uncertainty as the main cause for along track error. J. Ligeros[45] uses multi-aircraft real data to improve trajectory prediction accuracy considering aircraft flight level and constant airspeeds. The paper considers that a large part of the uncertainty about the evolution of flights stems from the fact that meteorological forecasts are inherently inaccurate, and among the different weather phenomena affecting aircraft Trajectory Predictors, wind speed is the most important. This approach is similar to the one presented in the Research in which wind error is considered as the most important source for trajectory prediction error. Wind is modelled as a sum of two components, a nominal and a stochastic one. Wind field is assumed as isotropic, and follow a Gaussian distribution with zero mean. It assumes as well, a strong correlation between wind errors in the same horizontal plane, a very strong correlation in time and a weaker correlation across different altitudes. Cross track error is evaluated but found to be considerably smaller, and consequently omitted.

Likewise, the Research will consider the cross track error negligible in comparison with along track error, and the wind error stochastic component to follow a Gaussian distribution with zero mean and defined standard deviation. Wind error will be assumed to be the same for both aircraft, an assumption that is totally accordant to the strong correlation in time (same horizontal plane) found in the paper.

Other studies[46, 47] consider that one of the components that mostly affect an aircraft trajectory is the wind, and that the effect is mostly produced through its speed. These studies examine the effect of wind correlation on aircraft probability estimation and an analysis of the correlation structure of the difference between the actual and the meteorological wind forecasts is presented. Wind speed is modelled as a sum of two components: a nominal, deterministic component (available through forecasts) and a stochastic component representing deviations from the nominal. Moreover, the stochastic component is similarly assumed to be zero mean and correlated in space and time, whereas the deterministic part of the wind is considered to be zero for simplicity (similarly, in the Research, this part will be considered as the nominal speed included in the flight plans). On the other hand, the vertical component of the wind is taken as small in comparison with the horizontal component. Wind is assumed to be given at each moment by a zero-mean Gaussian distribution with 5.35 m/s standard deviation (this value is settled taking into account[31]).

The assumption made in the Research in which the wind error is considered the same for both conflicted aircraft (Section 3.3 page 28) is supported by these papers. From them it can be extracted[44] that cross correlation is high (>0.5) for distances of about 400km (200NM), vertical differences of 2000m (6000 feet) and time intervals of about 150 minutes. The Research will consider the horizontal movement as independent from the vertical one (Section 3.3, aircraft flight level) and will include (Section 4) a time to CPA of 60 minutes. Finally, when dealing with cross track errors, the study considers a saturation value of 1NM (2σ deviation), and highlight that as aircraft technology advances, these values are likely to become smaller.

J. Hu [48] also addresses conflict detection from a probabilistic viewpoint, considering that the aircraft actual motions differ from the planned ones due primarily to wind uncertainty. In this respect, the approach is similar to the one followed under the Research, as it considers that a defined prescribed threshold value of the probability of conflict must not be surpassed. On the other hand, the paper considers that the random wind perturbations to the aircraft motions are spatially correlated and in neglecting that, erroneous evaluations when computing the probability of conflict could be taken into account. Confirming that statement, simulation results show that the wind correlation effect cannot be ignored when estimating the probability of conflict. The Research considers similarly, that both aircraft are affected by the same wind error.

Similarly to the Research, the paper considers initially both aircraft established at the same flight level and latterly, this approach is extended to address encounters in which the aircraft are performing vertical manoeuvres. In the same way, among all the factors affecting aircraft velocity, the paper considers the wind as the major one, and specifically, the wind contribution to the aircraft velocity is also modelled as the sum of two terms:

- A deterministic term, which represents the nominal wind velocity and is known through measurements and forecast. Within the Research this term will be included into the flight plan nominal speed.
- A stochastic term representing the effect of air turbulence and error in the wind speed measurements and forecast. Within the Research this term will be consider to follow a Gaussian distribution with zero mean and covariance $\boldsymbol{\sigma_w}$. Similarly, the paper considers for simplicity that the random contribution of the wind to the aircraft velocity remains isotropic, as there is no apparent direction preferential to others.

2.5 Summary

A new paradigm shift is needed in order to cope with the foreseen increase in air traffic demand whilst maintaining safety standards, reducing related costs and minimising environmental impact. As understood in this research, this paradigm shift should be from the current sector based to a trajectory based ATM system.

There are different trajectory definitions and different stakeholders in a transition to a TBO environment. Whereas some studies try to improve the real-time decision support tools used by air traffic controllers, the trajectories de-confliction analysis carried out under this research will try to identify potential conflicts further in advance, that is, in a pre-tactical planning layer, several hours (about 6 hours) before the operation takes place. This pre-tactical conflicts identification leads to reduce the air traffic controller's workload due to tactical conflicts resolution. Most of the studies consider the reduction in the uncertainty associated with the predicted trajectory as the critical enabler for TBO.

Although main factors affecting trajectory prediction are broadly analysed, some recently developed models do not include the wind uncertainty as one of the main aspects hindering ATM Decision Support Tools Utilisation. Some studies have shown a predominant daily value for RMS vector difference of about 6m/s and large errors of 10m/s occur for 3% time overall. This research will discuss the influence of wind errors, both in direction and in speed, on defining conflict-free trajectories.

If aircraft trajectories could be de-conflicted at a time in advance of the real-time operation taking place, the ATCO workload per aircraft would be significantly reduced and the global system capacity and safety could be increased. This is the purpose for conflict probability analysis within this research.

3. METHODOLOGY: CONCEPTUAL DEFINITION

Conflict detection consists of identifying all pairs of aircraft whose distance and altitude separations are predicted to be less than specified minimum values within the detection time horizon.

The purpose of the model developed under this research is to define the compatibility between two BTs (no conflict existence) so that they could become SBTs and, finally, RBTs under the following criteria:

- ATCO workload must be significantly reduced.
- Airspace capacity must be increased.
- Safety performance must be improved.

Keeping in mind the determination of trajectory compatibility in a pre-tactical timeframe, in order to reduce the ATCO tactical workload, the methodology used has tried to cope with this objective following the next steps:

1. Existing model analysis and enhancements identification.
2. Developed model limitations: scenario definition, horizontal / vertical movement discrimination.
3. Calculations I: angle variation between the initial and the final impact line.
4. Calculations II: Closest Point of Approach coordinates.
5. Determination of trajectories compatibility: trade-off between capacity and predictability.
6. Vertical movement analysis.

3.1 Existing model analysis and enhancements identification

A completed description of the enhanced model can be found in Annex I.

In this model the kinematics of each aircraft is converted into a finite set of sequenced segments and the lateral and vertical deviations of aircraft real trajectories from the segmentation modelling are considered. The speed is considered as known; furthermore, the law of uniform motion for each segment is assumed. No further speed uncertainties are considered.

Similarly, in the model proposed in this Research, the kinematics of each aircraft is again defined by a finite set of sequenced segments. However, the errors to be considered are based on the Total System Error (TSE) which includes the deviations between the desired trajectory and the real position finally flown, taking into account lateral deviations, vertical deviations and also longitudinal deviations. Therefore, the proposed model is a 4D model which will be focussed on RBTs and the way they are defined. Standard current definition for these routes is a succession of WPs and a predefined uniform movement between them. However, several factors such as the wind could cause the estimated speed (included in the RBT) and the real speed to differ. These differences may become extremely important and must be taken into account within this 4D model.

A similar approach should be considered in the segments where the aircraft are climbing or descending, where RBT definition will be based on the establishment of any condition when reaching the next WP, e.g. a defined target Flight Level. So the vertical movement profile between these two WP could not be considered as uniform.

On the other hand, in the previously reviewed model a potential conflict was identified when the minimum distance between two aircraft is less than an established minimum separation standard defined by two values, the minimum horizontal (R) and vertical (H) separations. During the en route phase of flight at European level, these values are 5 NM in radius and 1,000 ft in height.

However, these current minimum separation standards were determined many years ago and they are used to facilitate conflicts resolution in an ATC environment. For the proposed 4D model, compatibility of trajectories should not be based on minimum separation standards but on probability of conflicts that finally would require tactical ATCO intervention. This compatibility should be established based on the minimization of false alarms and misdetection probabilities caused by position prediction uncertainties.

3.2 Developed model limitations

Following the EUROCONTROL Concept Paper for Separation Safety Modelling[38] the presented model concentrates primarily on en route airspace as the collision risk will be simpler compared to terminal airspace.

Considering the typical flight performance for commercial aviation (coordinated turns and small bank angles), aircraft kinematics can be split into two independent horizontal and vertical movements. This approach is further supported by the fact that within the en route phase of flight, the aircraft are established at a determined flight level most of the time.

The practical consequence of the horizontal movement only initial analysis is that as a first approach it will be considered that both aircraft involved in the encounter are established at the same flight level. The analysis of short periods of time in which the aircraft is climbing or descending is introduced as an expansion of the horizontal movement.

For the purpose of trajectory compatibility analysis, the aircraft lateral position error can be considered as negligible. The lateral navigation performance for most airspaces, as those proposed by PBN, may give values as low as a lateral deviation of 0.1 nautical miles, 2σ. A PBN 0.1 implies that the aircraft lateral deviation is confined within 0.1NM at both sides of the track a 95% of the time (see Section 2.3).

The vertical relative movement will be also studied in a further step. When the aircraft are established at a defined flight level, a total vertical error can be determined, as for the operations in RVSM is defined a total vertical error of 200ft. On the other hand when aircraft are climbing or descending, vertical uncertainties are much greater as climbing rate varies with aircraft performance and the atmospheric characteristics.

3.3 Calculations I: angle variation between the initial impact line and the final impact line

In this Section, the horizontal components of the aircraft speed and the influence of wind errors on them will be analysed as independent from the vertical movement, being the analysis based on the model presented in Annex I.

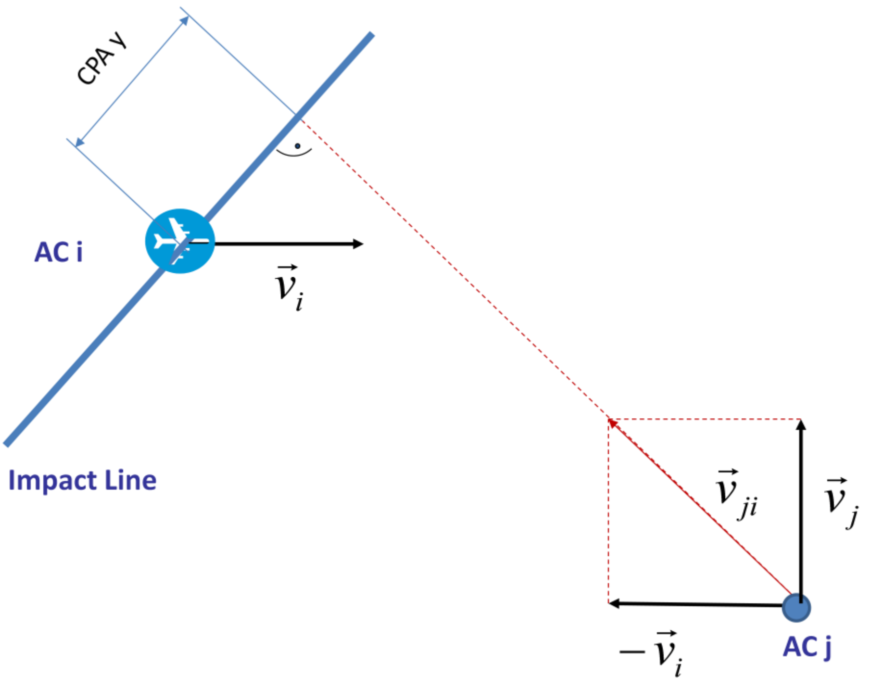


Figure 3.1. Horizontal approach definition

The horizontal movement model of the aircraft is shown in Figure 3.1 where the following parameters are used:

- $\overrightarrow{v_{ji}}$: horizontal component of the relative speed between the two aircraft i and j involved in a proximity event.
- Intruder aircraft (ACj) with relative speed $\overrightarrow{v_{ji}}$.
- Reference aircraft (ACi), assumed as static.
- The impact line: established as a generic projection line containing the centre of ACi and perpendicular to $\overrightarrow{v_{ji}}$. CPA_y could be calculated as the intersection point

of the straight line defined using the position of ACj with $\overrightarrow{v_{ji}}$ direction, and the impact line.

- Angles will be measured as the aircraft tracks, which are clockwise from the Magnetic North. Therefore, θ_i will be the ACi speed angle measured from the north, and θ_j and θ_{ji} angles are defined in the same way.

Predicted wind speed could be included as part of the aircraft speed information within the aircraft RBTs declarations, but its estimation has an error that modifies the initially predicted geometry of the encounter. As a result, due to the wind error estimation, ground speeds for both aircraft will change, so does the relative speed vector, and consequently the impact line. The angle variation between the initial impact line (no wind error conditions) and the final impact line (wind error influence) will be named $\delta\theta$ and it is shown in Figure 3.2. Note that the initial relative speed vector (no wind error) is named as $\overrightarrow{\boldsymbol{v_{ji0}}}$.

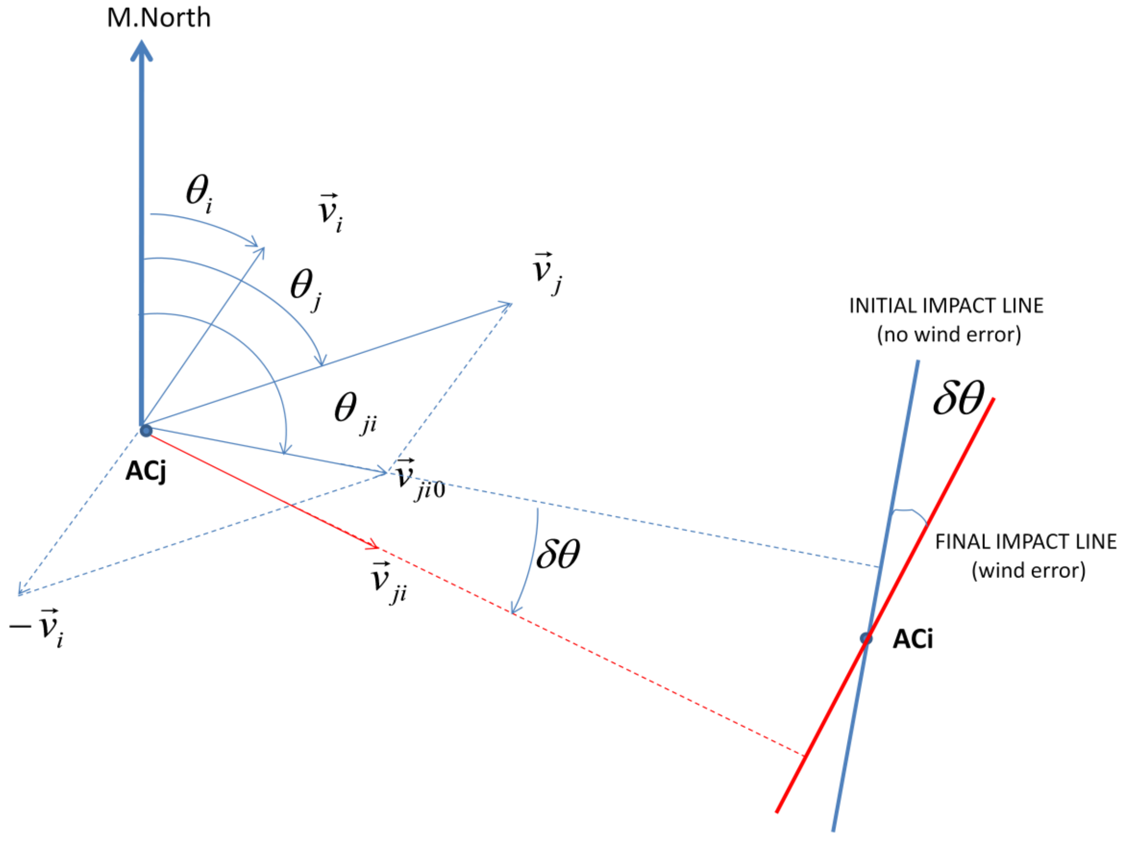


Figure 3.2. Impact line angle variation

The optimal air speeds and their directions (including predicted wind in the future scenario), for both aircraft involved in the encounter, are known parameters in the RBTs declaration and, therefore, the initial relative speed between them, $\overrightarrow{\boldsymbol{v_{ji0}}}$. The estimated relative speed $\overrightarrow{\boldsymbol{v_{ji}}}$ (considering wind error influence) and subsequently, $\delta\theta$, can be derived under the following assumptions:

- Wind unknown error will be taken as spatially and temporally constant within the encounter involved airspace and time, and then, common for both aircraft i and j.
- $|\vec{v_i}|$ and $|\vec{v_j}|$ will vary due to the previous unknown wind velocity error and this variation will depend on its direction and magnitude.
- $\vec{v_i}$ and $\vec{v_j}$ directions will not be affected by wind as the aircraft fly normally maintaining limited deviations following a predefined course established by the navigation computer.
- Other lateral uncertainties in the horizontal positioning will be considered negligible according to assumed navigation performance (see Sections 2.3 and 3.2).

As formerly stated, the impact line is defined as a generic projection line containing the centre of ACi (assumed as static reference) and perpendicular to $\overrightarrow{\boldsymbol{v_{ji}}}$. Considering the known parameters and the assumptions observed the following Equation (1) for $\delta\theta$ is obtained:

$$\boldsymbol{\delta\theta = atan\left[\frac{w_j*\sin(\theta_{ji}-\theta_j)-w_i*\sin(\theta_{ji}-\theta_i)}{v_{ji0}+w_j*\cos(\theta_{ji}-\theta_j)-w_i*\cos(\theta_{ji}-\theta_i)}\right]} \tag{1}$$

Where:

- $w_{j,i}$ are wind error components on $\overrightarrow{\boldsymbol{v_j}}$ and $\overrightarrow{\boldsymbol{v_i}}$ directions respectively,
- $\theta_{j,i}$ are $\overrightarrow{\boldsymbol{v_j}}$ and $\overrightarrow{\boldsymbol{v_i}}$ directions respectively, measured from Magnetic North,
- $\boldsymbol{v_{ji0}}$ is the initial relative speed modulus,
- θ_{ji} is $\overrightarrow{\boldsymbol{v_{ji0}}}$ direction measured from Magnetic North.

The whole set of calculations is presented in Annex II to this document.

3.4 Calculations II: CPA Coordinates

As formerly stated, conflict detection consists on identifying all pairs of aircraft whose distance and altitude separations are predicted to be less than specified minimum values within the detection time horizon. For the proposed model, this happens when the CPA coordinates are equal to or less than these pre-established values. The CPA coordinates variation due to the wind error influence is closely related to $\delta\theta$, calculated in the previous Section (see Figures 3.1 and 3.3).

Considering that the coordinates of a defined CPA (x, y, z) are directly related to the relative speed $\overrightarrow{v_{ji}}$, the expression for the CPA coordinates could be calculated as the intersection point of the straight line (defined using the position of aircraft j and whose direction is the same as $\overrightarrow{v_{ji}}$) and the impact plane.

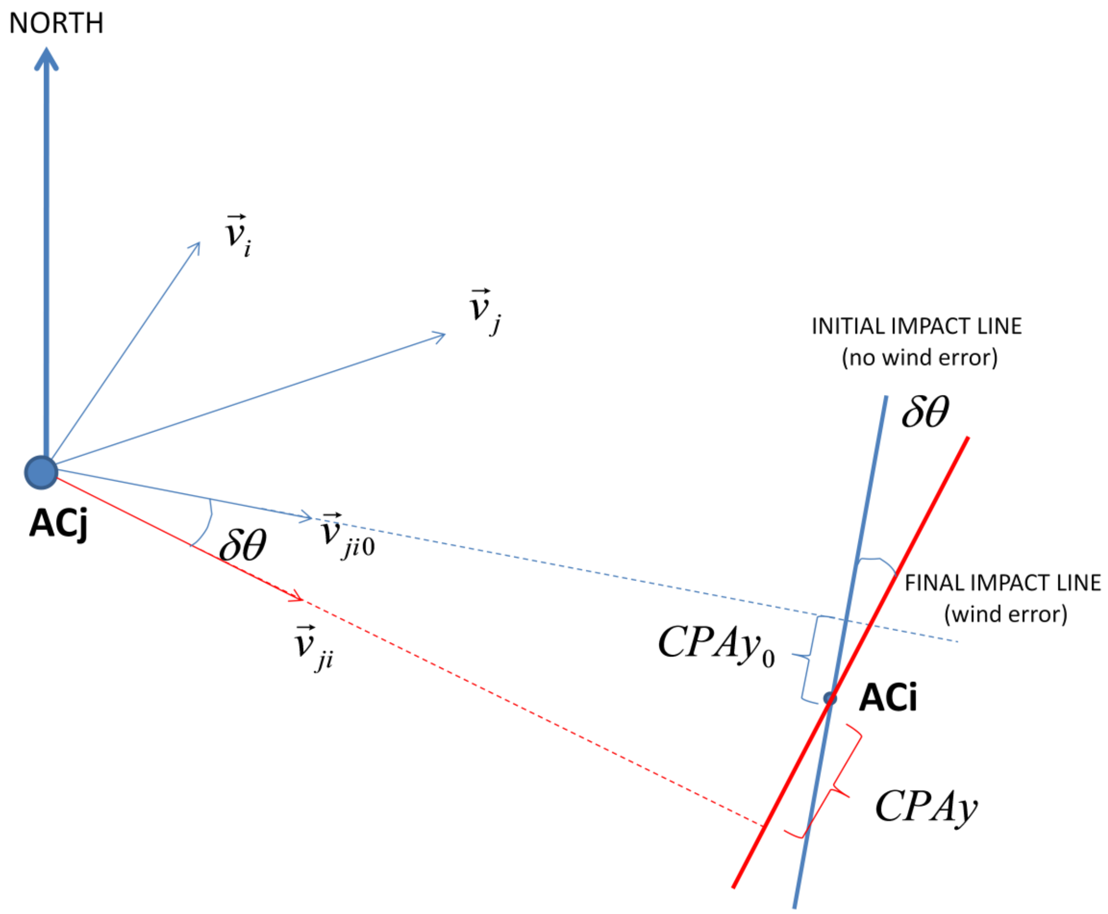


Figure 3.3. Relation between δΘ and CPA coordinates variation

In the following discussion the reference frame will be clockwise and centred in ACi (ACi≡O) having: Ox axis parallel to the horizontal component of intruder aircraft velocity and oriented towards this aircraft; Oy axis as the intersection line between the impact plane and the vertical plane, passing through the reference ACi, and Oz axis vertical and upward (see Figure 3.4).

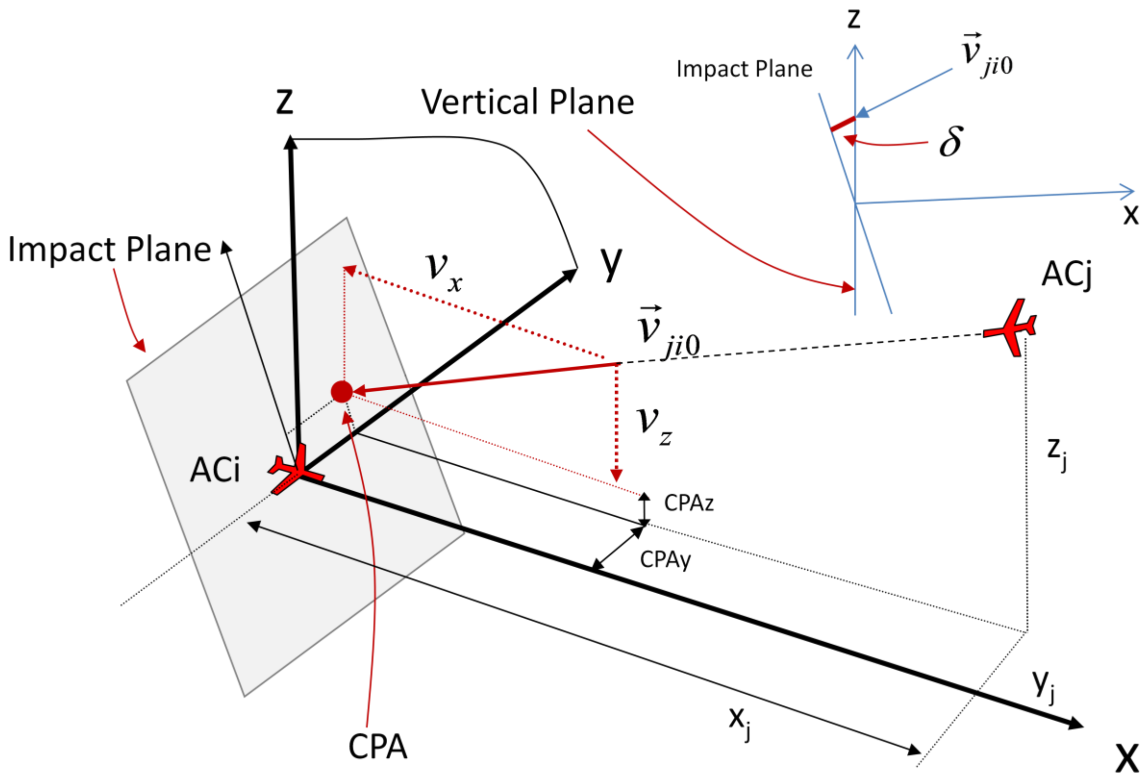


Figure 3.4. Reference frame and CPA coordinates

The 3D straight line equations can be expressed in parametric form as follows:

$$(x, y, z) = (x_j, y_j, z_j) + \lambda\,(v_x, v_y, v_z) \qquad (2)$$

Where (x_j, y_j, z_j) and (v_x, v_y, v_z) are respectively any point in the straight line and any vector parallel to it, and λ its parameter. In this case, (x_j, y_j, z_j) are the initial intruder aircraft position coordinates and (v_x, v_y, v_z) represent the relative velocity.

Taking into account that by definition the CPA is on the impact plane, CPA_x coordinate is very close to zero (see right upper corner in Figure 3.4), as δ is very small, assuming the relative velocity horizontal component (v_x) much higher than the vertical one (v_z). Then, the following condition can be applied:

$$x = x_j + \lambda v_x \approx 0 \tag{3}$$

As the impact plane is perpendicular to the relative velocity (impact plane definition) the λ parameter for the straight line becomes:

$$\lambda = \frac{x_j}{v_{jio}} = time\ to\ CPA = t_{CPA} \tag{4}$$

So, the estimated coordinates for the CPA relative to the reference aircraft ACi can be expressed as:

$$\hat{y} = y_j + t_{CPA} v_y$$
$$\hat{z} = z_j + t_{CPA} v_z \tag{5}$$

The previous estimated coordinates have been derived under the existence of some uncertainties contained in the different involved elements because they are planned or estimated values. The uncertainties in the initial relative position of ACj (y_j, z_j) are named as $\varepsilon_{y,zj}$ and in the calculated relative speed (v_y, v_z) are named as $s_{y,z}$.

Likewise, the expression for the true coordinates can be stated as:

$$y = y_j + \varepsilon_{yj} + t_{CPA}(v_y + s_y)$$
$$z = z_j + \varepsilon_{zj} + t_{CPA}(v_z + s_z) \tag{6}$$

Where:

- $\varepsilon_{y,zj}$ is the y or z component of the ACj initial position coordinates uncertainty,
- $s_{y,z}$ is the y or z component of the relative speed coordinates uncertainty.

Introducing the covariance matrix for estimation error of a state vector $\underline{x}$, given by the following expression:

$$Q = E[(\underline{x} - \underline{\hat{x}})(\underline{x} - \underline{\hat{x}})^T] \tag{7}$$

When it is applied to the previous Equations (5) and (6), it is obtained:

$$\left(\underline{x}-\hat{\underline{x}}\right)=\begin{bmatrix} y-\hat{y} \\ z-\hat{z} \end{bmatrix}=\begin{bmatrix} \varepsilon_{yj}+t_{CPA}s_y \\ \varepsilon_{zj}+t_{CPA}s_z \end{bmatrix} \tag{8}$$

$$Q=E\begin{bmatrix} \left(\varepsilon_{yj}+t_{CPA}s_y\right)^2 & \left(\varepsilon_{yj}+t_{CPA}s_y\right)\left(\varepsilon_{zj}+t_{CPA}s_z\right) \\ \left(\varepsilon_{yj}+t_{CPA}s_y\right)\left(\varepsilon_{zj}+t_{CPA}s_z\right) & \left(\varepsilon_{zj}+t_{CPA}s_z\right)^2 \end{bmatrix}$$

The previous expression for covariance matrix for the error in the CPA y and z coordinates estimation can now be simplified by using the previously introduced assumptions given in (Section 3.2):

- vertical and horizontal movements are assumed to be uncoupled and then their error as independent: $E[\left(\varepsilon_{yj}+t_{CPA}s_y\right)\left(\varepsilon_{zj}+t_{CPA}s_z\right)]=0$
- horizontal movement assumption; both aircraft are assumed as flying established at the same altitude and the vertical speed error: $s_z=0$,
- aircraft position error considered as negligible: ($\varepsilon_{y,zj}\approx 0$)

Under these assumptions the covariance matrix in (8) reduces to:

$$Q=E\begin{bmatrix} \left(t_{CPA}s_y\right)^2 & 0 \\ 0 & 0 \end{bmatrix} \tag{9}$$

Taking into account that s_y is the y component of the relative speed coordinates uncertainty mainly due to the influence of the wind error, it can be given in terms of the angular deviation of the estimated relative velocity, resulting (see Figure 3.5):

$$s_y=v_{ji0}*\delta\theta \tag{10}$$

And then,

$$Q=E\begin{bmatrix} \left(t_{CPA}v_{ji0}*\delta\theta\right)^2 & 0 \\ 0 & 0 \end{bmatrix}$$

$$Q_{11}={t_{CPA}}^2{v_{ji0}}^2*E(\delta\theta^2) \tag{11}$$

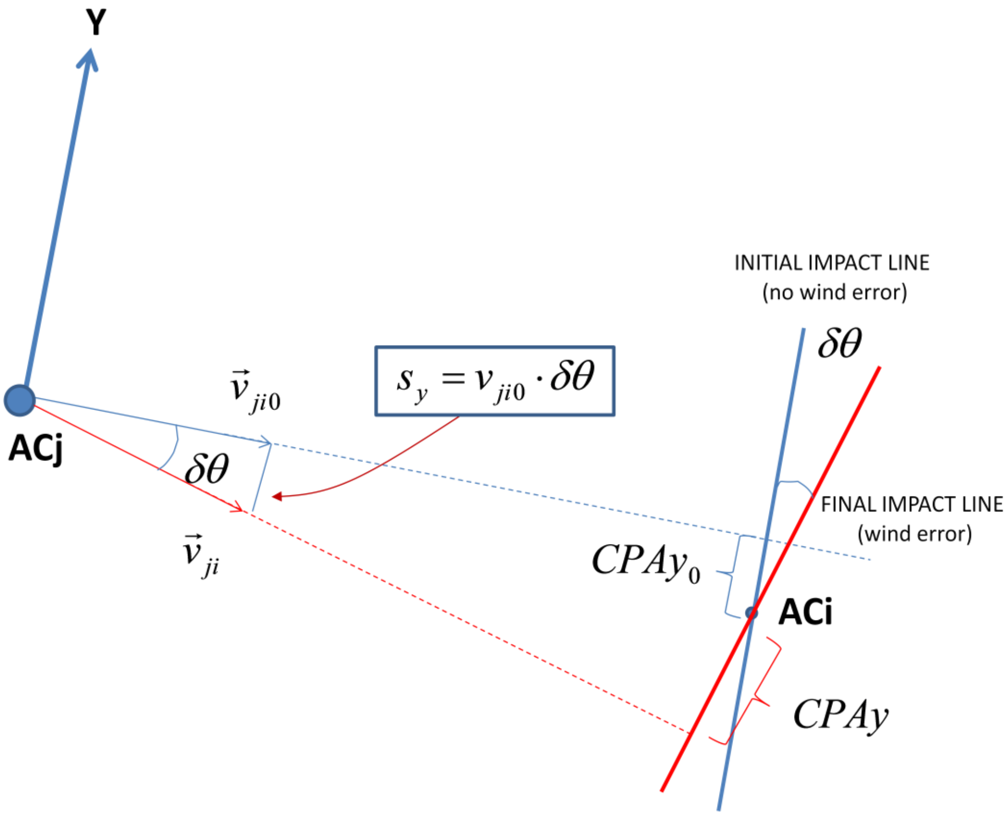


Figure 3.5. Relative speed coordinates uncertainty (y component)

Where $\delta\theta$ was introduced previously (1):

$$\boldsymbol{\delta\theta = atan}\left[\frac{w_j * \sin(\theta_{ji}-\theta_j) - w_i * \sin(\theta_{ji}-\theta_i)}{v_{ji0} + w_j * \cos(\theta_{ji}-\theta_j) - w_i * \cos(\theta_{ji}-\theta_i)}\right] =$$

$$atan\left[\frac{cos(\theta_j-\theta_w) * \sin(\theta_{ji}-\theta_j) - cos(\theta_i-\theta_w) * \sin(\theta_{ji}-\theta_i)}{\frac{v_{ji0}}{w} + cos(\theta_j-\theta_w) * \cos(\theta_{ji}-\theta_j) - cos(\theta_i-\theta_w) * \cos(\theta_{ji}-\theta_i)}\right]$$

It has been considered that the wind error projections on $\vec{v_j}$ and $\vec{v_i}$ are (see Figure 3.6):

$$w_{j,i} = w \cdot cos(\theta_{j,i} - \theta_w).$$

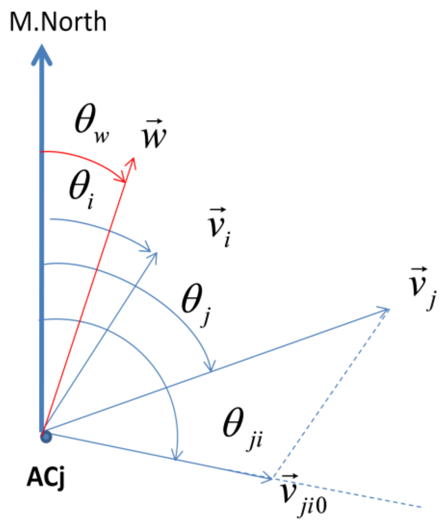


Figure 3.6. Wind projections

The expression for $\delta\theta$ calculation depends on the geometry of the encounter and the wind error direction through the three different angles $\theta_{j,i}$ and θ_w. Furthermore, it also depends on the ratio between the relative speed ($\boldsymbol{v_{ji0}}$) and the wind error estimation ($\boldsymbol{w}$). This expression could be rewritten as follows:

$$\boldsymbol{\delta\theta = atan\frac{a}{r+b}} \tag{12}$$

Where:

$$\boldsymbol{a = cos(\theta_j - \theta_w) * \sin(\theta_{ji} - \theta_j) - cos(\theta_i - \theta_w) * \sin(\theta_{ji} - \theta_i)}$$

$$\boldsymbol{b = cos(\theta_j - \theta_w) * \cos(\theta_{ji} - \theta_j) - cos(\theta_i - \theta_w) * \cos(\theta_{ji} - \theta_i)}$$

$$\boldsymbol{r = \frac{v_{ji0}}{w}}$$

It is clear that $\boldsymbol{v_{ji0} \gg w}$, and then $\boldsymbol{r \gg a, b}$. Then Equation (12) can be simplified as:

$$\boldsymbol{\delta\theta = atan\frac{a}{r+b} \approx \frac{a}{r+b}}$$

On the other hand, it would be desirable to express $\boldsymbol{\delta\theta}$ as a linear function of $\boldsymbol{\delta w}$. It can be done by using the first component of the Taylor Series development (components higher than first term are assumed negligible):

$$\boldsymbol{\delta\theta} \approx \boldsymbol{f}'(\mathbf{0})\boldsymbol{\delta w} \tag{13}$$

Where the derivative at zero is:

$$\boldsymbol{f}'^{(\mathbf{0})} = \frac{\partial}{\partial w}\left[\frac{a}{r+b}\right]_{w=0} = \frac{a * v_{ji0}}{w^2(r^2+b^2+2rb)}\bigg|_{w=0} = \frac{a}{v_{ji0}} \tag{14}$$

And then

$$\boldsymbol{\delta\theta} \approx \boldsymbol{f}'(\mathbf{0})\boldsymbol{\delta w} = \frac{a}{v_{ji0}}\boldsymbol{\delta w} \tag{15}$$

Introducing the expression (15) in the variance expression given by (11) results:

$$Q_{11} = t_{CPA}{}^2 v_{ji0}{}^2 * E\left[(\frac{a}{v_{ji0}}\boldsymbol{\delta w})^2\right] = t_{CPA}{}^2 a^2 * E[(\boldsymbol{\delta w})^2] = t_{CPA}{}^2 a^2 \sigma_w^2 \tag{16}$$

Where:

- t_{CPA} is the time for the conflict to happen, or time to CPA
- σ_w is the root mean square vector difference for wind error estimation
- a is a geometry factor which expression is:

$$\boldsymbol{a} = \boldsymbol{cos}(\boldsymbol{\theta_j} - \boldsymbol{\theta_w}) * \mathbf{sin}(\boldsymbol{\theta_{ji}} - \boldsymbol{\theta_j}) - \boldsymbol{cos}(\boldsymbol{\theta_i} - \boldsymbol{\theta_w}) * \mathbf{sin}(\boldsymbol{\theta_{ji}} - \boldsymbol{\theta_i}) \tag{17}$$

Taking now as reference axis for angles the direction of the relative velocity ($\overrightarrow{\boldsymbol{v_{ji0}}}$), the above equation can be simplified as:

$$\boldsymbol{a} = \boldsymbol{cos}(\boldsymbol{\theta_w} - \boldsymbol{\theta_i}) * \mathbf{sin}(\boldsymbol{\theta_i}) - \boldsymbol{cos}(\boldsymbol{\theta_w} - \boldsymbol{\theta_j}) * \mathbf{sin}(\boldsymbol{\theta_j}) \tag{18}$$

Finally, it can be summarised that the probability distribution for CPAy coordinate can be expressed by:

$$\sigma = t_{CPA} \quad a \quad \sigma_w \tag{19}$$

It can now be initially assumed for the wind statistical model to include two components, one estimated component introduced as part of the aircraft ground speed into the flight plan, plus a Gaussian distribution N(0, σ_w). This consideration has also been made by other authors[49, 50] according to whom the along track error at a time for aircraft in level flight is well modelled by a normal distribution.

3.5 Determination of trajectories compatibility

A potential conflict is nowadays identified when the minimum distance between two aircraft is, or is going to be in the short term, lower than an established minimum separation standard defined by two values, the minimum horizontal and vertical separations. During the en route phase of flight, in the ECAC airspace, these values are 5 NM horizontal distance and 1,000 ft in height.

However, these current minimum separation standards were determined many years ago and they are used to facilitate conflicts resolution in an ATC environment. Trajectories' compatibility should not be based on minimum separation standards but on probability of conflicts that finally would require tactical ATCO intervention. This compatibility should be established based on a trade-off between false alarm and misdetection probabilities.

This assumption is also made in [51] where a method of estimating conflict probability is developed in order to analyse medium term conflict detection and the implications for conflict resolution.

If a conflict is defined as two or more aircraft coming within the minimum allowed distance and altitude separation of each other, the minimum separation between trajectories to be declared as compatible would be established as a trade-off between capacity and predictability. The capacity, based on ATCO workload is related to the number of tactical interventions required by aircraft, whereas the predictability is related to the probability of exposure to risk, and could be defined as the degree of compliance between planned and actual aircraft positions, affecting the total system safety. Furthermore, this trade-off should take into consideration the Future ATM main goals defined under the European initiative[2], as the following measurable outcomes:

- 3 fold increase in capacity
- 10 fold increase in safety
- 50% reduction in ATM cost per flight

3.5.1 Capacity

Nowadays, for ATC purposes, the airspace is divided into sectors which are three dimensional volumes of airspace with specific dimensions and procedures depending on the type of traffic that goes through them and its physical characteristics. Each of these sectors is handled by an executive ATCO, and has a previously established capacity defined as the maximum number of aircraft that can be inside the sector within an hour. This capacity depends on the specific characteristics of each sector and it is considered as the maximum number of aircraft that the ATCO can manage, keeping the safety margins applied.

As the ATCO is able to control a limited number of aircraft, the number of available sectors must be increased to cope with an increment of air traffic demand. This has a clear limitation as tiny sectors cannot be properly managed and inter-sector coordination workload will grow as a consequence.

Current ATFM considers “conflict free” trajectories in a strategic/pre-tactical level if they do not exceed capacity at any involved “ATC sectors”. ATC sector capacity is mainly limited by ATCO conflict resolution workload for a given aircraft population.

As an example, some results providing a relative value of the risk for a given scenario have been obtained using real radar data in Maastricht UAC[36]. After processing 31 days of radar data (600 flights per sector a day) more than 45,000 proximate events were identified in the en route airspace assigned to the Maastricht UAC, which involves approximately a 50% of conflicted aircraft. Considering the total number of ATC sectors in that specific airspace, the conclusions obtained show about 75 potential conflicts per sector a day.

As a summary, the current sector management philosophy is based on a physical division of the airspace, the assignation of a defined capacity to any of the volumes in which the airspace is divided, and the allowance to enter these volumes only if this capacity is not exceeded. In the medium term the potential conflicts are not detected, and it is in the short term (tactical operation) when the conflicts are finally solved. The capacity limitation is in this case the human being, that is, the ATCO.

The new flow management philosophy proposed under this research will be based on a strategic detection of the conflicts, the de-confliction of the trajectories prior to the flight, the reduction of the potential conflicts, and as consequence a capacity increase.

If the conflicts per day to be solved by the ATC could be reduced this would decrease significantly the ATC workload involved in conflict resolution.

3.5.2 Predictability

Predictability is the degree to which a correct prediction or forecast of a system's state can be made either qualitatively or quantitatively.

When analysing the reduction of separation standards using automation tools, some studies[52] show criteria which use levels of predicted conflict uncertainty as acceptable for air traffic controller's decision support. As an example, the accepted medium term conflict probability is $5x10^{-2}$, since a reasonable level of missed detection is allowed, whereas the probability of conflict for short term separation assumed is 10^{-3} since the sector controller is responsible for assuming the final separation.

If we assume a threefold increase in the future air traffic demand[5, 36] the total number of flights per sector and per day could reach 1800 for the same number of existing sectors. Taking into account the previous probability range, the resulting number of conflicts/sector/day to be solved tactically is shown in Table 3.1 for both the current and future air traffic demand (n.conflicts=n.flights*Pconf).

Probability for a conflict	Number of conflicts/sector/day (current air traffic demand)	Number of conflicts/sector/day (threefold increase in demand)
$5x10^{-2}$ (current medium term prob. assumed)	30	90
$4x10^{-2}$	24	75
$3x10^{-2}$	18	54
$2x10^{-2}$	12	36
10^{-2}	6	18
$5x10^{-3}$	3	9
10^{-3} (current short term prob. assumed)	0.6	1.8

Table 3.1. Probability for a conflict to happen and resulting number of conflicts/sector/day (present and future)

As previously stated, some studies assume a medium term conflict probability of 5.10^{-2}. Nowadays this implies 30 conflicts/sector/day to be solved by the ATC (see Table 3.1). Similarly, in the short term the probability assumed is 10^{-3}, which is 0.6 conflicts/sector/day.

Considering a threefold traffic demand increase, the conflict detection tool developed under this research should, at least, provide a similar performance to the medium term automation tools previously considered, even despite an increase in the air traffic demand. From Table 3.1, in order to reach 36 conflicts/sector/day or less, the probability to be assumed should be at least $2x10^{-2}$. This value should even be lower if an increased in the current system capacity is needed.

Based on these probabilities the distance between two trajectories to be considered as compatible can be derived from Equation (19).

3.6 Vertical movement analysis

3.6.1 General.

The analysis developed under this research will concentrate primarily on trajectory compatibility for the en route phase of flight, that is, the one which comprises from the completion of initial climb through cruise altitude and completion of controlled descent to the fix where the standard arrival is initiated.

Within the en route phase of flight, the aircraft are most of the time established at a determined flight level. However, as this doesn't cover 100% of the flight, the vertical movement, its uncertainties and the way it influences the trajectory compatibility determination must be analysed.

The en route phase of flight includes the following sub-phases[53]:

- Climb to Cruise: From completion of initial climb to arrival at initial assigned cruise altitude.
- Cruise: Any level flight segment after arrival at initial cruise altitude until the start of descent to the destination (is the longer sub-phase).
- Change of Cruise Level: Any climb or descent during cruise after the initial climb to cruise, but before descent to the destination.
- Descent to standard arrival: descent to the fix where the standard arrival is initiated

When identifying the number of possible geometries for the encounters between two aircraft that could became a conflict it could be stated that any of them can be included into one the configurations shown in Table 3.2.

	Aircraft i/j	Aircraft j/i
1	Flight level	Flight level
2	Flight level	Climbing or descending
3	Climbing or descending	Climbing or descending

Table 3.2. Geometry configurations

A conflict has been defined as two aircraft coming below the minimum allowed distance and altitude separation of each other. It is obvious then, that only when the aircraft involved in the vertical movement is going to cross the level of the other aircraft, a potential conflict is possible, and only when in that precise moment the distance between the two aircraft is less than the minimum allowed distance the conflict is certain.

Nowadays, the potential conflicts between aircraft are identified by the ATCO when the foreseen distance between the aircraft involved is less than 5NM and 1000ft. The process followed is:

1. The conflict detection tools provide the minimum horizontal distance that is going to exist between two aircraft trajectories,
2. If this estimated distance is less than 5NM, and the aircraft altitudes are lower than the minima, a tactical action to be taken by the controller is triggered.

Again, the different configurations shown in Table 3.2 are to be considered. It is well understood that when the minimum predicted horizontal distance detected by the conflict detection tools is less than 5NM, and the encounter reflects configuration 1, being the two aircraft established at the same flight level, an action must be taken to avoid the conflict.

Similarly, when this occurs, but the encounter involves configuration 2 or 3, it could be assumed that action would only be taken if the distance between the two aircraft is less than 5NM in the very moment the vertical separation between the aircraft is less than 1.000 feet.

However, this is not what happens in the real operation. The standard working mechanisms used by ATCO deal with configurations 1, 2 and 3 in the same way, that is, taking tactical actions if the minimum horizontal distance foreseen by the conflict prediction tools is less than the allowed and if the flight levels of the aircraft are the same or are supposed to be crossing within the encounter whereabouts. The key factor is to define the encounter whereabouts.

Consequently, as the main goal of the trajectory de-confliction analysis developed so far is to reduce tactical actions taken by controllers, two trajectories are going to be considered as not compatible in a pre-tactical stage if the horizontal projection of them is less than a minimum distance defined, and the flight levels can be crossing in any time close to the encounter occurrence. This interval is going to be defined. To achieve this goal, the main characteristics of the climb/descent are going to be assessed. The analysis will concentrate on climb but could be also applied to descent.

3.6.2 Time intervals definition for conflict determination

For a specific aircraft and flight, many vertical profiles are possible, depending on the aircraft/engine type, weight, atmospheric conditions, bleed air settings and other vertical flight planning parameters.

There is an optimum pressure altitude to fly a plane, based on its weight. As the weight of the plane changes, so does its optimum altitude. Therefore, as fuel burns during cruise, the optimum altitude increases. In addition, as fuel burns off, the airplane's tendency is to climb.

The objective for an aircraft efficient flight is to climb as high as feasible after takeoff to reach an altitude, where fuel consumption is minimal (optimum altitude). Under normal circumstances, 4000 feet step-climbs are used to save fuel over long distance flights. The normal procedure to accomplish this is to first climb to an altitude, which is slightly above (1000 to 2000 feet) the optimum altitude at takeoff. Then maintain this cruising altitude, until the optimum altitude has drifted upwards to an altitude approximately 2000 feet above your present altitude. This process takes approximately 3 hours (required time to burn off the necessary fuel weight).

The decision to climb also includes the effects of head/tailwinds and ride conditions (icing may also be a consideration for lower cruise altitudes).

The rate of climb depends on the power and the weight. The density of air has significant effects on the airplane's performance. As air becomes less dense, it reduces:

- available power because the engine takes in less air,
- thrust because the propeller is less efficient in thin air, and
- lift because the thin air exerts less force on the airfoils.

The optimal rate of climb to be used in every case cannot be easily settled. What can be assured is that the normal rate of climb/descend for a turbojet varies between a v_{smax} and a v_{smin}.

To accommodate this rate of climb uncertainties, vertical buffers can be defined (see Figure 3.7) to include error in modelling the vertical profile. The higher the difference between the maximum rate of climb and the minimum rate of climb is, the larger the altitude buffer area will be.

It will be assumed that the top of descent or the top of climb point coordinates are defined, and their uncertainties will not be considered. The reason for that is that the horizontal uncertainties have been already analysed and the minimum distance obtained for trajectory compatibility determination includes them.

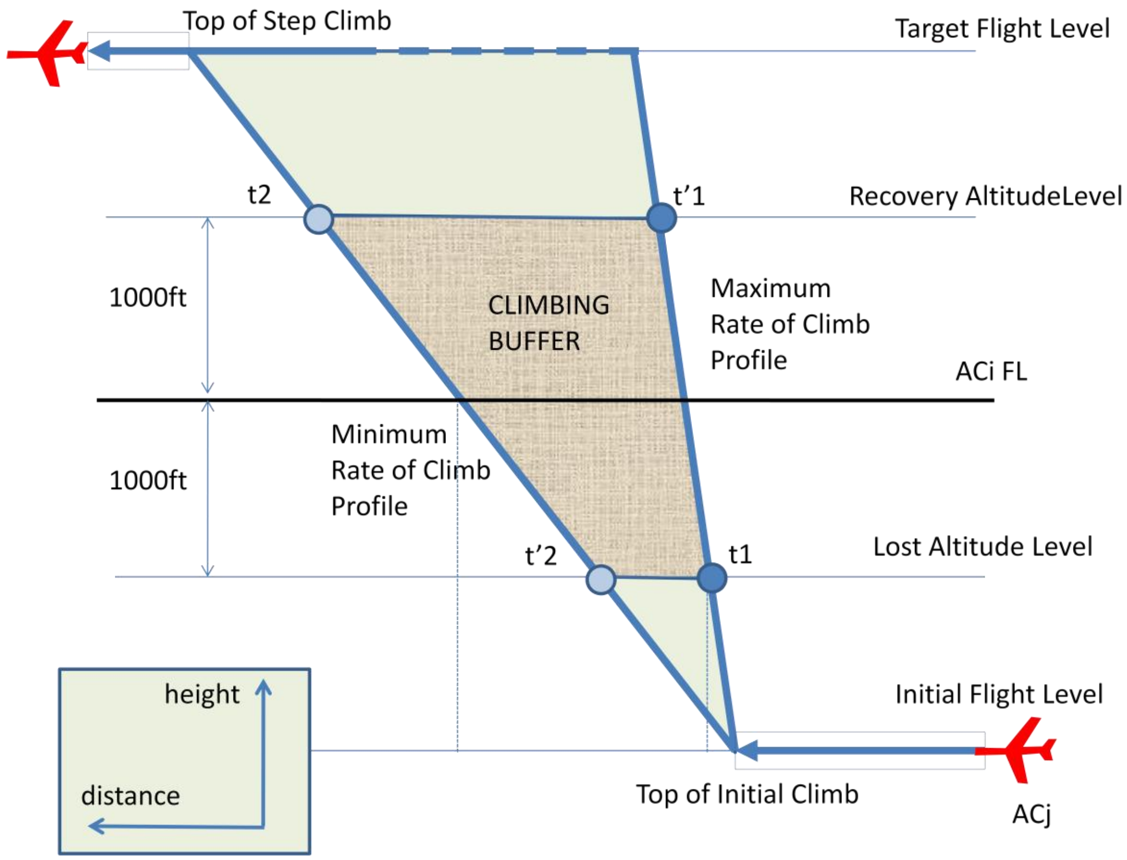


Figure 3.7. Altitude buffer for maximum and minimum rate of climb

As an example, if an aircraft ACj established at an initial FL starts climbing up to an specific new target FL crossing the FL of another aircraft ACi, a potential conflict could be “a priori” identified (assuming that the minimum horizontal distance between both aircraft is less than the established). The conflict will exist when the vertical distance between the two aircraft is less than 1.000ft, which starts when ACj crosses the called Lost Altitude Level (LAL), and ends when it crosses the called Recovery Altitude Level (RAL) (minimum altitude between the two aircraft 1.000ft). Depending on the rate of climb, LAL would be crossed at t1 or t’2, and RAL at t’1 or t2.

Figure 3.8 shows an encounter vertical and horizontal profile.

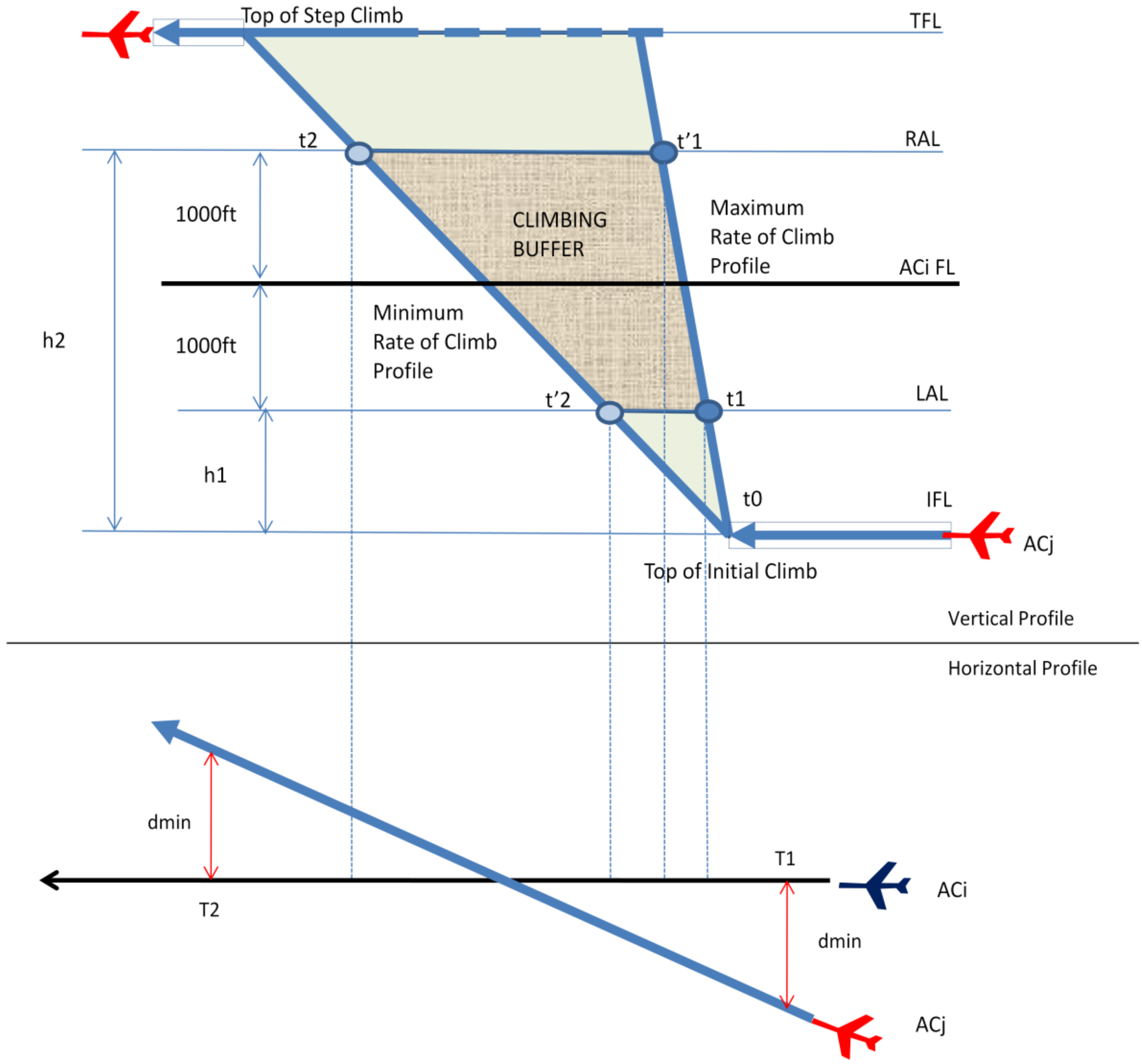


Figure 3.8. Potential conflict determination

Looking into the horizontal profile it can be concluded that between the interval T1 and T2 the two aircraft will be closer than the minimum allowed distance. Being:

- T1: time when the minimum distance between aircraft is less than the minimum standard horizontal separation and decreasing.
- T2: time when the minimum distance between aircraft is less than the minimum standard horizontal separation and increasing.

On the other hand, and as stated above, the vertical profile shows that between the interval t1and t'1(maximum rate of climb), or between the interval t'2 and t2 (minimum rate of climb), the aircraft vertical distance will be less than 1000ft.

A potential conflict will happen if both intervals, the horizontal and the vertical one, are overlapped, that is mathematically:

$$(T1, T2) \cap (t1, t'1) \neq \emptyset \text{ (max.} rate\ of\ climb)$$

or

$$(T1, T2) \cap (t'2, t2) \neq \emptyset\ (min.rate\ of\ climb)$$

In this particular case the two trajectories will be considered as not compatible.

Similarly, Figure 3.9 shows an encounter in which two trajectories could be defined as compatible. In this case the horizontal and vertical intervals are not overlapped, that is mathematically:

$$(T1, T2) \cap (t1, t'1) = \emptyset$$

or

$$(T1, T2) \cap (t'2, t2) = \emptyset$$

It is not necessary, however, to include both intervals (t1,t'1) and (t'2,t2) in the calculation process. From now on, it would be considered only the interval (t1,t2) as the one in which the vertical separation between both aircraft is not guaranteed. As we cannot assure the rate of climb the aircraft will maintain, taking this interval in our calculations will involve a conservative approach to the trajectory compatibility determination as all the possible rates of climb for every aircraft would be included.

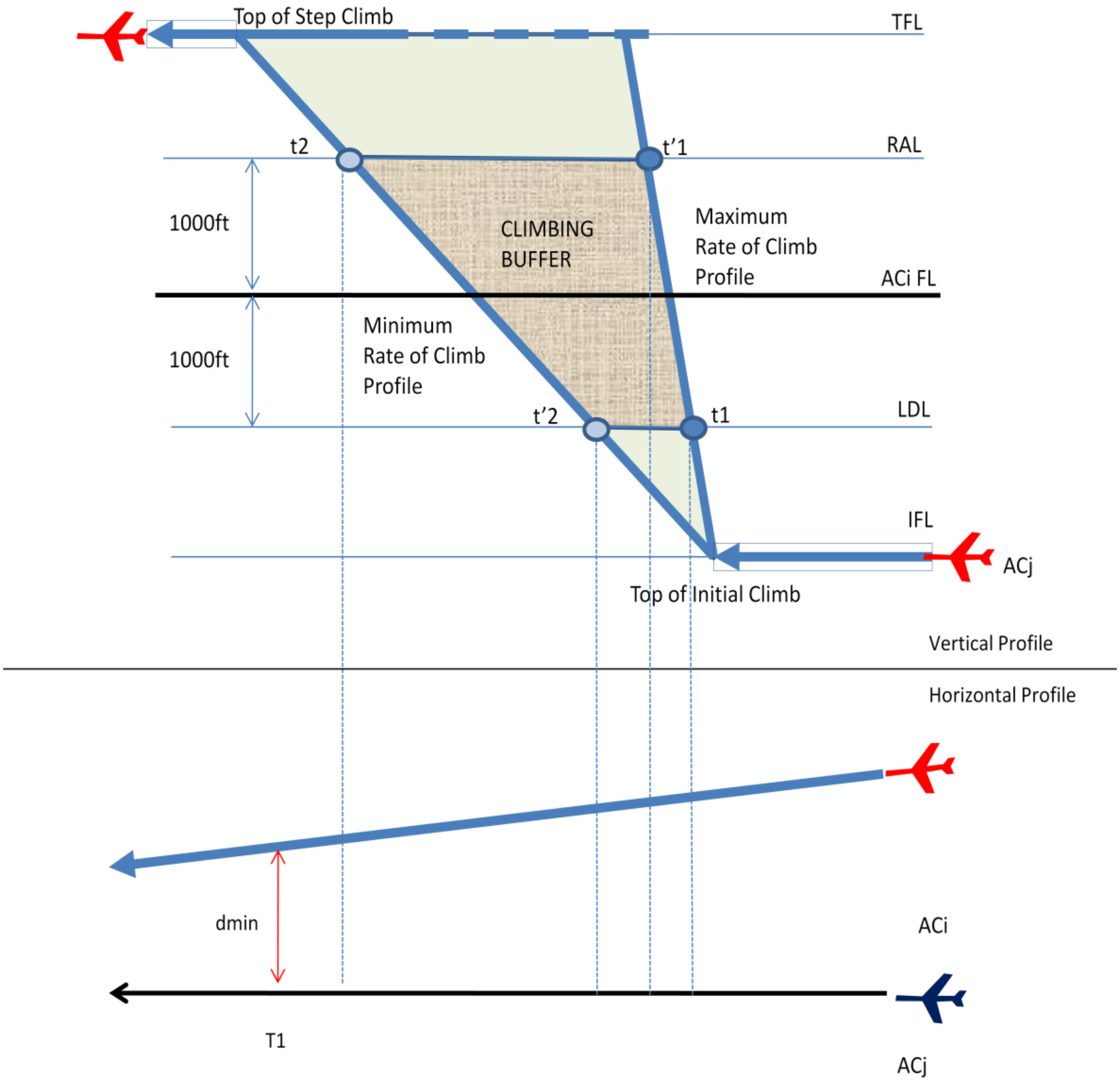


Figure 3.9. Compatible trajectories

As part of the process for trajectory compatibility determination the intervals (T1, T2) and (t1,t2) should be calculated and identified if any overlap exists. The conflict time interval (T_C) will be defined as the interval in which a potential conflict between two trajectories is possible, that is mathematically:

$$T_C = (T1, T2) \cap (t1, t2)$$

As a summary, Figure 3.10 presents a flow chart showing the process to be followed to determine the trajectories compatibility.

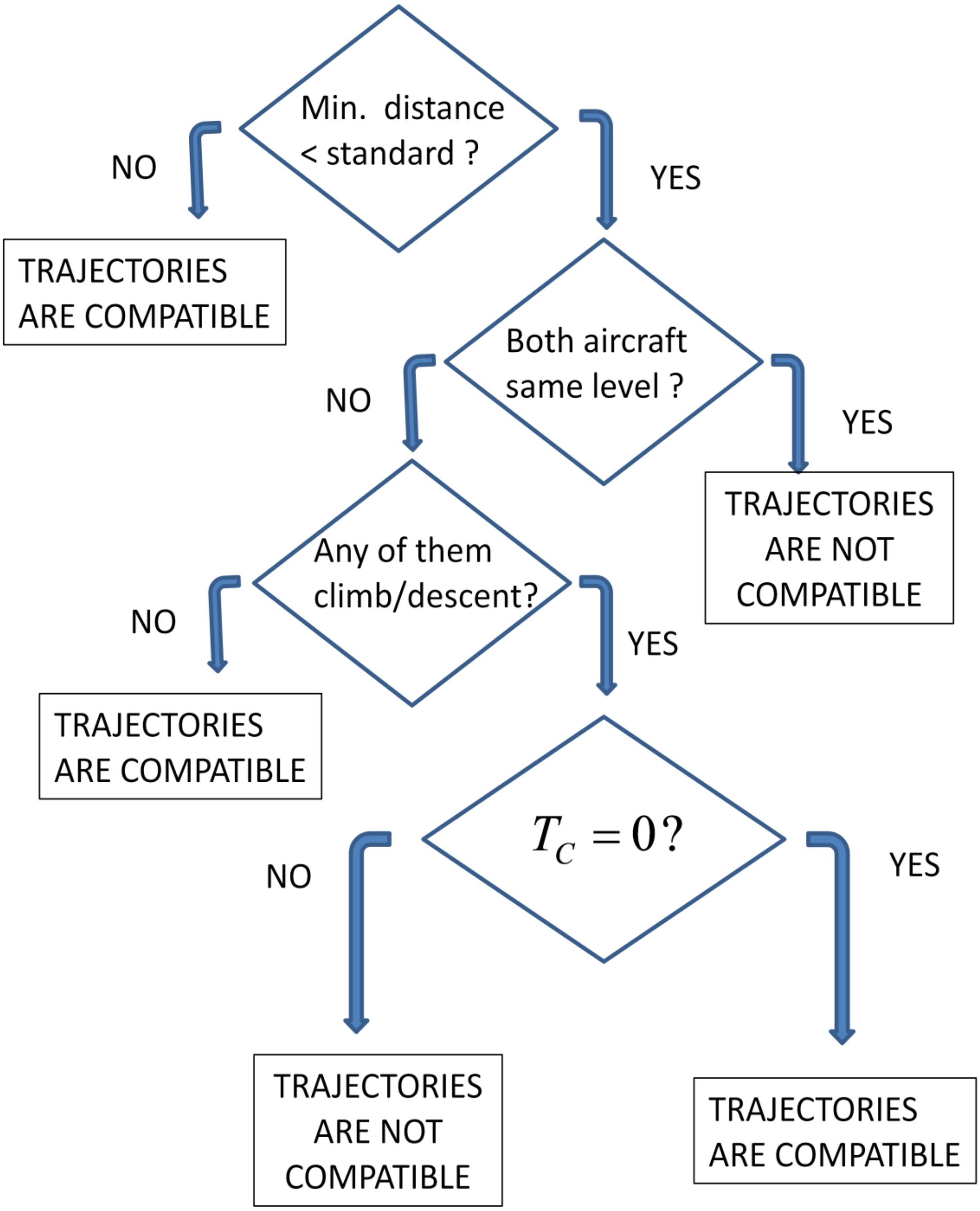


Figure 3.10. Flow Chart

3.7 Summary

The aircraft kinematics has been split into horizontal and vertical movement, analysed separately one from the other in order to simplify the approach.

The Closest Point of Approach of two aircraft trajectories is calculated and the effect of wind error on its determination is analysed in two different steps:

1. The impact line angle variation due to the wind error effect is calculated,
2. The parameters involved in the definition of the uncertainties associated to the CPA coordinates are identified.

The new criterion to define two trajectories as compatible based on a trade-off between capacity and predictability is explained.

The analysis of the potential conflicts when one or both aircraft involved in the encounter are climbing or descending is presented. This analysis is based on the current method followed by the ATCO in the daily operation. The buffering area and the conflict time interval are defined.

4. ANALYSIS

4.1 Minimum distance to declare two trajectories as compatible

As a conclusion from Section 3, the probability distribution for CPAy coordinate is determined by:

$$\sigma = t_{CPA} \quad a \quad \sigma_w \tag{19}$$

Each of the factors composing Equation (19) will be analysed and some initial considerations and results shown. The numerical results and graphs have been obtained using MATLAB software (see Annex IV).

4.1.1 Time to CPA (t_{CPA})

As it has been previously stated the estimation for t_{CPA} is:

$$time\ to\ CPA = \frac{x_j}{v_{ji}}$$

Once a potential conflict is detected, and segments of the trajectories involved are modelled, the t_{CPA} is defined as the time for the conflict to happen. To determine its value the predicted trajectories definition and the normal time horizon that is currently used by the prediction tools must be considered.

Network Management tools will typically work with the flight profile for the whole flight (that is an average of two hours). Whereas tactical tools may predict the flight only with regard to the current ATC sector, with the looking ahead time being less than 20 minutes.

As the trade-off between expected trajectories accuracy and look-ahead time must be established, an intermediate value of **1 hour** for the calculations presented in this research will be settled.

4.1.2 Wind error estimation: $\boldsymbol{\sigma_w}$

Taking into account previous Sections of this document, it will be considered an initial wind error RMS value of 6 m/s (12kt)[26]. This value has been obtained under the following assumptions:

- A predominant daily value for RMS vector difference is of 4.5-5.5 m/s range. This value was obtained taking into account all possible forecast projections (from 0 to 6 hours).
- The forecast errors grow with the time in advance of the forecast projection, being the RMS vector difference values increase of about 1.5 m/s from 1 to 6 hours.

As it is considered that the RBT will be presented at least, about 6 hours before the operation time, a value for the RMS vector difference of 5.5m/s plus a 0.5m/s increment is settled (because most of the measures in the referenced study have been done for projections less than 6 hours in advance).

This value (6 m/s=12kt=0.2NM/min) is very similar to the one obtained in other analysis of conflict detection among aircraft on level flights[40], in which a rate of growth of along track RMS error of 0.22NM per minute is reported.

4.1.3 Geometry factor: $\boldsymbol{a}$

The influence of the encounter geometry on the CPA coordinates variation due to the wind error affection is expressed through the so-called geometry factor.

Considering the expression obtained for the geometry factor calculation (18) (all angles are measured from the relative velocity $\overrightarrow{\boldsymbol{v_{ji0}}}$):

$$\boldsymbol{a} = \boldsymbol{cos}(\boldsymbol{\theta_w} - \boldsymbol{\theta_i}) * \sin(\boldsymbol{\theta_i}) \quad - \; \boldsymbol{cos}(\boldsymbol{\theta_w} - \boldsymbol{\theta_i}) * \sin\left(\boldsymbol{\theta_j}\right) \qquad \textbf{(18)}$$

The variation of $\boldsymbol{a}$ for different wind angles, $\boldsymbol{\theta_w}$, and different encounter geometries $(\boldsymbol{\theta_j}, \boldsymbol{\theta_i}, \frac{v_j}{v_i})$ will be presented.

The geometry of the encounter itself is dependent on the angle between the tracks followed by the aircraft ($\boldsymbol{\theta_j}, \boldsymbol{\theta_i}$) and their speeds ratio ($\frac{v_j}{v_i}$)**.** Given $\boldsymbol{\theta_j}$, $\boldsymbol{\theta_i}$ is established by (see Annex III):

$$\boldsymbol{\theta_i = \pi - arcsin\left[\frac{v_j}{v_i}\, sin\theta_j\right]} \qquad \textbf{(20)}$$

On the other hand, the geometry is totally defined considering the direction of the wind, $\boldsymbol{\theta_w}$, in relation to the angle between the aircraft tracks**.**

As previously indicated, it must be taken into account that the origin of angles has been settled in $\overrightarrow{v_{ji0}}$ direction, and must be highlighted that under this reference there are some geometries that are not possible and, therefore, are being ignored in the analysis. These configurations are the following:

- $\boldsymbol{\theta_i or\ \theta_j = 0, \pi}$ This would assume two aircraft flying a track with the same heading or opposite heading. Although some studies[42] consider the user-preferred trajectories as a total removal of the current flight level constraints based on the east/north west/south flying routes, this Research still considers the current segregated cruise altitudes. Taking this into account, tracks with opposite heading are operationally only possible if one of the aircraft is climbing or descending. This case is initially not considered, as only the horizontal movement is being under analysis at this stage. On the other hand, tracks with same heading are exposed to the same winds and then, compatibility will be easily identified.
- $\boldsymbol{\theta_i or\ \theta_j = \pi/2}$ It is not possible due to obvious geometrical reasons.

In order to carry out a sensitivity analysis to equation (18) three speeds ratios, $\frac{v_j}{v_i}$, have been settled: 1 (same speed), ½ , and 1/8.

4.1.3.1 Speeds ratio, $\frac{v_j}{v_i} = 1$

If the aircraft speeds are considered to be equal, for every angle between tracks ($\boldsymbol{\theta_j}$, $\boldsymbol{\theta_i}$), a different geometry factor could be calculated with wind error angle variation.

As an example, Table 4.1 presents for two different encounter geometries, the wind angle that would produce a maximum in Equation (18) (this obviously implies a maximum value in the probability distribution for CPAy coordinate, σ, Equation (19)). In the first case the calculated $\boldsymbol{a}$ maximum value is 1, whereas in the second case this maximum value is 0.34. It is obvious that the first encounter geometry ($\theta_j = 45$) provides a higher $\boldsymbol{a}$ value.

$\boldsymbol{\theta_j}$ ($\boldsymbol{\theta_i}$)	$\boldsymbol{\theta_{wmax}}$	$\boldsymbol{a}$
45 degrees (135 degrees)	0 degrees	1
10 degrees (170 degrees)	0 degrees	0.34

Table 4.1. Parameters determination (same speed)

Taking this into consideration, Figure 4.1 presents the calculation of the geometry factor "$\boldsymbol{a}$" increasing $\boldsymbol{\theta_j}$ **f**rom 10 to 80 degrees (colour legend is explained), $\boldsymbol{\theta_w}$ from 0 to 180 degrees**.**

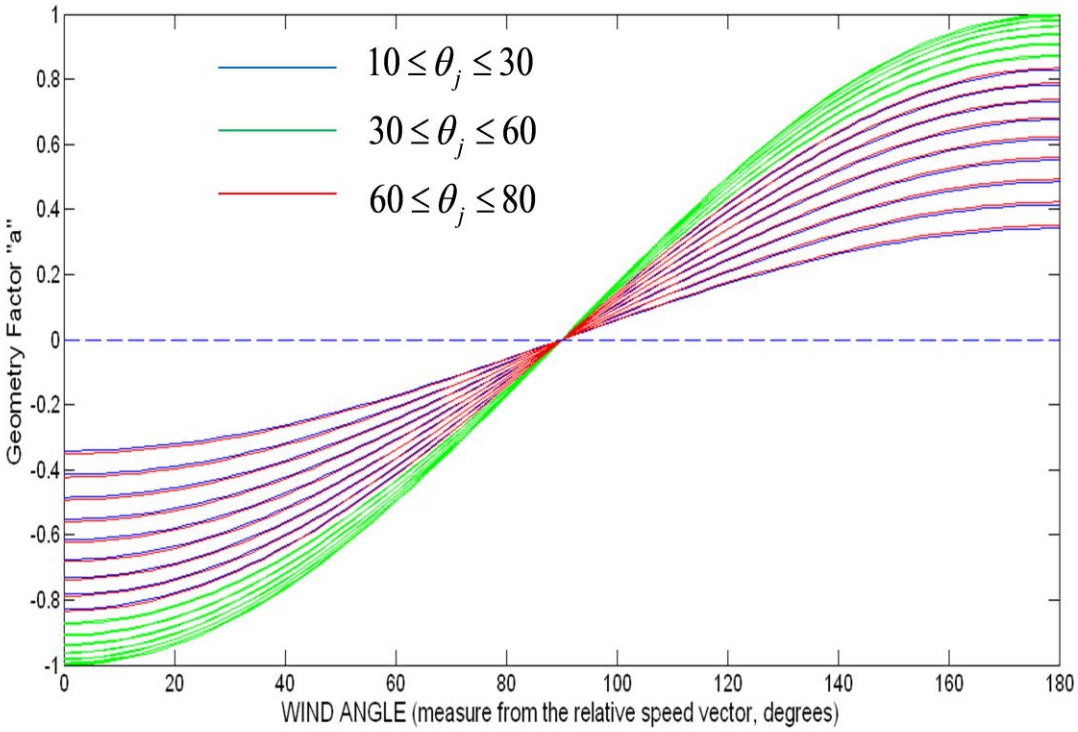


Figure 4.1. Geometry factor calculation for different encounter configurations ($\frac{v_j}{v_i}$ = 1).

The Figure 4.1 shows symmetrical sinusoid functions whose zero value are at $\boldsymbol{\theta_w = \pi/2}$ and peak at $\boldsymbol{\theta_w = 0, \pi}$. This implies that the wind "effect" is maximum ($\boldsymbol{a}$ max) when it has the same direction of the relative speed vector, and minimum ($\boldsymbol{a}$ =0) when it is perpendicular to it.

One of the most interesting results to analyse is the geometry of the encounter for which the geometry factor "$\boldsymbol{a}$" reaches its absolute maximum value. Being the wind angle for higher error 0 and 180 degrees, the aircraft j angles for "$\boldsymbol{a}$" maximum are presented in Figure 4.2. From this Figure it could be deduced that the encounter geometry that would produce a maximum value for the probability distribution for CPAy coordinate, σ, (equation (19)), for speeds ratio equal to 1, is when θ_j=45 degrees.

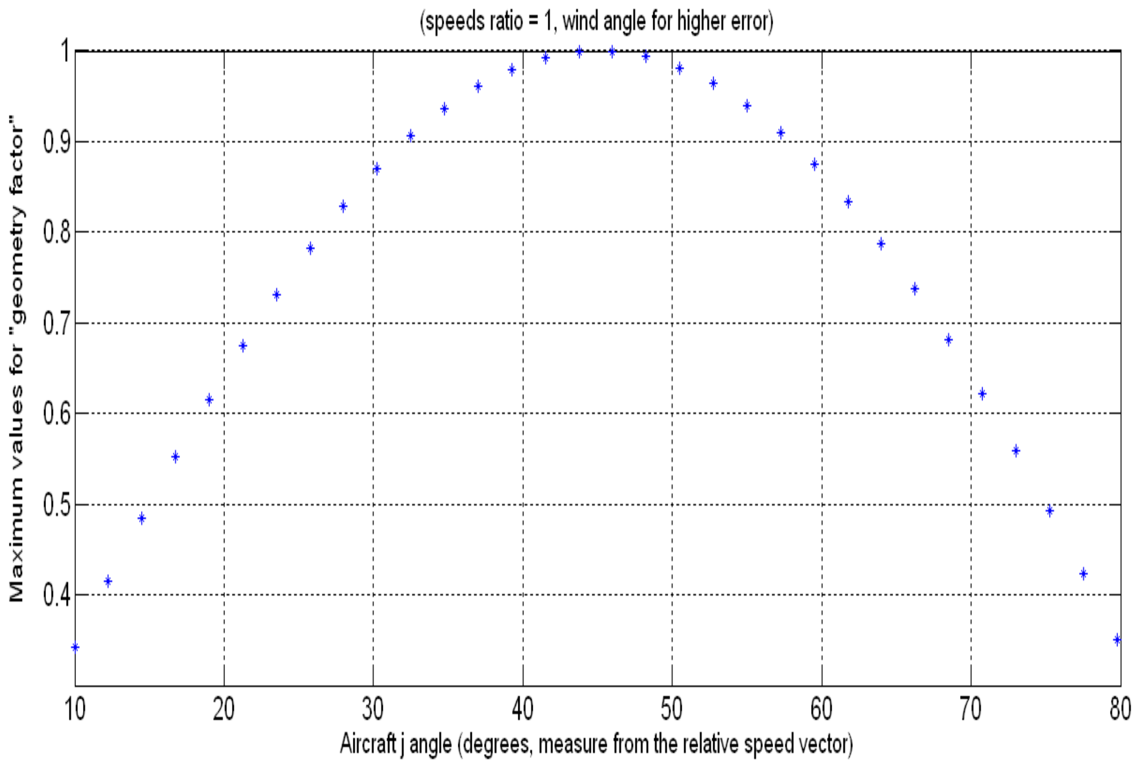


Figure 4.2. Aircraft j angle for a maximum. Speed Ratio = 1

Increasing θ_j from 10 to 80 degrees, the correspondent θ_i angle, and the calculated θ_w for which "$\boldsymbol{a}$" is maximum is presented in Figure 4.3. From it can be learnt, again, that when both aircraft have the same speed, a wind direction parallel to the relative speed vector (θ_w=0), makes "$\boldsymbol{a}$" reach its maximum value.

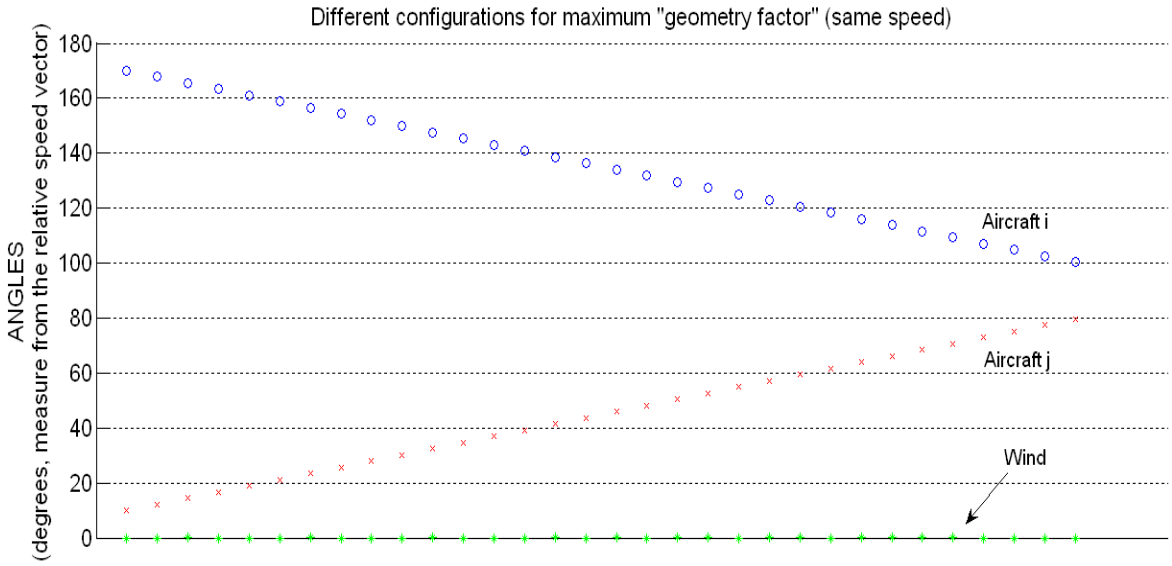


Figure 4.3. Encounter geometry for "*a*" maximum. ($\frac{v_j}{v_i} = 1$).

Figure 4.4 shows the encounter geometrical configurations included in Table 4.1. From this Table and previous Figures analysis, it could be stated that the nearer the angle between the aircraft routes is to 90 degrees, the higher is the geometry factor, and vice versa. When both aircraft have the same speed, a maximum value in the probability distribution for CPAy coordinate, σ, would be obtained for an angle between routes equal to 90 degrees and a wind error direction parallel to the relative speed vector.

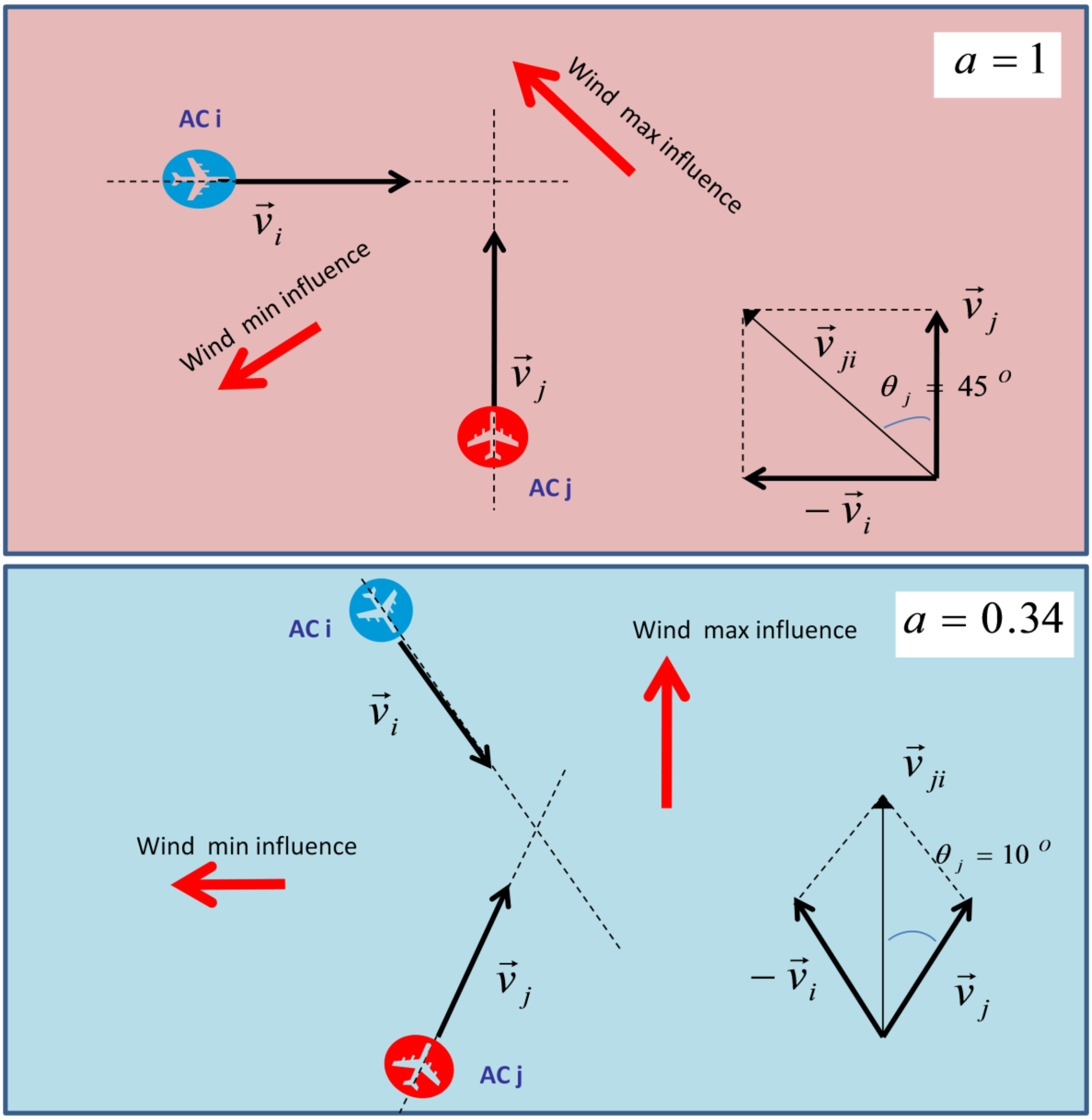


Figure 4.4. Encounter geometry analysis ($\frac{v_j}{v_i} = 1$). (Note that the wind vectors are not proportional)

4.1.3.2 Speeds ratio, $\frac{v_j}{v_i} = ½$

In contrast to the results presented in the previous Figures, a speed ratio different from one reflects that the maximum or minimum values for "***a***" are not always obtained for wind angles equalling zero, 90 or 180 degrees.

As an example, Table 4.2 presents for two different encounter geometries, the wind angle that produces a maximum in the geometry factor.

θ_j (θ_i)	θ_{wmax}	a
63 degrees (153 degrees)	36 degrees	0.99
10 degrees (175 degrees)	5 degrees	0.26

Table 4.2 Parameters determination speed ratio ½

Figure 4.5 presents the calculation of the geometry factor "$\boldsymbol{a}$" increasing θ_j from 10 to 80 degrees (colour legend is explained), θ_w from 0 to 180 degrees and settling speeds ratio as ½ .

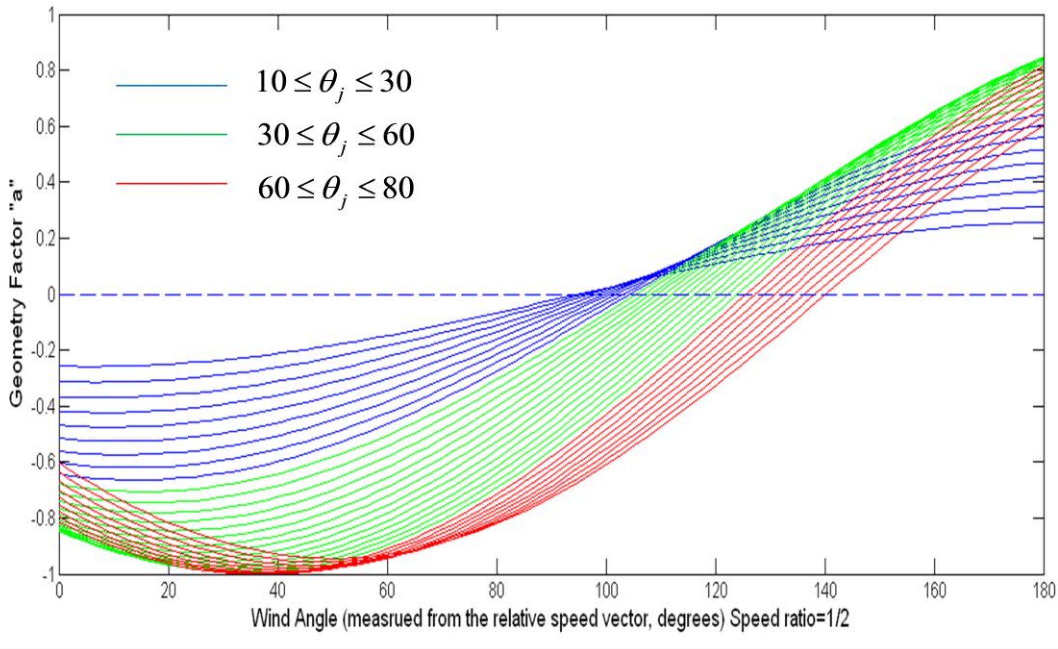


Figure 4.5. Geometry factor calculation for different encounter configurations ($\frac{v_j}{v_i}$ = ½).

It is observed that in this case the maximum values for the geometry factor are reached by the green lines, and some of the first red ones, that is, for an angle range from 50 to 80 degrees. This is more precisely seen in Figure 4.6.

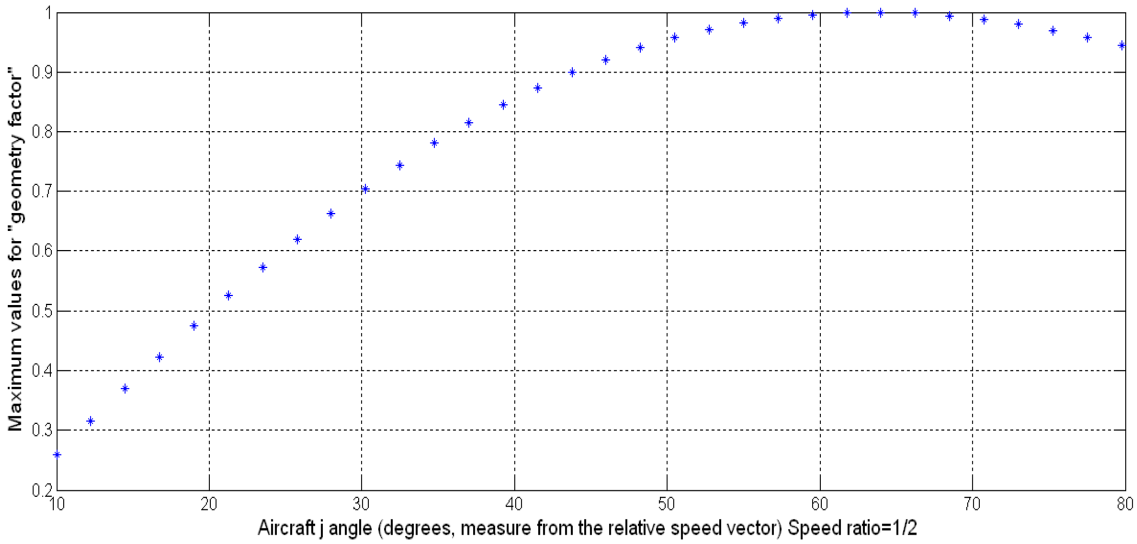


Figure 4.6. Maximum "*a*" values. Speed ratio ½

Increasing θ_j from 10 to 80 degrees, the correspondent θ_i angle, and the calculated θ_w for which "***a***" is maximum is presented in Figure 4.7. Whereas in the previous case if the wind direction is the same of the relative speed vector (θ_w=0), "***a***" reaches its maximum value, when speed ratio is ½ the worst configuration (a maximum) is produced when the wind direction is close to the aircraft whose speed is minor (in this case ACj).

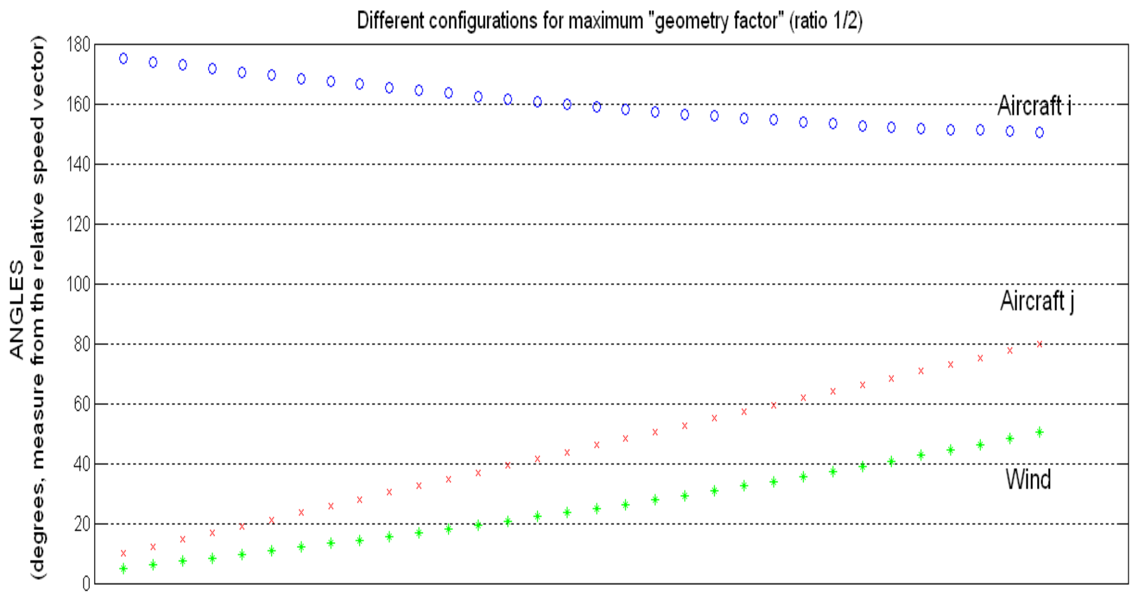


Figure 4.7. Encounter geometry for "*a*" maximum. ($\frac{v_j}{v_i}$ = ½).

Figure 4.8 shows the encounter geometrical configuration included in Table 4.2 that provides a geometry factor of 0.99. From this Table and previous figures analysis, it could be stated that the nearer the wind angle is from θ_j(aircraft whose speed is minor) the higher is the value obtained for the geometry factor.

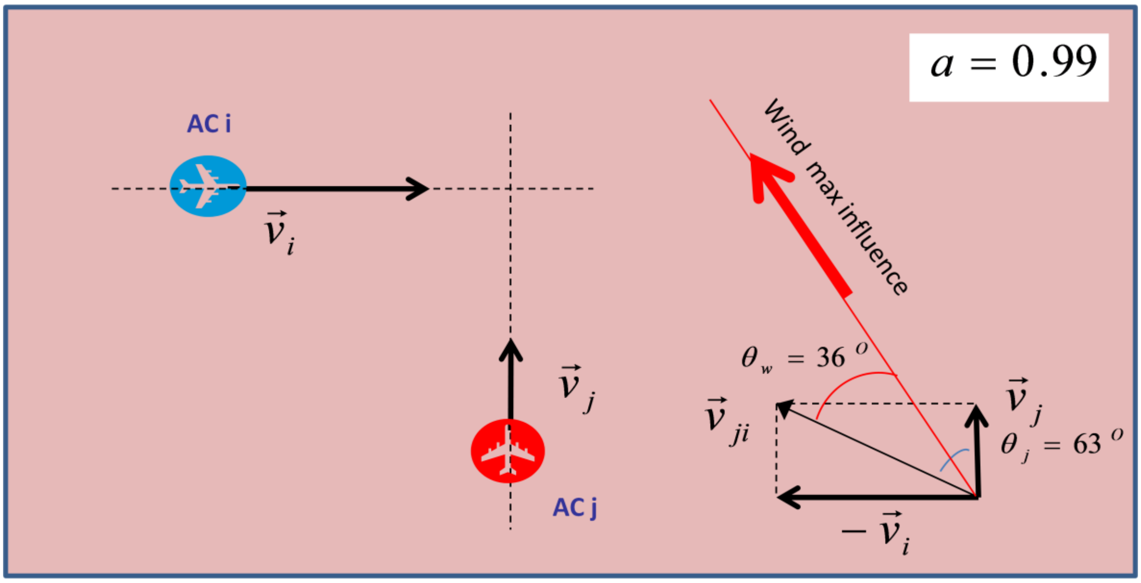


Figure 4.8. Encounter geometry analysis ($\frac{v_j}{v_i}$ = ½). (Note that the wind vectors are not proportional)

4.1.3.3 Speeds ratio, $\frac{v_j}{v_i}$ = 1/8

This case also reflects that the maximum or minimum values for "***a***" are not always obtained for wind angles equalling cero, 90 or 180 degrees.

As an example, Table 4.3 presents for two different encounter geometries, the wind angle that produces a maximum in the geometry factor.

$\boldsymbol{\theta_j}$ ($\boldsymbol{\theta_i}$)	$\boldsymbol{\theta_{wmax}}$	$\boldsymbol{a}$
79.7 degrees (172.9 degrees)	72.7 degrees	0.99
10 degrees (178.5 degrees)	8.8 degrees	0.19

Table 4.3. Parameters determination speed ratio 1/8

Figure 4.9 presents the calculation of the geometry factor "$\boldsymbol{a}$" increasing θ_j from 10 to 80 degrees (colour legend is explained), θ_w from 0 to 180 degrees and settling speeds ratio as 1/8 .

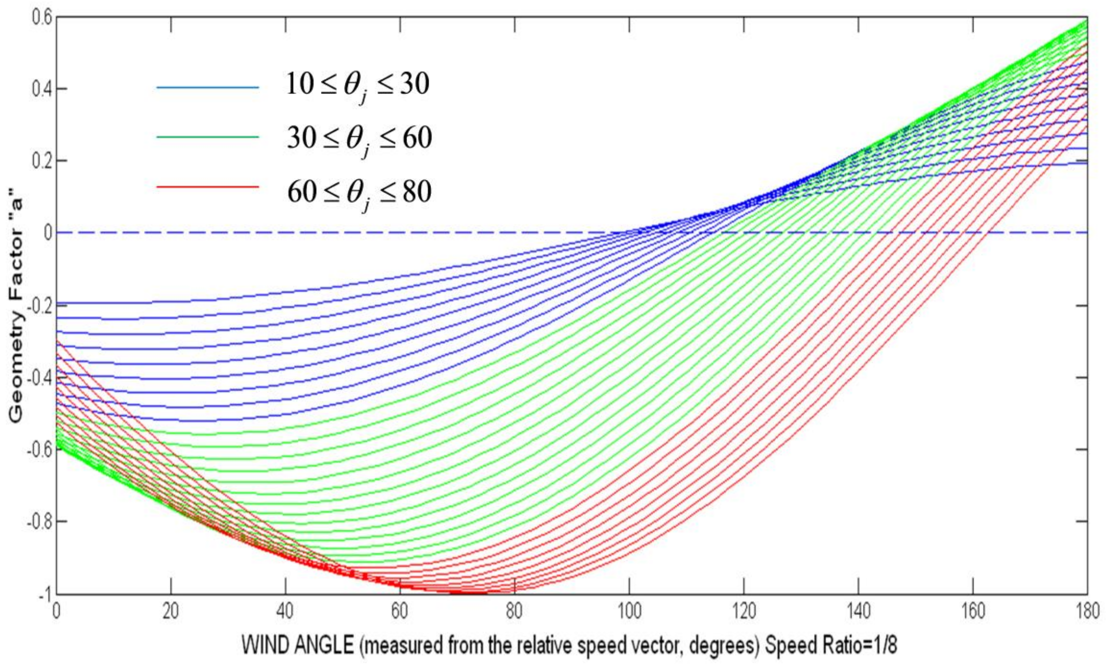


Figure 4.9. Geometry factor calculation for different encounter configurations ($\frac{v_j}{v_i}$ = 1/8).

It is observed that in this case the maximum values for the geometry factor are reached by the red lines, that is, for an angle range from 60 to 80 degrees. This is more clearly seen in Figure 4.10.

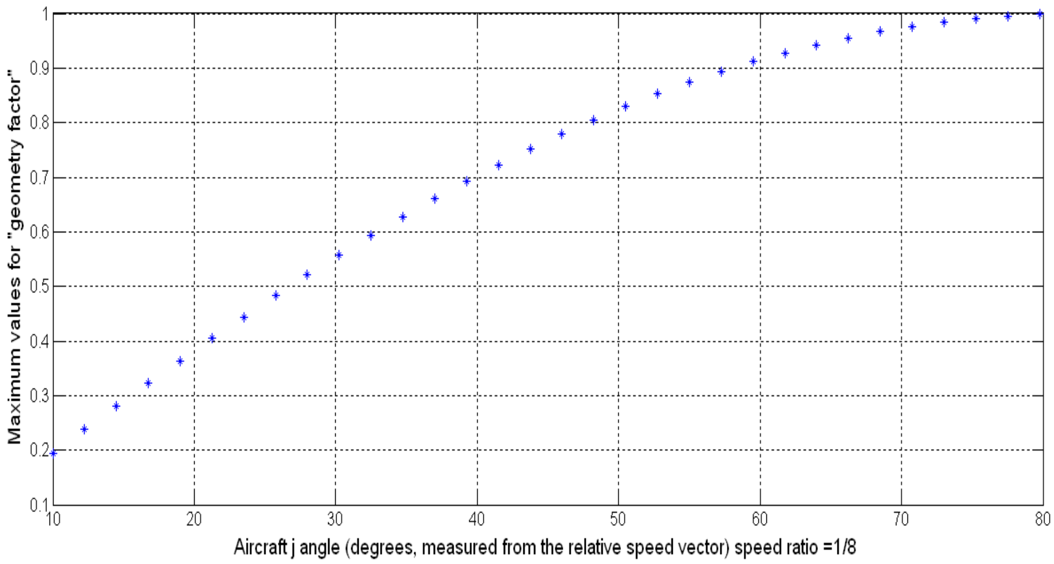


Figure 4.10. Maximum "*a*" values. Speed ratio 1/8

Increasing θ_j from 10 to 80 degrees, the correspondent θ_i angle, and the calculated θ_w for which "***a***" is maximum is presented in Figure 4.11. As in the previous case the worst configuration (***a*** maximum) is produced when the wind direction is close to the aircraft whose speed is minor (ACj). Comparing with the previous case (speeds ratio=1/2) the wind direction for "***a***" maximum is even closer to ACj velocity.

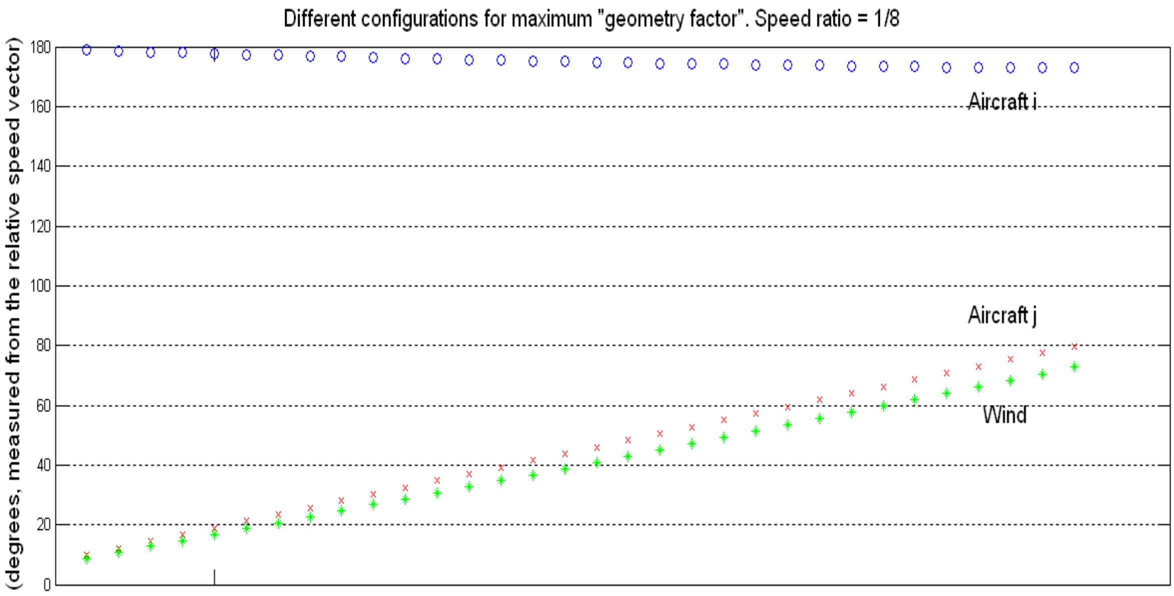


Figure 4.11. Encounter geometry for "*a*" maximum. ($\frac{v_j}{v_i}$ = 1/8).

Figure 4.12 shows the encounter geometrical configuration included in Table 4.3 that provides a geometry factor of 0.99. From this Table and previous Figures analysis, it could be stated that the nearer the wind angle is to θ_j(aircraft whose speed is minor) the higher is the value obtained for the geometry factor.

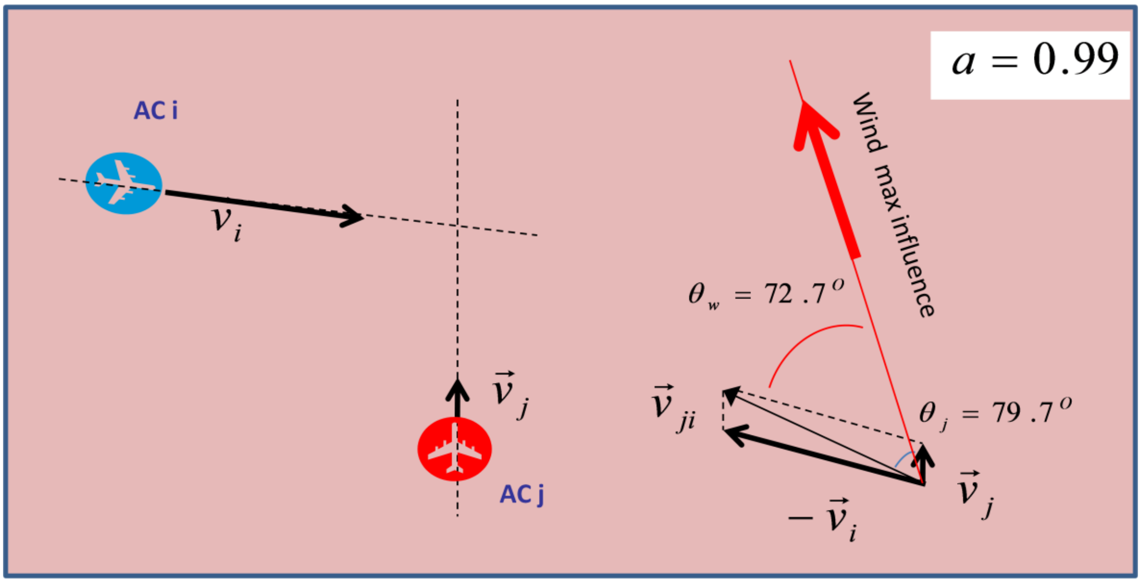


Figure 4.12. Encounter geometry analysis ($\frac{v_j}{v_i}$ = 1/8). (Note that the wind vectors are not proportional)

4.1.4. Minimum distance for trajectory compatibility calculation

From the above presented results the "***a***" value for every specific wind angle could be calculated knowing the aircraft speeds and the encounter angles for both aircraft (data known throughout the flight plan).

Whether the prevailing winds in the airspace where the encounter is to happen could be known in advance, an accurate value for the geometry factor "***a***" could be calculated. If no previous information about the wind field is available, the wind angle that produces the higher error should be chosen in order to be conservative.

As previously stated (Section 3.4) the probability distribution for CPA coordinates determination is being modelled through a Gaussian distribution with σ = $t_{CPA} \;\; a \;\; \sigma_w$:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-1}{2}\left(\frac{x}{\sigma}\right)^2}$$

Figure 4.13 shows the probability density functions obtained setting the following values for the parameters determining σ (19):

- As the speed range for turbojets is very similar, from now on a ratio between aircraft speeds equal to 1 will be considered.
- t_{CPA} = 60 min
- σ_w = 6 m/s
- a = maximum values obtained for the different geometry configurations (see Figure 4.2)

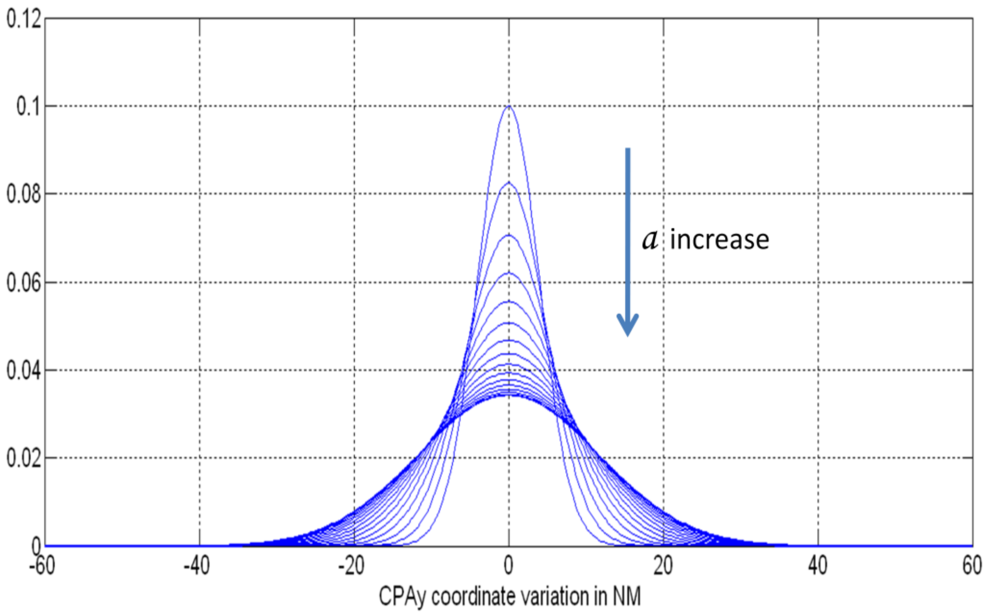


Figure 4.13. Probability density functions for maximum "a" values and same speed (Figure 4.2).

This functions show the probability distribution of the CPAy coordinate due to the wind error effect on the aircraft speed.

If the CPAy coordinate could be accurately calculated the minimum distance between two aircraft trajectories would be exactly known (see Figure 3.1). The longitudinal uncertainty in the trajectory prediction due to the wind error effect on the aircraft speed makes the CPAy coordinate to follow one of the probability density functions that have been previously calculated (see Figure 4.14).

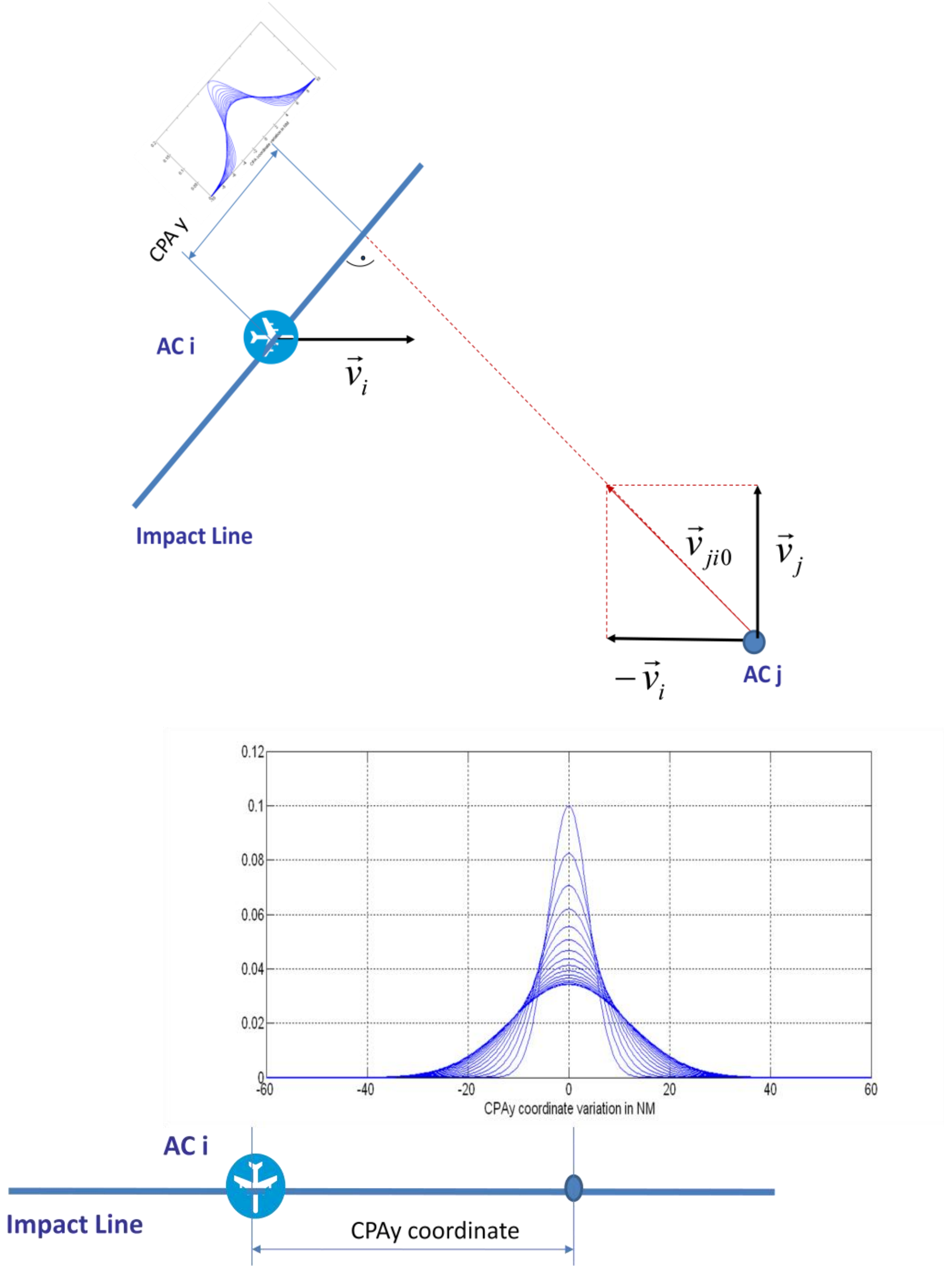


Figure 4.14. Error in the CPAy coordinate calculation due to the wind uncertainty

It is now to be considered that the minimum separation between the aircraft involved in the encounter must be, at least, equal to the current minimum standard separation, which is 5 NM. Furthermore, it must be settled the probability for a conflict to happen that is going to be assumed.

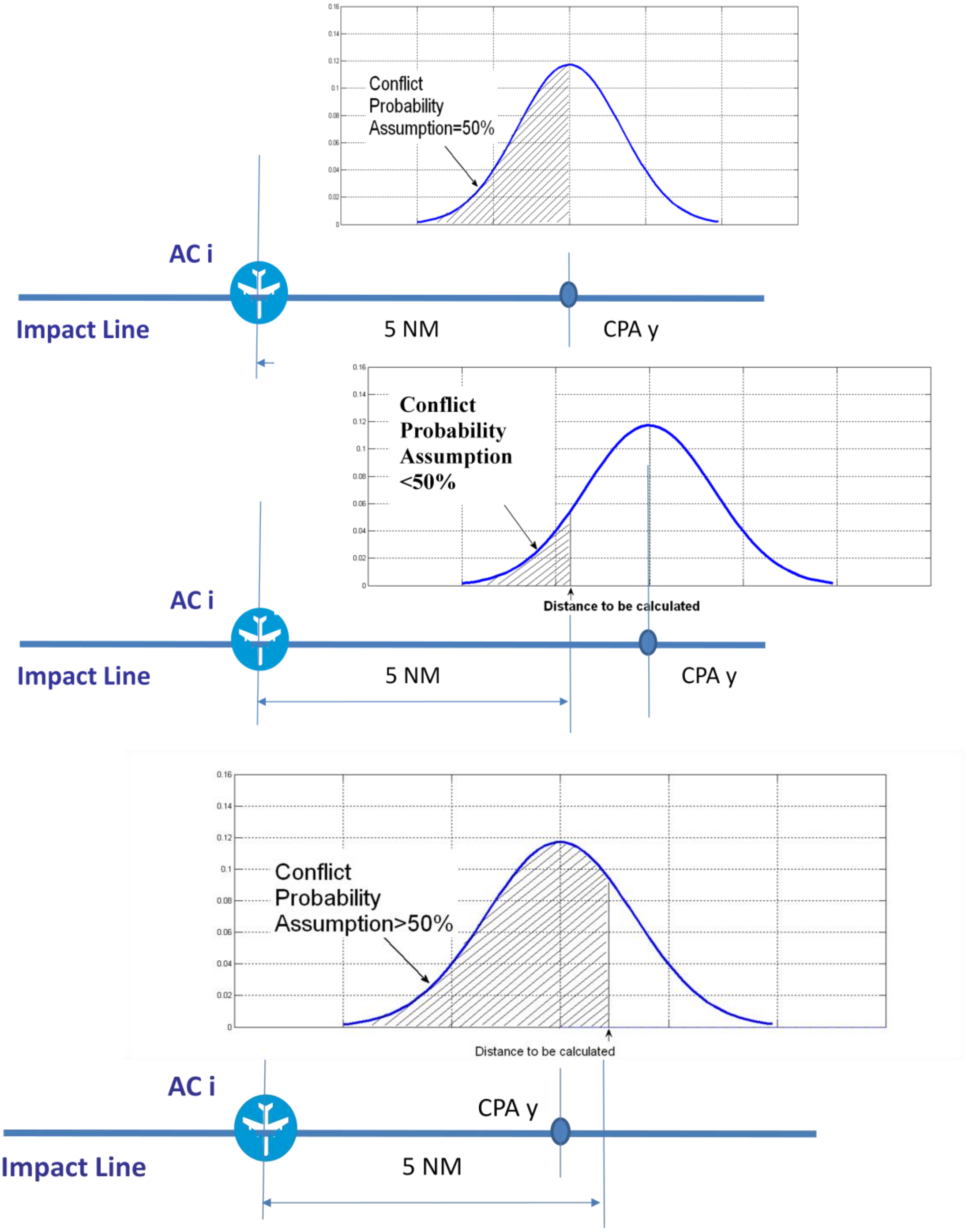


Figure 4.15. Probability of conflict and extra distance calculation (notice distances are not proportional)

Based on this probability, the extra distance to be added to determine compatibility between trajectories will be calculated. Figure 4.15 shows graphically the criteria for calculation.

If the probability for a conflict to happen that is going to be assumed is 50% (Figure 4.15, upper part) the minimum distance to consider two trajectories as compatible results to be the current standard minimum separation, 5 NM. In this case, there is a 50% probability that the aircraft trajectories minimum separation could be less than 5 NM.

If the probability for a conflict assumed is less than the 50% (Figure 4.15, central part), the minimum distance to consider two trajectories as compatible will be more than 5 NM and the extra distance to be added could be calculated. Similarly, if the probability assumed would be more than a 50% (Figure 4.15, lower part), the minimum distance for trajectory compatibility determination would be less than the prescribed minimum standard separation.

The probability for a conflict to happen to be assumed involves a specific number of real time conflicts per sector and day to be solved by the ATC (Section 3.5). Using the following integral that equals the probability for a conflict to happen that is going to be assumed the "extra distance, x" to be added to the standard minimum separation, is to be calculated based on the following integral with x as unknown:

$$Pconf(x) = \int_{-\infty}^{x} f(\tau)\, d\tau = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x} e^{\frac{-1}{2}\left(\frac{\tau}{\sigma}\right)^2}\, d\tau$$

Figure 4.16 shows the minimum distance between two trajectories for them to be considered as compatible for different probabilities of conflict assumed, varying from 50% down (Section 3.5, Table 3.1). It is obvious that for a conflict probability assumption of 0.5 (50%), the minimum distance to declare two trajectories as compatible will be 5NM. The less the probability to be assumed is, the higher the extra distance to be added.

The red line is calculated using the maximum geometry factor value calculated in Figure 4.2 (θ_j =45, speeds ratio=1), whereas the blue line is calculated using the minimum of the geometry factor in the same Figure 4.2 (θ_j =10/80, speeds ratio=1).

The Figure reflects a variation from 5NM (50% probability) up to 35 NM (red line) or 15 NM (blue line). Two extracts from this Figure are shown in Figures 4.17 and 4.18 which focus in a probability range from 5.10^{-2} to 10^{-3} (see Section 3.5, Table 3.1).

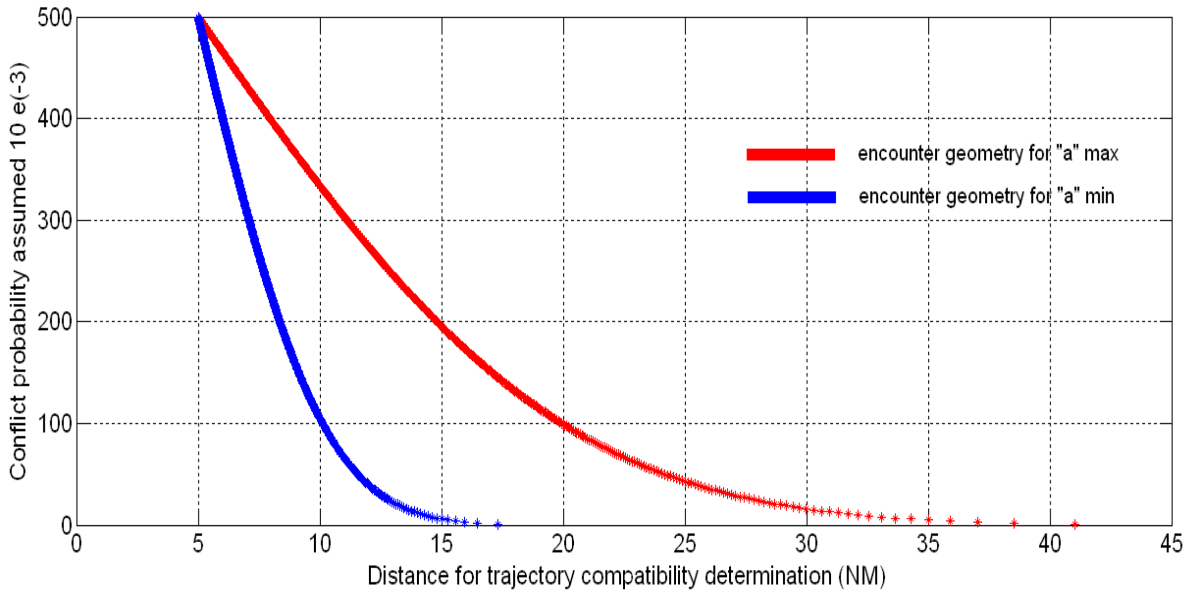


Figure 4.16. Probability of conflict versus distance for trajectory compatibility

In particular, Figure 4.17 shows the minimum distance for trajectory compatibility determination for a geometry encounter configuration that produces a maximum in the geometry factor (Figure 4.4 upper part, red shadow area). Each probability determines a number of conflicts/day assuming a total amount of traffic of 1,800 movements/sector/day (see Section 3.5, Table 3.1). As an example, if a conflict probability of 2.10^{-2} is assumed, the minimum distance for trajectory compatibility determination would be 29NM, and the total number of conflicts to be solved tactically by the air traffic controller would be 36.

On the other hand, Figure 4.18 shows the minimum distance for trajectory compatibility determination for a geometry encounter configuration that produces a minimum in the geometry factor (Figure 4.4 down, blue shadow area). In this case, if a conflict probability of 2.10^{-2} is assumed, the minimum distance for trajectory compatibility determination would be about 13NM and the resulting total number of conflicts to be solved tactically by the air traffic controller would be also 36.

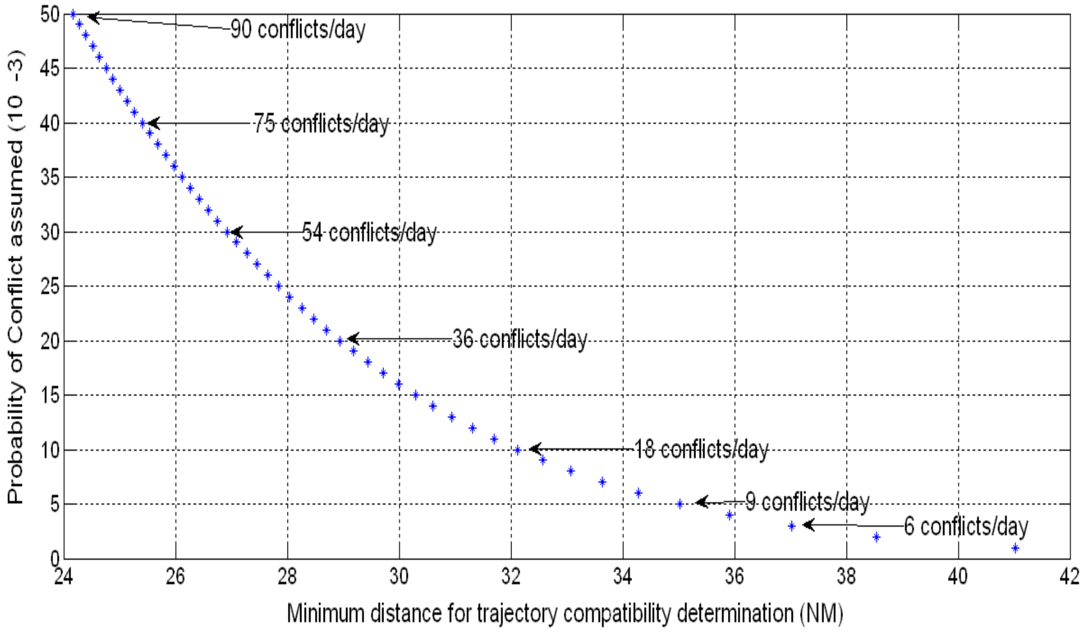


Figure 4.17. Probability of conflict (from 5.10^{-2} to 10^{-3}) and distance for trajectory compatibiliy calculation: encounter geometry for maximum geometry factor

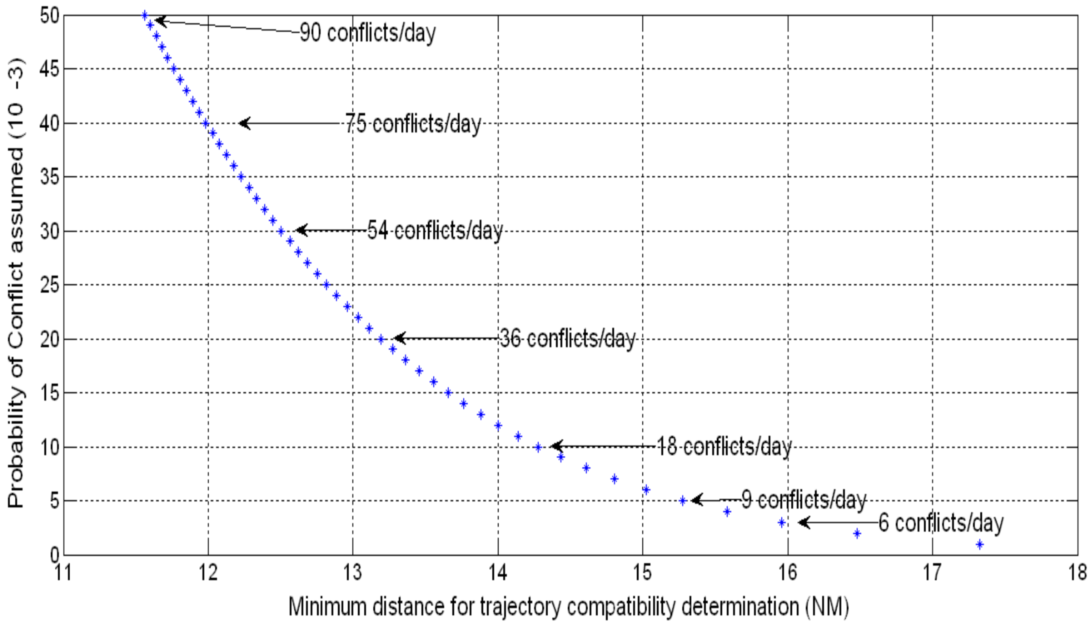


Figure 4.18. Probability of conflict (from 5.10^{-2} to 10^{-3}) and distance for trajectory compatibiliy calculation: encounter geometry for minimum geometry factor

As stated in Section 3.5.2, a probability of 2.10^{-2} would provide a similar airspace capacity to the one obtained nowadays with the medium term automation tools (threefold demand increase). In order to improve the current system capacity, that is one of the main goals of the new ATM paradigm shift[5], the value for the probability assumed should be lower.

If, as an example, the probability assumed under our research was 5.10^{-3}, the total number of conflicts to be solved tactically by the ATC would be reduced down to 9. The minimum distance to declare two trajectories as compatible would be 15NM (minimum geometry factor) or 35NM (maximum geometry factor).

The analysis made considers the wind error vector angle that produces the maximum deviation. Whether the prevailing winds in the airspace where the encounter is to happen were known a more accurate value for the minimum allowed distance for trajectories compatibility determination could be settled.

4.2 Vertical movement: time intervals & numerical values

Considering that the trajectories of the two aircraft involved in the encounter will be known through the RBTs declaration, as part of the process for trajectory compatibility determination the intervals (T1, T2) and (t1,t2) and the conflict time interval T_C should be calculated and identified if any overlap exists between them (Section 3.6.2).

As the minimum distance between two trajectories to be declared as compatible has been estimated as 35NM (worst case), T1and T2 will be determined as (see Figure 3.8):

- T1: time when the minimum distance between the two aircraft is 35NM and decreasing
- T2: time when the minimum distance between the two aircraft is 35NM and increasing

On the other hand, the interval (t1, t2) will be determined as:

- t1: instant when the minimum vertical separation between the two aircraft is 1.000ft but decreasing (rate of climb = v_{smax})
- t2: instant when the minimum vertical separation between the two aircraft is 1.000ft increasing, (rate of climb = v_{smin})

The normal rate of climb/descent for a turbojet varies between a v_{smax} = 3000ft/min and a v_{smin}=1000ft/min.

As our objective is to define the conditions under which two trajectories are going to be declared as compatible, in order to be conservative, the above interval will be increased, and the rate of climb included in the analysis will vary from 500ft/min to 4000ft/min. Doing this, the inclusion of any possible rate of climb/descent is guaranteed.

Taking t0 as the top of climb time, the expression for t1 and t2 will be (see Figure 3.8):

$$t1 = t0 + h1/v_{smax}$$

$$t2 = t0 + h2/v_{smin}$$

Being:

- h1: height/altitude in feet to reach the Lost Altitude Level
- h2: height/altitude in feet to reach the Recovery Altitude Level (it is obvious that h2=h1+2,000ft)

Considering the previously defined en route sub-phases, different types of airspaces could be identified depending on the characteristics of the traffic flying through them.

Most of the aircraft within the airports whereabouts are climbing to cruise level/descending from cruise level, whereas the airspace at higher altitudes includes mostly aircraft established at cruise level or changing from one cruise level to a more optimised one.

On the other hand, the magnitude of the climbing/descending is not similar either. While changes in cruise level involve a minor altitude change (mostly 2,000ft or 4,000ft), climbing to cruise/descending from cruise involve a major altitude change (mostly more than 10,000ft).

It is obvious that these differences influence directly the above defined intervals calculation, and it could be concluded that it would be more feasible to declare two trajectories as compatible in a mostly cruise airspace. This statement is explained through the following numerical examples.

4.2.1 Major altitude change : 12,000ft

As a first numerical example an intruder aircraft climbing from FL240 up to FL360 crossing the reference aircraft FL330 will be considered. If the top of initial climb time is established at 00:30 the results obtained would be:

- t1=00:32 (v_{smax}=4,000ft/min)
- t2=00.50 (v_{smin}=500ft/min)
- T_C: 18 minutes, between 00:32 and 00.50
- Horizontal distance flown in T_C=135NM (considering aircraft air speed = 450kt)

If in any time during the T_C the minimum horizontal distance between the two aircraft is 35NM or less, the two trajectories would be declared as not compatible.

4.2.1 Minor altitude change : 2,000ft

As a second numerical example an intruder aircraft climbing from FL320 up to FL340 crossing the reference aircraft FL330 will be considered. If the top of initial climb time is established at 00:30 the results obtained would be:

- t1=00:30
- t2=00.34 (v_{smin}=500ft/min)
- T_C: 4 minutes, between 00:30 and 00.34
- Horizontal distance flown in T_C=30NM (considering aircraft air speed 450kt)

If in any time during the T_C the minimum horizontal distance between the two aircraft is 35NM or less, the two trajectories would be declared as not compatible.

4.3 Summary

The influence of the three factors involved in the CPA determination ($\boldsymbol{t_{CPA}}$, $\boldsymbol{\sigma_W}$, $\boldsymbol{a}$) is analysed and some numerical values settled.

The minimum distance to declare to trajectories as compatible is calculated based on the assumption of a determined conflict probability, since the ATCO will continue being responsible for the final real time separation. The selected conflict probability would involve the ATCO tactical workload reduction even considering a threefold increase in the future air traffic demand.

Within the vertical movement, the climbing vertical buffers are analysed for different airspaces (different altitude changes). Uncertainties in the rate of climb/descent introduce large buffers for times and distances affecting the trajectories compatibility determination.

5. DISCUSSION

Airspace capacity is limited by several inter-linked factors including controller workload, traffic distribution and procedures. Aircraft cannot fly an optimal horizontal route or vertical profile and as traffic demand continues to increase, then so do delays. It should be noted that 61% of the ATFM delay is due to a lack of en route capacity (see Figure 1.1).

The current sector management philosophy is based on a physical division of the airspace, the assignation of a defined capacity to any of the volumes in which the airspace is divided (sectors), and the allowance to enter these sectors only if capacity is not exceeded. In the medium term the potential conflicts are not detected, and it is in the short term (tactical operation) when the conflicts are finally solved. The capacity limitation is in this case the human being, that is, the ATCO. On the other hand, the trajectory management philosophy is based on a strategic detection of the conflicts, the de-confliction of the trajectories prior to the flight, the significant reduction of the potential conflicts, and as a consequence the increase in capacity.

Workload is the demand placed on an operator's mental resources used for attention, perception, reasonable decision-making and action. Nowadays, one of the most critical aspects for air navigation in high traffic density areas is the ATCO workload, due to its tactical nature and the immediate effects of any possible committed error. Moreover, it is extremely difficult to quantify this workload, being one of the subjects involving further research, for its overall impact on the economic and operational safety aspects of the air transport system development.

Controller task load and workload are to be distinguished[54]. The task load must be understood as the ratio between consumed and available times, closely related to the number of tasks and the occurrence frequency for any specific job. On the other hand, workload refers to the overall effect on the worker of physical, sensorial and mental capabilities to develop these tasks.

The triggers determining the tasks to be done in every specific time could be obtained by analysing the radar data and the flight plans (air traffic demand), and the voice and text messages received in the working position. Meteorological and airspace information (navaids status, airports, military areas...) can affect the number and the performance of these tasks.

The way these tasks are performed is also conditioned by the temporal pressure and the rules and procedures to be fulfilled in order to keep the safety and economy requirements. Moreover, the final decisions chosen by the ATCO have influence on the resources used, and therefore in the final workload.

The effects of the different tasks performed by the ATCO have two components, one objective, conditioned by the above described factors, and other subjective, related to its reaction against the required tasks. The latter is dependent, among other factors, on the ATCO's experience, qualifications and skills.

Different studies and techniques have tried to measure these elements. Among them, the following are highlighted:

- Subjective workload evaluation:
  - Physical symptoms measured from the physiologic response[55,56]
  - Philological symptoms, measured by the observed workload[57] and secondary tasks[58]
  - Feelings, measured by subjective tests or perceived workload[59]
- Objective evaluation of the ATCO performance using the activity rate[60]:

As a conclusion, it can be observed that workload determination is very complex and an overall reference model does not exist. A broadly accepted model is the so called Wickens[61] model, which considers as a basic task to be performed by the ATCO the information processing, that consume its attention resources to respond to the different tasks developed during his activity. According to this model the resources are used in:

- Perception,
- Working memory utilisation,

- Decision-taking and response-selection,
- Response execution.

Because human resources are limited, the level needed for a specific task can exceed the amount available. Under these circumstances, task load can also be defined as the ratio of the resources required by the task to the amount of available resources. Therefore, workload is an individual experience, and workload measurement methods must take into account human variability.

The overall ATCO workload is calculated through the evaluation of the resources spent in different tasks such as coordination, procedures fulfilment, conflict detection, conflict resolution or aeronautical information provision. The task load produced by each of these factors do not remain the same even from one duty period to another, and could be variable with meteorological conditions or other external factors such as military area activation.

As an example, turbulence or cumulonimbus (CB) could cause all the aircraft within a sector to require the same flight levels or heading changes to avoid weather disturbances, which not only would increase the conflict detection and resolution task load, but would also hinder the operation as fewer options for conflict resolution remain possible. Therefore, some flight levels cannot be taken due to turbulence, or areas cannot be overflown due to CB. Similarly, military activity could increase the coordination workload between civil and military air traffic control.

On the other hand, the pilot/ATCO voice communications are, not only the most important means, but also a very limited one, and as a consequence one of the main sources of task load increase. Most of the current ATCO tasks involve the use of communications (conflict resolution, aeronautical information provision, procedures fulfilment) and in high density areas its constant use must be carried out accurately.

As a consequence, if the total numbers of conflicts to be solved by the ATCO could be reduced, the total number of tasks to be performed would be fewer, less coordination between sectors would be necessary and a minor use of communications to provide instructions should be required. On the other hand, if the aircraft are flying their preferred routes, the current working procedures will be adapted to this new situation and fewer instructions will be provided in the future, implying less workload due to procedures fulfilment.

The developed tool tends to reduce the ATCO workload devoted to conflict resolution. It is assumed that this would involve a parallel increase in the capacity. Sector capacity is normally measured as the total number of aircraft that can be handled in a sector during a fixed period of time, normally an hour. This value depends on the physical characteristics of the sector, the traffic flow pattern, the collateral airspaces, and the existing constraints such as military area activation. ATCO workload spent in coordination, supervision, or tactical actions is measured and the resulting capacity is calculated. There are different methodologies applied to sector capacity calculations, but all of them take into account the ATCO workload as a function of these parameters.

Much of the controller’s workload is spent in tactical actions related to conflict avoidance between two or more aircraft. If Decision Support Tools could be used to identify potential conflicts further in advance, the controller workload would be reduced.

As an example, some studies[36] have shown that within the current ATM system philosophy the ATCO must solve about 75 potential conflicts per sector and day. Nowadays, a conflict is identified when the minimum distance between two aircraft is going to be less than 5NM (horizontal distance) and 1,000 ft in height vertical separation.

However, these current minimum standards were determined many years ago and they are used to facilitate conflicts resolution in an ATC environment. From this research point of view, trajectory compatibility should not be based on minimum separation standards but on probability of conflicts that finally would require tactical ATCO intervention. This compatibility is then based on a trade-off between capacity and predictability. The higher the probability for a conflict to occur assumed by the conflict prediction tools, the greater the number of conflicts the ATCO must deal with. Some studies[42] assumed a conflict probability for medium term decision support tools of about

$5x10^{-2}$, with current air traffic demand levels, which suggests that the ATCO must solve 30 conflict / sector /day. Considering a threefold increase in the air traffic demand, this value would reach 90 conflicts/sector/day.

As for the future ATM system, the increase in the air traffic demand should lead to, not only an increase in safety, but also an increase in the current system capacity. Therefore, this research proposes to reduce the current 75 conflicts per sector per day to 9 conflicts per sector per day. This would lead to a clear increase in the current capacity. The probability of conflict assumed in this Research with the future demand levels would be $5x10^{-3}$, which is in accordance with other authors'conclusions[42]. Due to the ATM system uncertainties, it is not feasible to reduce the post resolution conflict probability to zero when the time to go to the predicted conflict is longer than a few minutes, but the intent is to reduce ATCO workload although they will continue to have ultimate responsibility for ensuring proper separation at all times.

The main issue dealing with Trajectory Based Operations is the definition of an accurate trajectory and the analysis of the uncertainties associated with it. One of the main factors affecting this definition of conflict-free trajectories are the atmospheric parameters, and, in particular, the influence of wind errors. These are considered to be the most important source of trajectory prediction errors and are included as such in this research.

As a first conclusion obtained from the trajectory compatibility analysis carried out, if the two aircraft involved in an encounter were established at the same flight level, the minimum distance between them to declare their trajectories as compatible would be between 15 NM and 35NM, depending on the encounter geometry. These distances have a reasonable value which allows us to intuit that the pre-tactical trajectory compatibility determination is possible in a planning time of about 6 hours before the flight takes place. Even though some assumptions have been made to obtain these values, they are not far from the reality and higher values for the minimum distance obtained could still be assumed by the future system leading to a capacity increase.

Only a coarse approach to the vertical movement is presented, but it could be clearly stated that it would be easier to declare two trajectories as compatible in a mostly cruise airspace. Most of the aircraft within the Terminal Control Area are climbing to cruise level/descending from cruise level, whereas the airspace at higher altitudes includes mostly aircraft established at cruise level or changing from one cruise level to a more optimal level. The magnitude of the climbing/descending is very different in each environment. While changes in cruise level involve a minor altitude change (mostly 2,000ft), climbing to cruise/descending from cruise involve a major altitude change (mostly more than 10,000ft). The uncertainties in the trajectory definition grow with the magnitude of the level change and the vertical buffers to be applied could be so large than the final resultant capacity may not be increased at all.

If the prevailing winds in the airspace where the conflict occurs are known, and the aircraft performance could be better predicted, a more accurate value for the minimum allowed distance for trajectories compatibility determination could be determined. Both, wind and aircraft performance, require a better knowledge of atmospheric behaviour.

5.1 Summary of key findings

The results obtained and presented in this research show that the minimum horizontal distance between two trajectories to be declared as compatible varies between **15 and 35 NM** depending on the encounter geometry configuration, assuming that the time to CPA is up to **1 hour**, a RMS value for wind error of **6m/s** and a controller workload in the future ATM limited to **9 conflicts/sector/day**.

The assumptions made include the consideration that both aircraft are established at the same flight level and the aircraft lateral position error is negligible. As the range of speeds for turbojet aircraft is very similar, to obtained previous results it has been considered for the final calculations that $|\vec{v_j}| = |\vec{v_i}|$**.** A further inclusion of the vertical movement permits the establishment of a methodology to analyse trajectory compatiblity when one of the aircraft is climbing or descending.

If the CPAy coordinate could be accurately calculated the minimum distance between two aircraft trajectories would be accurately known (see Section 3.3, Figure 3.1). The longitudinal uncertainty in the trajectory prediction due to the wind error effect on the aircraft speed makes the CPAy coordinate follow one of the probability density functions that have been previously calculated (see Section 4.1.4, Figure 4.13). The three factors affecting probability distribution for CPA coordinates determination are described in Table 5.1 below.

t_{CPA}	a	σ_w
1 hour	Dependant on the encounter geometry ($\vec{v_j}$, $\vec{v_i}$, Θ_w)	6 m/s

$\vec{v_j}$	$\vec{v_i}$	Θ_w
Known through the Flight Plan		Prevailing wind data could be used if available. The “worst case” has been chosen for the analysis.

t_{CPA}: time to the Closest Point of Approach
a: geometry factor
σ_W: RMS value for wind error
$\vec{v_j}$: Aircraft j speed
$\vec{v_i}$: Aircraft i speed
Θ_w: Wind error angle measure from the relative speed vector

Table 5.1. Key factors affecting the probability distribution for CPA coordinates determination

If the speed of both aircraft is considered to be the same, the encounter geometries that provide a maximum and a minimum value of “a” are shown in Figure 5.1. As can be seen, an angle between trajectories of 90 degrees provides the maximum value (minimum distance for trajectory compatibility 35NM), whereas angles near 180 degrees or near 0 degrees provides a minimum (minimum distance for trajectory compatibility 15NM).

On the other hand, Figure 5.2 shows the wind angle that produces maximum and minimum deviation for an angle between tracks of 90 degrees. The maximum wind influence occurs when the wind direction is parallel to the relative speed vector, whereas the contrary takes place when the wind direction is perpendicular to it. The maximum wind influence has been considered in this research. If the prevailing winds in the airspace where the encounter is to happen were known, then a more accurate value for the minimum allowed distance for trajectories compatibility determination could be calculated.

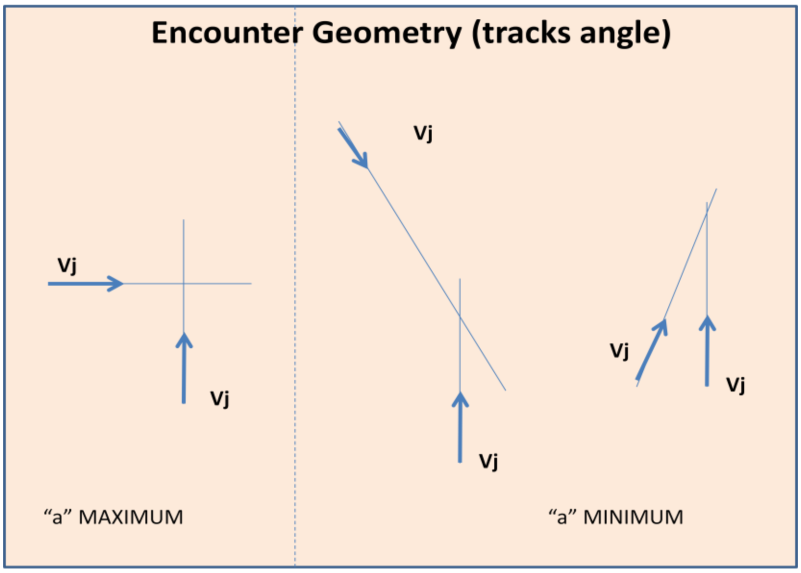


Figure 5.1. Different encounters geometry for maximum and minimum deviation. Same speed.

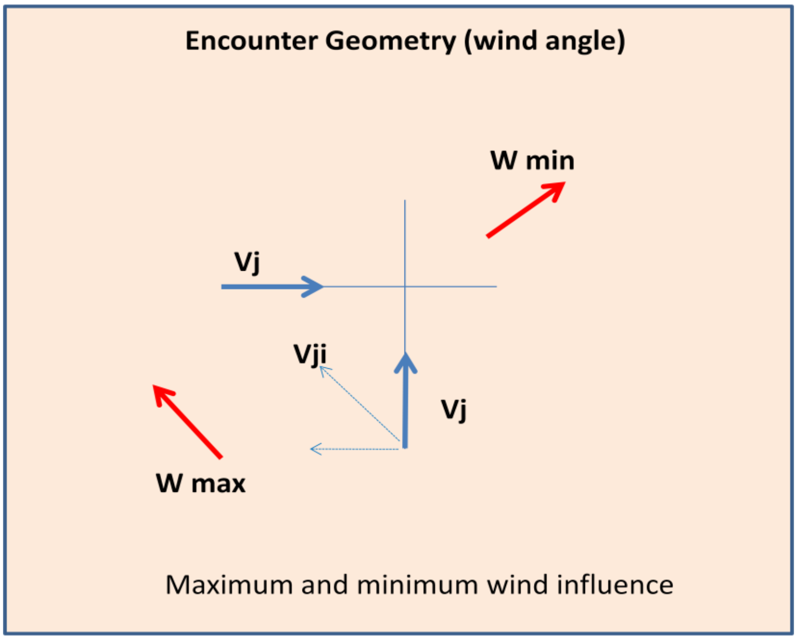


Figure 5.2. Wind angles for maximum deviation. Same speed.

If the speed of both aircraft is not the same, the lower the ratio v_j/v_i is, the closer the wind direction for maximum deviation is from the aircraft j trajectory (see Figure 5.3).

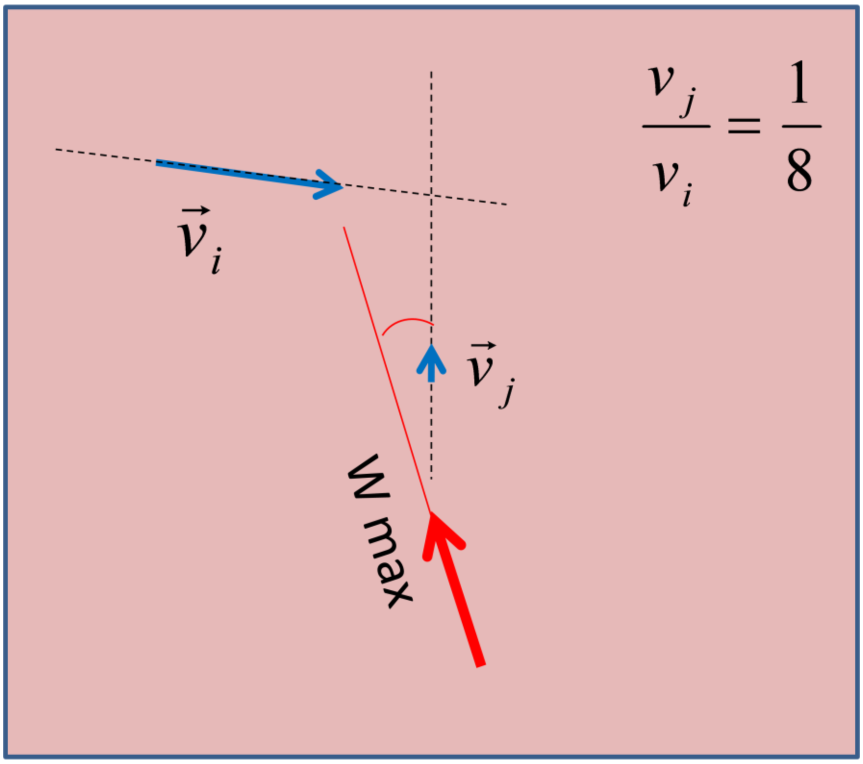


Figure 5.3. Speeds ration 1/8. Geometry conclusions

Trajectory compatibility determination has been made based on a trade-off between capacity and predictability. In particular, Figure 4.17 (Section 4.1.4) shows the minimum distance for trajectory compatibility determination for a geometry encounter configuration that produces the maximum geometry factor. Each probability gives a number of conflicts/day assuming a total amount of traffic of 1,800 movements/sector/day (threefold demand increase, see Section 3.5, Table 3.1).

In order to improve the current system capacity the probability for a conflict to happen assumed under the research is $5x10^{-3}$, being in this case the total number of conflicts to be solved tactically by ATC reduced down to 9 conflicts/sector/day. The minimum distance, to declare two trajectories as compatible, results in 15NM (minimum geometry factor) or 35NM (maximum geometry factor).

When including the vertical movement analysis as part of the process for trajectory compatibility determination the intervals (T1, T2) and (t1,t2) should be calculated and identified if any overlap exists. The intervals definition is as follows:

- T1: time when the minimum distance between aircraft is less than the minimum standard horizontal separation and decreasing
- T2: time when the minimum distance between aircraft is less than the minimum standard horizontal separation and increasing
- t1: instant when the minimum vertical separation between the two aircraft is 1,000ft but decreasing (rate of climb = v_{smax})
- t2: instant when the minimum vertical separation between the two aircraft is 1,000ft increasing (rate of climb = v_{smin})

The conflict time interval (T_C) has been defined as the interval in which a potential conflict between two trajectories is possible, that is mathematically:

$$T_C = (T1, T2) \cap (t1, t2)$$

As the objective is to define the conditions under which two trajectories are going to be declared as compatible, in order to be conservative the rate of climb included in the analysis will vary from 500ft/min to 4,000ft/min.

The trajectories of the two aircraft involved in the encounter are known through their flight plans and will be split into a defined number of segments in which the movement could be parameterised. Each of the segments from one trajectory will be compared to all the segments defining the other trajectory, and the minimum horizontal distance between them will be calculated. If this distance is less than the one pre-established to define two trajectories as compatible, and either of the aircraft is climbing or descending the process to be followed to determine the final trajectories compatibility is presented in Figure 5.4.

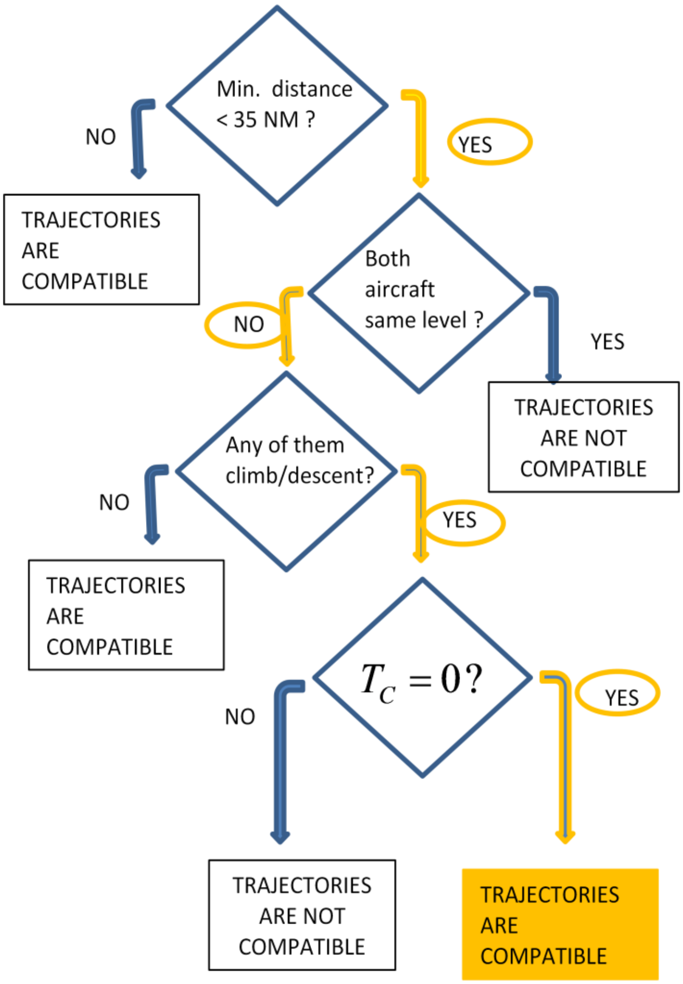


Figure 5.4. Flow chart application

5.2 Operational Point of View on the implications of TBO

The implications of the results are assessed through a small scale questionnaire of air traffic controllers. The main objective of the questionnaire is to survey Air Traffic Controllers' opinions in respect to:

- changes expected to happen in their work in the long term due to SESAR implications,
- job changes and the correspondent sector capacity evolution,
- factors hindering Trajectory Based Operations.

The parameters of the survey are the following:

- Population: 243 air traffic controllers on duty from Madrid Air Traffic Control Centre
- Average age (broadly): 43 years
- Years of experience on duty (broadly): 11 years
- Sample (randomly distributed): 26 responses to the survey

The sample (26 responses) represents approximately the 10% of the on-duty ATCOs in Madrid ACC. The basic set of data was obtained through a particular realisation carried out randomly.

Questions included in the questionnaire are only related to professional issues and not to personal appreciations. On the other hand, the set of questions are presented as clustered and classified.

The main assumptions made include:

- The ATCO population in Madrid ACC has similar training and professional skills.
- Collected data from the sample respond to the professional perception of the whole population.

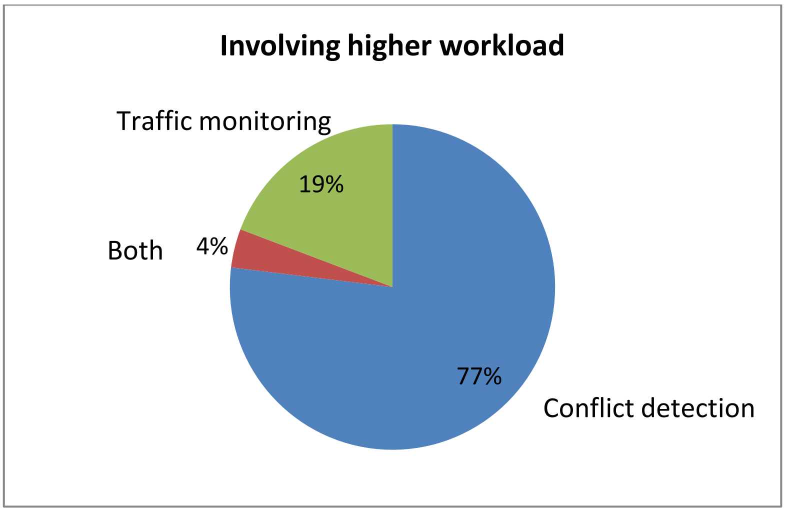
Under these assumptions it can be concluded that the statistical inference provides a high level of confidence for the estimated percentages obtained, taking into consideration the population homogeneity and the specific questions included.

The questionnaires delivered and the responses obtained are included in Annex VI. The results of the survey are the following:

a) **Current perception of their job**

(Which task involves a higher workload? / Could workload be a reason for less efficiency?)

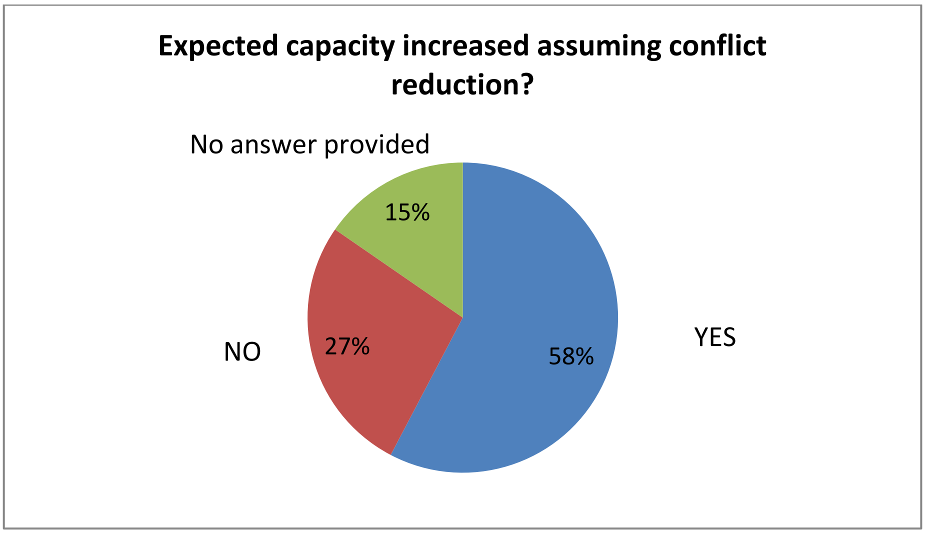
In respect to current perception of their job it could be concluded that most of them (more than the 75%) consider that conflict detection and resolution involve a higher workload than traffic monitoring. Only a minor percentage (4%) considers that both conflict detection/resolution and traffic monitoring involve a similar workload. On the other side, all responses obtained consider that a high workload implies a less efficient operation.



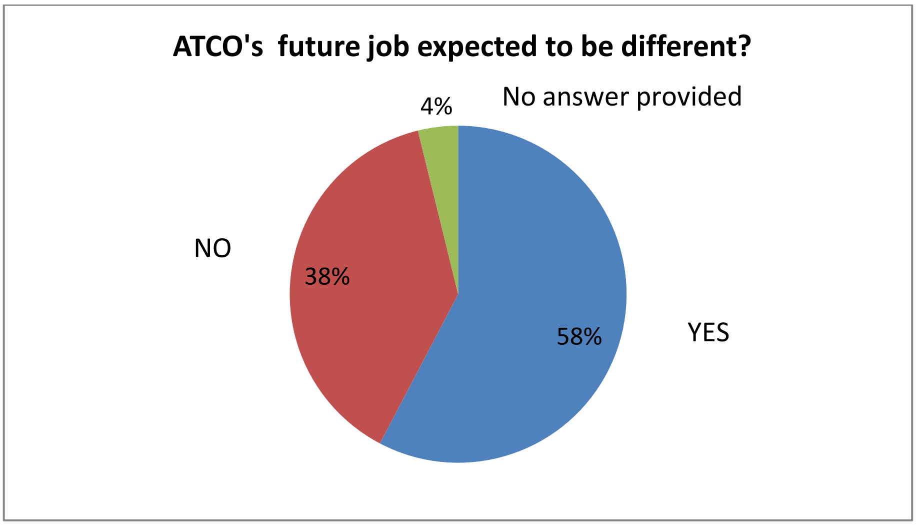
b) Perception of their future job

(Could be sector capacity increased in the future assuming conflict reduction? /ATCO's job expected to be different?)

Regarding the opinion about changes of the ATCO's job in the future, a positive answer is obtained to the possibility of a sector capacity increase in case of dramatic conflict reduction in 60% of the responses. However, this percentage is less than that obtained when asking about the task involving a higher workload (77%, conflicts detection and resolution). This may underline a lack of trust in the system and the general opinion that capacity increase cannot be extracted easily from conflict reduction.

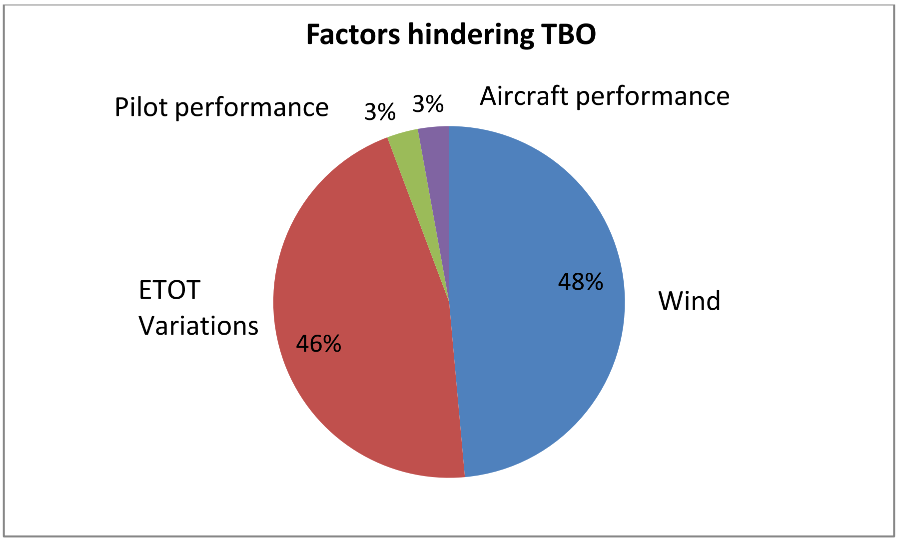


The above percentage is similar to the one obtained when deciding if the ATCO's job will be different in the future (60%). Although the conclusion shows a common belief that the new role would imply mainly monitoring, both the lack of trust in the system, and the new potential risks appeared in the system due to under work or complacency, appeared as responses.

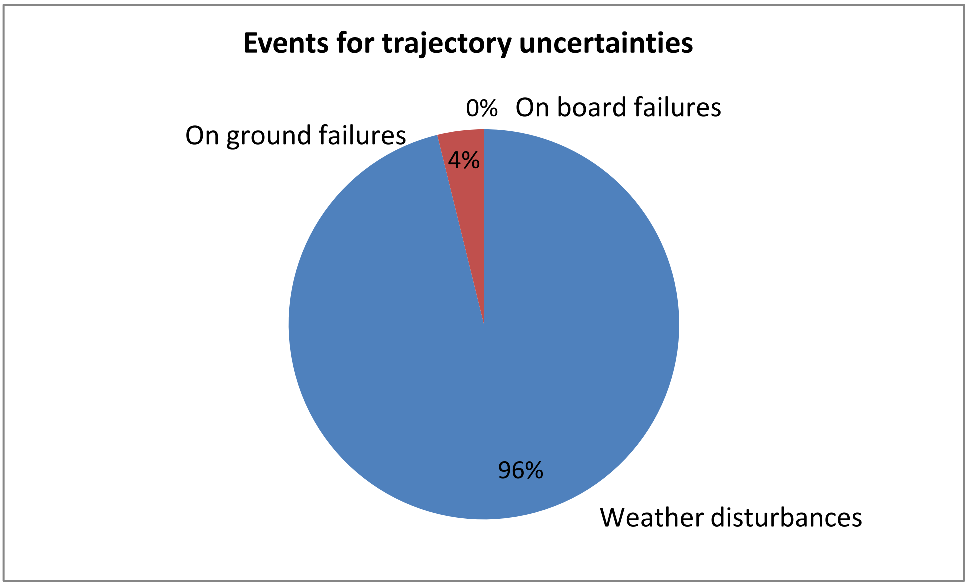


c) Perception of the factors hindering TBO

When analysing factors hindering TBO, the responses are divided almost equally between wind (48%) and variations in the estimated take-off time (46%). The other options' percentages are not significant in relation to these factors.



In the long term (a whole year operation) the weather disturbances are acknowledged to be the most likely to happen, with almost 100% of responses.



As a conclusion, conflict detection and resolution are perceived as the tasks involving a higher workload although closely related to traffic monitoring. A dramatic reduction of conflicts will imply a reduction of the workload due to conflict detection and resolution; however, the capacity increase associated with this reduction is not directly proportional to it. If the amount of traffic to be monitored increases, so does the task load. Overall workload is a parameter difficult to be evaluated, involving many aspects of the operation, hence not easy to be extracted directly from the conflicts reduction.

Although ATCOs foresee a change in their future job, mainly involving an increase in monitoring and supervision activities and a reduction of the conflict resolution ones, they are concerned about how contingencies and emergencies can be managed maintaining the current system safety performance. The lack of confidence in the future system performance can be learnt from the questionnaire responses. An increment in the air traffic demand, based on the future increase of the level of automation, rely on the performance of the future system and the capacity of response in case of failure. Contingency measures should be adopted to provide the future system with the necessary backup in order to avoid the human factor to be the weak element of the overall system.

Both wind and the variations in the estimated take-off time are equally considered to be the main factors hindering trajectory based operations. Both elements can produce an along track error which makes the aircraft arrive earlier or later to the referenced way points and consequently, make the trajectory differ significantly from the estimated one. Foreseen conflicts determination is totally dependent on the accurate trajectory determination, and an aircraft arriving sooner or later could involve the lack of existence of any conflict or, on the contrary, the appearance of a previously inexistent conflict. Both factors must be included when analysing trajectory uncertainties and pre-tactical trajectory de-confliction.

When looking into the possible system disruptions likely to happen in the long term and necessary to be included in a contingency analysis, the weather disturbances are perceived as the most probable, as it is difficult to find an ATCO who has not experienced a difficult working environment due to bad weather conditions. Meteorological events are very often difficult to be foreseen and air traffic demand is very dependent on them.

In relation to the Research findings, the results support the fact that conflict pre-determination and consequently, reduction, involve a significant decrease in the ATC workload. The ATCO perception on the most important factors hindering TBO agrees with the ones included in the Research. Similarly, meteorological events are considered as the most probable disturbances causing disruptions in the overall system performance.

6. CONCLUSIONS

6.1 Thesis Aims and Objectives

Linking back to Chapter 1, each of the Thesis objectives will be discussed:

- **Analysis of the new paradigm shift from sector management to trajectory management.**

  A new paradigm shift is needed in order to cope with the foreseen increase in air traffic demand whilst maintaining safety standards, reducing related costs and minimising environmental impact. As understood in this research, this paradigm shift should be from the current sector based to a trajectory based ATM system.

  The current sector management philosophy is based on a physical division of the airspace, the assignation of a defined capacity to any of the volumes in which the airspace is divided (sectors), and the allowance to enter these sections only if this capacity is not exceeded. In the medium term the potential conflicts are not detected, and it is in the short term (tactical operation) when the conflicts are solved.

  Current ATFM considers “conflict free” trajectories in a strategic/pre-tactical level if they do not exceed capacity at any involved “ATC sectors”. ATC sector capacity is mainly limited by ATCO conflict resolution workload for a given aircraft population. The capacity limitation is in this case the human being, that is, the ATCO.

  Under this research it has been analysed when two aircraft trajectories can be declared as compatible in a pre-tactical stage of the operation, in order to provide a DST in the new paradigm shift from current ATM based on sector management, to future ATM based on trajectory management. The research has led to clearly reduce the ATCO workload due to tactical interventions, increasing airspace capacity and improving safety performance.

- **Analysis and estimation of the main uncertainties affecting the trajectory definition.**

  The main issue dealing with Trajectory Based Operations is the definition of an accurate trajectory and the analysis of the uncertainties associated with it. One of the main factors affecting this definition of conflict-free trajectories is the atmosphere and, in particular, the influence of wind errors. These are considered to be the most important source of trajectory prediction errors and are included as such in this research.

For the purpose of trajectory compatibility analysis, the aircraft lateral position error can be considered as negligible. The lateral navigation performance for most airspaces, as those proposed by PBN, may give values as low as a lateral deviation of 0.1 nautical miles 2σ. A PBN 0.1 implies that the aircraft lateral deviation is confined within 0.1NM at both sides of the track a 95% of the time (see Section 2.3).

Similarly, when aircraft are established at a defined flight level a total vertical error can be determined as be considered as negligible, as for the operations in Reduced Vertical Separation Minimum (RVSM) is defined a total vertical error of 200ft[62] for 99% of the total flight time.

When analysing longitudinal uncertainties it is considered that aircraft fly most of the time at a constant Mach Number airspeed rather than at a constant ground speed and, as a consequence, the effects of wind modelling and prediction errors accumulate with time. Airlines use wind estimation to minimise flight costs by appropriate choice of a route, cruise level and by loading the minimum necessary fuel on board. The performance of ATM DST depends on the accuracy of the wind predictions.

On the other hand, when aircraft are climbing or descending vertical uncertainties are much greater as climbing rate varies with aircraft performance and the atmospheric air speed, temperature and density. In the Research the aircraft kinematics is split into horizontal and vertical movements which are analysed as independent

- **Revisit existing trajectory models and identify their possible enhancements**

  There are different trajectory definitions and different stakeholders in a transition to a TBO environment. Most of the studies consider the reduction in the uncertainty associated with the predicted trajectory as the critical enabler for TBO, but whereas some studies try to improve the real-time decision support tools used by air traffic controllers, the trajectory de-confliction analysis carried out under this research tries to identify potential conflicts further in advance, that is, in a pre-tactical planning layer, several hours (about 6 hours) before the operation takes place. This pre-tactical conflicts identification leads to reduce the ATCO workload due to tactical conflict resolution.

  Although main factors affecting trajectory prediction are broadly analysed, some recently developed models do not include the wind uncertainty as one of the main aspects hindering ATM Decision Support Tools Utilisation. Some studies have shown a predominant daily value for RMS vector difference of about 6m/s and large errors of 10m/s occur for 3% time overall. This research has discussed the influence of wind errors, both in direction and in speed, on defining conflict-free trajectories.

  In particular, in the enhanced model the kinematics of each aircraft has been converted into a finite set of sequenced segments and only the lateral and vertical deviations of aircraft real trajectories from the segmentation modelling have been taken into account. The speed has been considered as known, furthermore it was assumed the law of uniform motion for each segment. No further speed uncertainties were included.

  On the other hand, in the previously reviewed model a potential conflict was identified when the minimum distance between two aircraft is less than an established minimum separation standard defined by two values, the minimum horizontal and vertical separations. For the proposed model, trajectories compatibility has not been based in minimum separation standards but in probability of conflicts that finally would require tactical ATCO intervention.

- **Establish the criteria for trajectory compatibility**

  If as an example, the probability assumed under our research is 5.10^{-3}, the total number of conflicts to be solved tactically by the ATC would be reduced down to 9, if the minimum distance to declare two trajectories as compatible in a pre-tactical planning time (about 6 hours before the flight takes place) would be 35NM.

  Only a coarse approach to the vertical movement is presented, but it could be clearly stated that it would be easier to declare two trajectories as compatible in a mostly cruise airspace. While changes in cruise level involve a minor altitude change (mostly 2,000ft), climbing to cruise/descending from cruise involve a major altitude change (mostly more than 10,000ft). The uncertainties in the trajectory definition grow with the magnitude of the level change and the vertical buffers to be applied could be so large than the final resultant capacity may not be increased at all.

- **Show conclusions to improve Trajectory Based Operations**

  The new flow management philosophy proposed under this research is based on a strategic detection of the conflicts, the de-confliction of the trajectories prior to the flight, the reduction of the potential conflicts, and as consequence the increase in the capacity.

  If the conflicts per day to be solved by the ATC could be reduced this would decrease significantly the ATC workload involved in conflict resolution.

  The main issue dealing with Trajectory Based Operations is the definition of an accurate trajectory and the analysis of the uncertainties associated with it. One of the main factors affecting this definition of conflict-free trajectories are the atmospheric parameters, and, in particular, the influence of wind errors. These are considered to be the most important source of trajectory prediction errors and are included as such in this research.

  Where the prevailing winds in the airspace where the conflict occurs are known, and the aircraft performance could be better predicted, a more accurate value for the minimum allowed distance for trajectories compatibility determination could be determined. Both, wind and aircraft performance, require a better knowledge of atmospheric behaviour.

6.2 Research limitations and further work.

Even though lateral, longitudinal and vertical uncertainties are discussed in the research, the influence of wind errors are the only included in the final calculations. Other kinds of uncertainties such as changes in the estimated take-off time, or the possible airspace disruptions due to extreme weather conditions, could produce a significant impact on trajectory prediction error and should be analysed in the future.

From the daily operation in a control room it can be concluded that on a daily basis most of the trajectories followed by the airlines are located accurately "in the predicted line". In contrast, when looking into the expected times to reach a previously defined waypoint, the divergences between the expected and the real time are notorious. This statement is supported from the results obtained from the questionnaire presented in this document. In them, most of the ATCOs interviewed choose as the main factors that make an aircraft planned trajectory differs from the real flown, the wind and the variations in the estimated take-off time.

In that respect, it is obvious, that factors affecting aircraft nominal ground speed variations are the most important to analyse when defining conflict-free trajectories. In particular, wind uncertainty is the one included in the calculations although other factors such as differences in the estimated time of departure should be included in a further step.

Nowadays, the flights affected by regulation are given a Calculated Take-Off Time (CTOT) which implies that aircraft must take off during a time range between CTOT - 5 minutes and CTOT + 10 minutes. This is the only effective Air Traffic Management slot that the flight must respect. The ATFM slot allocation measure is based on the universally accepted principle that delays on the ground are safer and less costly than those in the air. Any forecast delay somewhere in the system is thus anticipated at the departure airport prior to the take-off and the traffic is controlled in a safe and simple manner.

One of the main conclusions of the Research is that the main issue dealing with TBO is the definition of an accurate trajectory and the analysis of its uncertainties. The atmospheric behaviour has been concluded as one of the main sources of trajectory prediction errors, but it is obvious that the fulfilment of the CTOT is extremely important. The current 15 minutes range is excessive for our purpose and a narrower margin should be implemented. Probably, any value higher than 30 seconds should not be admitted into the new system definition. Further analysis on this subject should be made in the future.

The increase in capacity has not been properly evaluated. A comparison between the current sector capacity and the future “sector like” capacity should be made in order to better understand the advantages of the paradigm shift proposed. This comparison could be made through a simulation of a specific airspace block to compare the current capacity under the sector based philosophy versus the new approach.

A sensitivity analysis should be undertaken in order to better understand the trade-off between capacity and predictability, increasing or decreasing the number of conflicts to be solved by the ATCO, the obtained variation in the sector capacity, and the probability of conflict that is to be assumed should be studied.

In order to make a proper evaluation of the capacity increase due to the conflict resolution in a pre-tactical stage of the operation, the effect that each of the factors affecting the final ATCO workload should be assessed.

On the other hand, the role of the ATCO is to ensure the safe and expeditious flow of air traffic through the airspace for which they have responsibility. A controller must remain alert and effective throughout that part of their assigned shift which involves operational duty, ready to cope with unexpected or unforeseen situations. The workload of a controller must be accurately assessed to permit optimum efficiency.

If it is too high for too long, they may be overstretched. If it is too low for too long, this not only constitutes an inefficient application of resources but is likely to increase the chances of a controller becoming distracted from their primary task. A controller experiencing significant periods of under work during a particular shift may become bored and distracted from their primary task. Repetition of this over many consecutive shifts may lead to complacency.

Consequently, if the conflict resolution task is reduced to a minimum, the controller work during the operational duty will be different from the situation experienced nowadays, and a further analysis should be done in order to re-define the new tasks, avoiding under work and its consequences. This conclusion is also obtained from the questionnaire's responses analysis.

Finally, a detailed analysis of the vertical movement should be completed including the possibility of providing an accurate estimation of the rate of climb/descent depending on individual aircraft performance and atmospheric characteristics.

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ANNEX I. EXISTING 3D MODEL DESCRIPTION

The existing model provides an individual probability of potential collision (severity) for each individual encounter, based on the kinematics of the encounter and the minimum lateral and vertical separation at the Closest Point of Approach (CPA).

The formulation allows the estimation of the severity for each individual potential aircraft's encounter and the expected probability of collision for all aircraft's pairs who have potentially violated the separation standards.

To do this, stored tracks, obtained from Radar Data Processing systems, are processed and segmented to convert the tracks of each aircraft into a finite set of sequenced segments, in which the law of uniform motion is assumed.

In order to model the aircraft, they are represented by a cylinder of diameter λ_{xy} and height λ_z as indicated in Figure I.1.

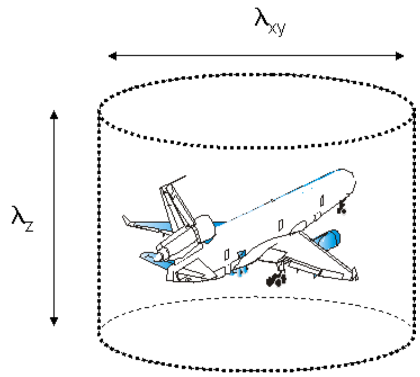

Figure I.1. Aircraft representation

Two aircraft are taken as colliding if their cylinders touch. With this bounded and closed airspace region representing the aircraft, a "collision cylinder" is settled as a larger cylinder of twice the dimensions represented in Figure I.1, and defined by height $2\lambda_z$ and radius $2\lambda_{xy}$ (see Figure I.2).

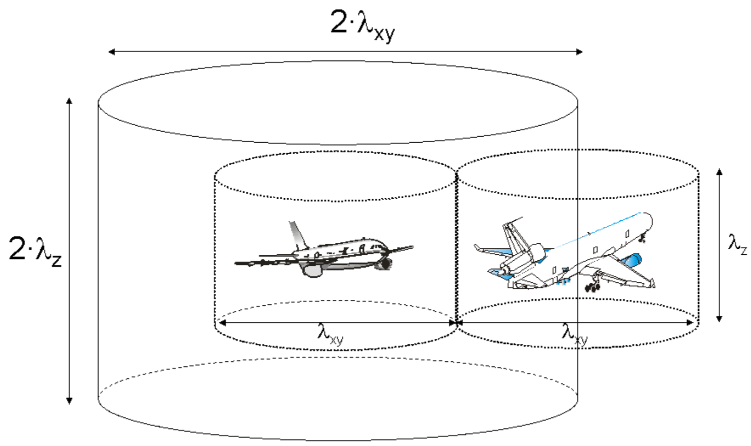

Figure I.2. Collision Cylinder

On the other hand, all high density traffic ATC scenarios have established minimum separation standards defined by two values, the minimum horizontal (R) and vertical (H) separations. When two aircraft are closer than these distances the ATC system is considered to have failed. These values (R, H) allow us to use another cylinder shaped protection model for all aircraft which should be free of any other aircraft to fulfil this separation minima (see Figure I.3). This volume is called the "conflict cylinder" as it is considered that two aircraft within it are potentially violating these separations and therefore exposed to risk.

During the en route phase of flight, for example, the conflict cylinder would be 5 NM in radius and 2,000 ft in height.

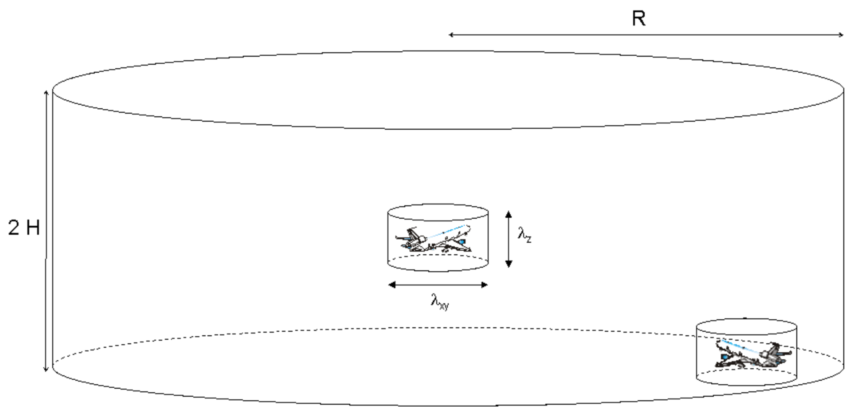

Figure I.3. Conflict Cylinder

A summary of the modelling cylinders defined so far is presented in the following Table.

Cylinder	Diameter	Height
Aircraft representation	λ_{xy}	λ_z
Collision	$2\lambda_{xy}$	$2\lambda_z$
Conflict	2R	2H

Table I.1. Modelling cylinders definition.

When the civil aircraft are climbing or descending, it is considered that pitch angles are small and so, vertical and horizontal dimensions have small changes. Therefore, all the "modelling cylinders" will be considered as horizontal, as indicated on Figure I.4.

As all the cylinders are considered parallel, the longitudes and surfaces ratios among them will be constant when they are projected onto any plane.

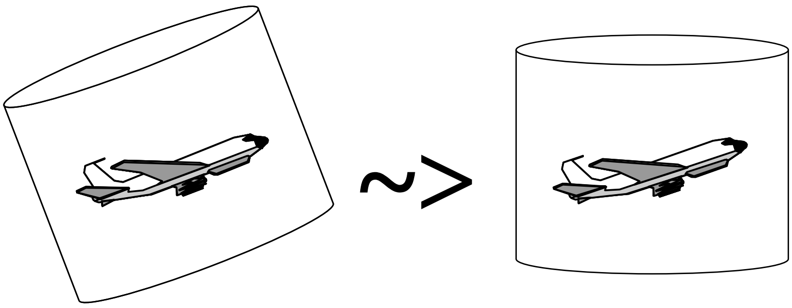

Figure I.4. Horizontal modelling cylinders

Taking into account the modelling cylinders described above, the following parameters are also defined:

- $\overrightarrow{v_{ji}}$ is the relative velocity vector between the two aircraft i and j involved in a proximity event (considered as constant as previously stated).
- Intruder aircraft (ACj) will be represented as a point (effectively at the centroid of the aircraft cylinder) and its speed will be the relative velocity vector $\overrightarrow{v_{ji}}$.
- Reference aircraft (Aci) will be represented by a cylinder twice the dimensions of a single aircraft cylinder and will be stationary. This cylinder has been previously defined as the collision cylinder.
- The impact plane is defined as a generic projection plane containing the centre of Aci (assumed as static) and perpendicular to $\overrightarrow{v_{ji}}$. This plane is represented in Figure I.5.

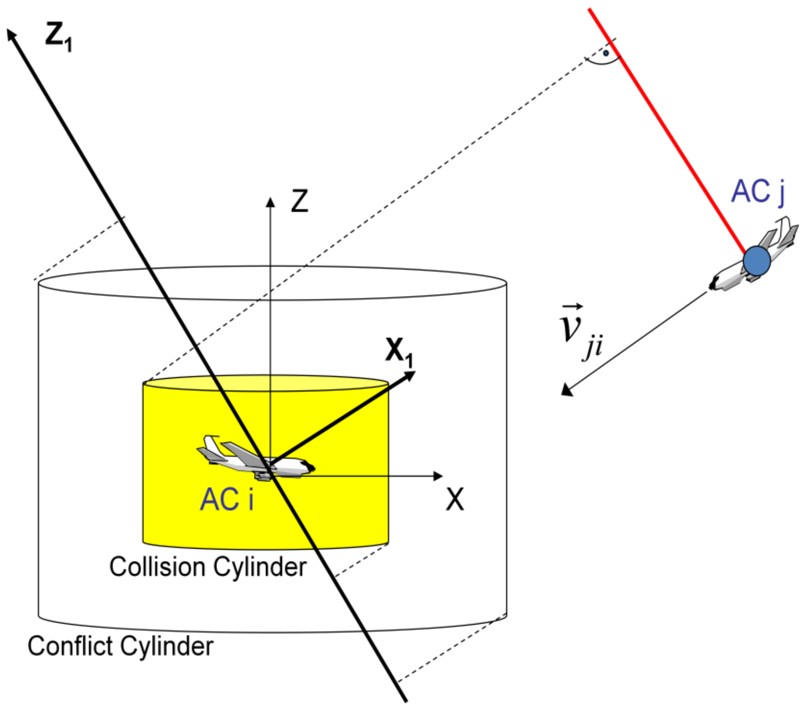

Figure I.5. Impact Plane definition

Furthermore, two projected areas and a projected position onto the impact plane are defined:

- The collision area is defined as the projection of the collision cylinder ($2\lambda_{xy}$,$2\lambda_z$)

- If the conflict cylinder would be settled in ACi, being its centroid the one of the cylinder as well, it could be also defined the conflict area as the projection of the conflict cylinder (2R, 2H).
- CPA_P is a point which coordinates y_{1p} and z_{1p} are obtained by projecting intruder aircraft.

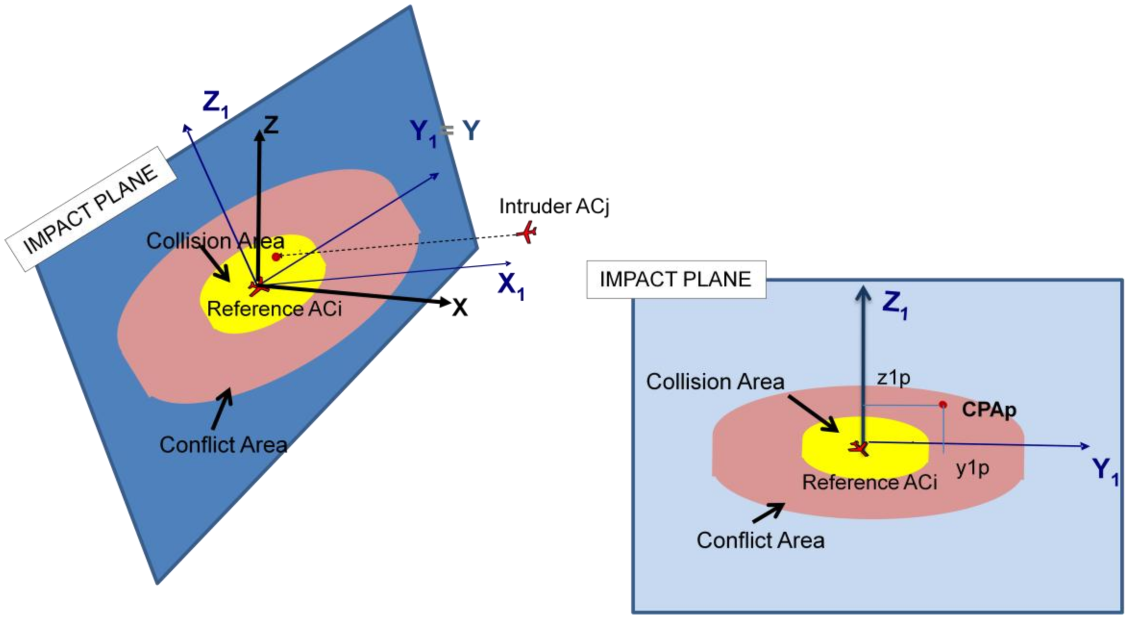

Figure I.6. Collision Area, Conflict Area and Projected CPA

Figure I.6 shows that a conflict will occur if ACj encounters the stationary conflict area, that is, if the CPA_p coordinates (y_{1p}, z_{1p}) are inside the conflict area. In the same way, a collision will occur if ACj encounters the stationary collision area, that is, if the CPA_p coordinates are inside the collision area.

This model estimates the severity of the encounter using the conditional probability of a potential collision P_a for each particular aircraft encounter by:

- Providing an individual probability of collision of each individual encounter based on the:
  - geometry of the encounter (collision area and conflict area dimensions),

- the minimum predicted lateral separation at the CPA (y_{1p}),
- the minimum predicted vertical separation at the CPA (z_{1p}).

- Taking into consideration the radar data errors and the segmentation errors.
- Assessing the severity of each individual potential encounter.

The identification and analysis of potential conflicts is based on aircraft track segmentation. Track segmentation identifies when an aircraft is turning, changing its vertical attitude, or modifying its speed, so that to replace the full detailed track of each aircraft with a series of line segments.

This assumption is based on the characteristics of the "en route" scenarios, in which most aircraft follow a regular behaviour, with "3D segmented" paths. In other words, the paths are made with an ordered sequence of "straight" sections, with punctual altitude or course changes. In addition, the speed of the aircraft in each segment is mainly uniform.

The purpose of the segmentation is to replace the track of each aircraft with a series of sections obtained from the Radar Data Processing.

From this, the CPA_p coordinates are obtained projecting ACi and ACj segmented trajectories, using an elementary kinematic model. As they cannot be taken as the real ones due to the errors on the trajectory predictor model used, every change in the straight segment will bring a different point of impact on the plane that is, a CPA'_p (y'_{1p},z'_{1p}). Considering this, $f_1(y'_{1p}, z'_{1p})$ will be used, assuming that can be statistically determined, as the bi-dimensional probability density function (pdf) of the CPA'_p coordinates (y'_{1p},z'_{1p}) for each projected segment associated to an individual encounter (see Figure I.7).

Furthermore, errors due to the track segmentation and the differences between this and the real aircraft trajectories must be also taken into account. For every projected CPA'_p (y'_{1p},z'_{1p}) there is also an associated error as shown in Figure I.8. The probability density function $f_2(y_1,z_1)$ represents the distribution of y_{1p} and z_{1p} coordinates errors due to the errors in the segmentation process.

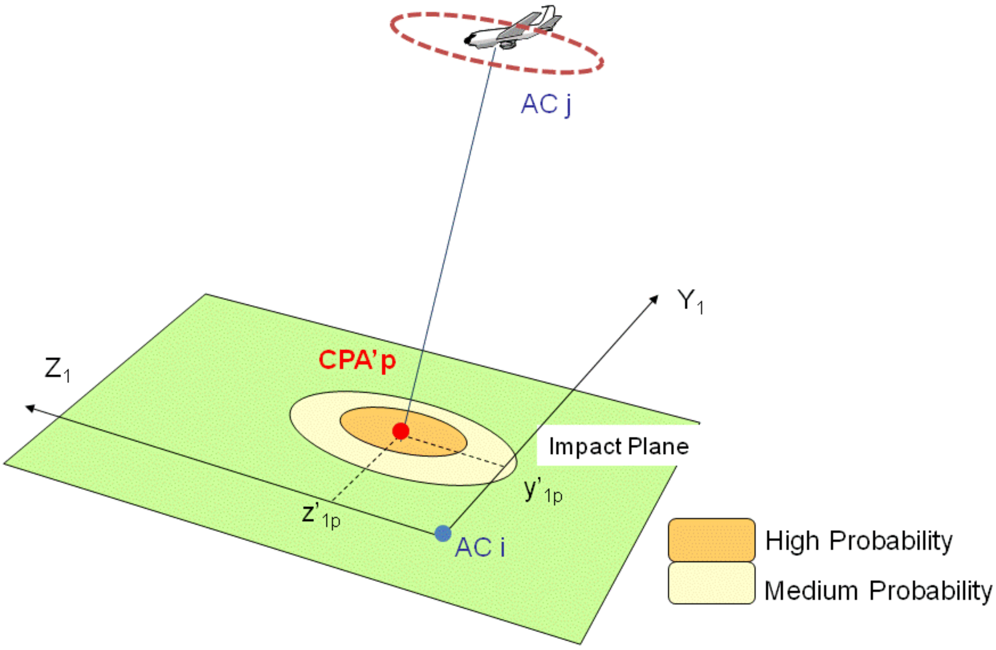

Figure I.7. Changes in the CPA coordinates due to Radar and Segmentation errors

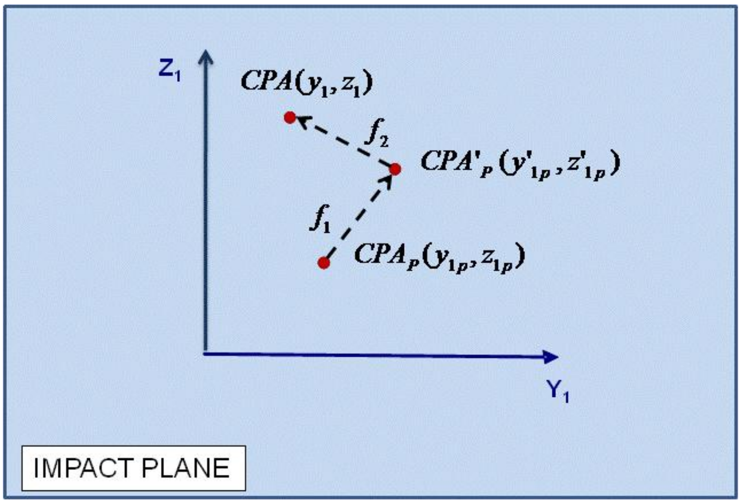

Figure I.8. Variation of CPA coordinates affected by f_1 and f_2

The probability of potential collision is obtained from the convolution of the two different probability density functions. The first one contains all errors derived from the projection of the trajectories (they are extrapolated beyond the last position considered).

The second one is given by the probability density function for lateral and vertical deviations of aircraft trajectories from the segmentation modelling.

ANNEX II. CALCULATIONS

The horizontal movement model of the aircraft is shown in Figure 3.2 where the following parameters are defined:

- $\overrightarrow{\boldsymbol{v_{ji}}}$: horizontal component of the relative speed between the two aircraft i and j involved in a proximity event.
- Intruder aircraft (ACj) with relative speed $\overrightarrow{v_{ji}}$.
- Reference aircraft (ACi), assumed as static.
- The impact line: established as a generic projection line containing the centre of Aci and perpendicular to $\overrightarrow{v_{ji}}$. CPA_y could be calculated as the intersection point of the straight line defined using the position of ACj with $\overrightarrow{v_{ji}}$ direction, and the impact line.
- Angles will be measured as the aircraft tracks, which are clockwise from the Magnetic North. Therefore, θ_i will be the ACi speed angle measured from the north, and θ_j and θ_{ji} angles are defined in the same way.

In order to determine the impact line considering wind effects on aircraft speeds, the following assumptions are taken into account:

- Wind unknown error ($\vec{w}$) will be taken as spatially and temporally constant within the encounter involved airspace and time, and then, common for both aircraft i and j.
- $|\vec{v_i}|$ and $|\vec{v_j}|$ will vary due to the previous unknown wind velocity error and this variation will depend on its direction and intensity.
- $\vec{v_i}$ and $\vec{v_j}$ directions (that is θ_j and θ_i) will not be affected by wind as the aircraft fly normally maintaining limited deviations following a predefined course established by the navigation computer.
- Other lateral uncertainties in the horizontal positioning will be considered negligible according to assumed navigation performance (see Section 3.2).

If $\overrightarrow{\boldsymbol{v_{ji0}}}$ is the relative speed between ACi and ACj under no wind error effects, it could be stated the following (see Figure II.1):

$$\overrightarrow{v_{ji0}} = \overrightarrow{v_j} - \overrightarrow{v_i} = v_j\overrightarrow{\mu_j} - v_i\overrightarrow{\mu_i}$$

Where:

$$\overrightarrow{\mu_j} = \overrightarrow{\mu_{ji\parallel}}\cos(\theta_{ji} - \theta_j) + \overrightarrow{\mu_{ji\perp}}\sin(\theta_{ji} - \theta_j)$$
$$\overrightarrow{\mu_i} = \overrightarrow{\mu_{ji\parallel}}\cos(\theta_{ji} - \theta_i) + \overrightarrow{\mu_{ji\perp}}\sin(\theta_{ji} - \theta_i)$$

Being $\overrightarrow{\mu_{ji\parallel}}$ and $\overrightarrow{\mu_{ji\perp}}$ the unitary vectors parallel and perpendicular to $\overrightarrow{v_{ji0}}$ respectively.

It is obvious that the following is fulfilled:

$$\overrightarrow{v_{ji0}} \cdot \overrightarrow{\mu_{ji\parallel}} = v_{ji0}$$
$$\overrightarrow{v_{ji0}} \cdot \overrightarrow{\mu_{ji\perp}} = 0$$

Being:

$$\overrightarrow{v_{ji0}} = \overrightarrow{v_j} - \overrightarrow{v_i} = v_j\overrightarrow{\mu_j} - v_i\overrightarrow{\mu_i} = v_j\overrightarrow{\mu_{ji\parallel}}\cos(\theta_{ji} - \theta_j) + v_j\overrightarrow{\mu_{ji\perp}}\sin(\theta_{ji} - \theta_j)$$
$$-v_i\overrightarrow{\mu_{ji\parallel}}\cos(\theta_{ji} - \theta_i) - v_i\overrightarrow{\mu_{ji\perp}}\sin(\theta_{ji} - \theta_i)$$

The following two equations are obtained:

$$\overrightarrow{v_{ji0}} \cdot \overrightarrow{\mu_{ji\parallel}} = v_j\cos(\theta_{ji} - \theta_j) - v_i\cos(\theta_{ji} - \theta_i) = v_{ji0}$$
$$\overrightarrow{v_{ji0}} \cdot \overrightarrow{\mu_{ji\perp}} = v_j\sin(\theta_{ji} - \theta_j) - v_i\sin(\theta_{ji} - \theta_i) = 0$$

As the modules and directions of the speed for both aircraft involved in the encounter are known parameters and therefore the initial relative speed between them (no wind), considering the above stated assumptions the new relative speed (wind error influence) can be calculated.

As formerly stated, the impact line is defined as a generic projection line containing the centre of ACi (assumed as static) and perpendicular to $\overrightarrow{v_{ji}}$. The angle variation between the initial impact line (no wind error) and the final impact line (wind error influence) named as δΘ is shown in Figure II.1 and can be calculated as follows:

$$\delta\theta = atan\left[\frac{\overrightarrow{v_{ji}} \cdot \overrightarrow{\mu_{ji\perp}}}{\overrightarrow{v_{ji}} \cdot \overrightarrow{\mu_{ji\parallel}}}\right]$$

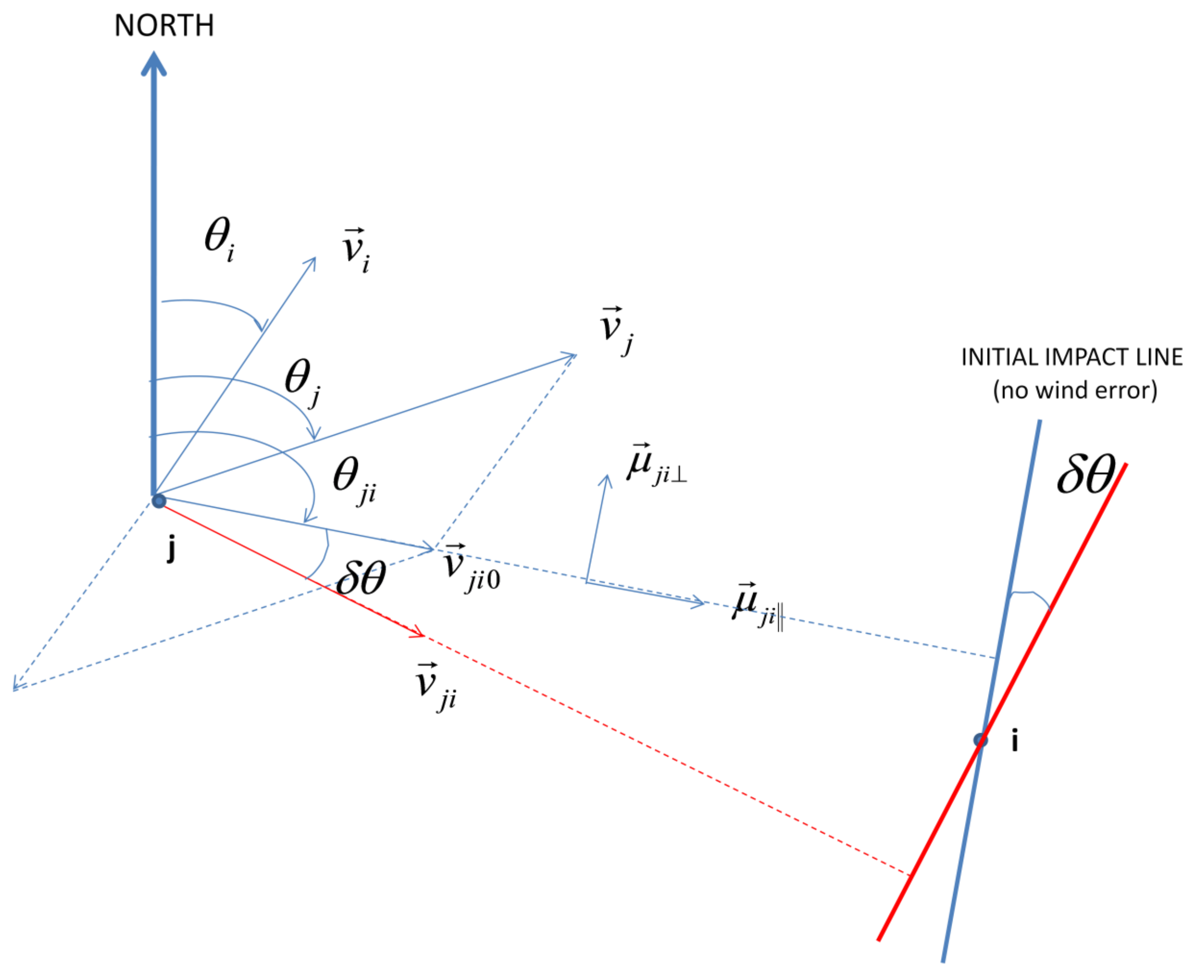

Figure II.1. δΘ calculation

The new relative speed between the two aircraft will be given by:

$$\overrightarrow{v_{ji}} = \overrightarrow{v_{ji0}} + \vec{w} + \overrightarrow{\delta_{ji}}$$

Where $\vec{w}$ is taken as the wind error vector and $\overrightarrow{\delta_{ji}}$ as any other possible noise due to other uncertainties. The above expression can be developed as follows:

$$\overrightarrow{v_{ji}} = \overrightarrow{v_{ji0}} + \vec{w} + \overrightarrow{\delta_{ji}} = v_{ji0}\overrightarrow{\mu_{ji\parallel}} + w_j\overrightarrow{\mu_j} - w_i\overrightarrow{\mu_i} + \delta_j\overrightarrow{\mu_j} - \delta_i\overrightarrow{\mu_i}$$

Where $w_{j,i}$ and $\delta_{j,i}$ are the components of the wind error vector and the noise on the ACj and ACi speed directions respectively.

And using:

$$\overrightarrow{\mu_j} = \overrightarrow{\mu_{ji\parallel}}\cos(\theta_{ji} - \theta_j) + \overrightarrow{\mu_{ji\perp}}\sin(\theta_{ji} - \theta_j)$$
$$\overrightarrow{\mu_i} = \overrightarrow{\mu_{ji\parallel}}\cos(\theta_{ji} - \theta_i) + \overrightarrow{\mu_{ji\perp}}\sin(\theta_{ji} - \theta_i)$$

The following expression for $\overrightarrow{v_{ji}}$ can be obtained:

$$\begin{aligned}\overrightarrow{v_{ji}} = v_{ji0}\overrightarrow{\mu_{ji\parallel}} &+ w_j \cdot [\overrightarrow{\mu_{ji\parallel}}\cos(\theta_{ji} - \theta_j) + \overrightarrow{\mu_{ji\perp}}\sin(\theta_{ji} - \theta_j)] \\ &- w_i \cdot [\overrightarrow{\mu_{ji\parallel}}\cos(\theta_{ji} - \theta_i) + \overrightarrow{\mu_{ji\perp}}\sin(\theta_{ji} - \theta_i)] \\ &+ \delta_j \cdot [\overrightarrow{\mu_{ji\parallel}}\cos(\theta_{ji} - \theta_j) + \overrightarrow{\mu_{ji\perp}}\sin(\theta_{ji} - \theta_j)] \\ &- \delta_i \cdot [\overrightarrow{\mu_{ji\parallel}}\cos(\theta_{ji} - \theta_i) + \overrightarrow{\mu_{ji\perp}}\sin(\theta_{ji} - \theta_i)]\end{aligned}$$

Therefore,

$$\delta\theta = atan\left[\frac{\overrightarrow{v_{ji}} \cdot \overrightarrow{\mu_{ji\perp}}}{\overrightarrow{v_{ji}} \cdot \overrightarrow{\mu_{ji\parallel}}}\right] =$$
$$= \text{atan}\left[\frac{(w_j + \delta_j)\sin(\theta_{ji} - \theta_j) - (w_i + \delta_i)\sin(\theta_{ji} - \theta_i)}{v_{ji0} + (w_j + \delta_j)\cos(\theta_{ji} - \theta_j) - (w_i + \delta_i)\cos(\theta_{ji} - \theta_i)}\right]$$

Considering the known parameters and the assumptions observed (other uncertainties in the horizontal positioning will be initially considered negligible) Equation (1) for $\delta\theta$ is obtained.

$$\boldsymbol{\delta\theta = atan\left[\frac{w_j * \sin(\theta_{ji} - \theta_j) - w_i * \sin(\theta_{ji} - \theta_i)}{v_{ji0} + w_j * \cos(\theta_{ji} - \theta_j) - w_i * \cos(\theta_{ji} - \theta_i)}\right]} \quad \textbf{(1)}$$

ANNEX III. RELATION BETWEEN θ_j AND θ_i

Figure III.1 shows the relation between θ_j and θ_i , considering as the origin of angles the relative velocity. It can be stated that:

$$v_j \cdot sin\theta_j = v_i \cdot sin\beta$$

$$\theta_i = \pi - \beta$$

$$\theta_i = \pi - \arcsin\left(\frac{v_j}{v_i} \cdot sin\theta_j\right)$$

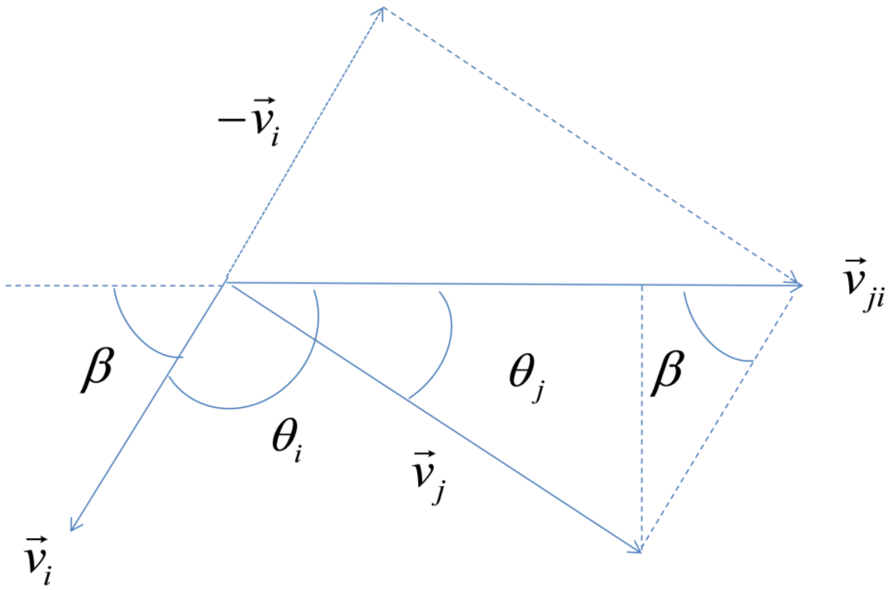

Figure III.1. Relation between θ_j and θ_i.

ANNEX IV. MATLAB PROGRAMS

PROGRAM 1: Data matrix calculation: matrixcal.m

This program has been developed to analyse the expression obtained for the geometry factor calculation (18):

$$\boldsymbol{a} = \boldsymbol{cos(\theta_w - \theta_i) * \sin(\theta_i)} \quad - \boldsymbol{cos(\theta_w - \theta_j) * \sin(\theta_j)}$$

The speed ratio is settled in the first code line, and after that, for every θ_j (tethaj) the correspondent θ_i (tethai) is calculated using (20):

$$\boldsymbol{\theta_i = \pi - arcsin\left[\frac{v_j}{v_i}\, sin\theta_j\right]}$$

θ_j variation is established from 10 degrees to 80 degrees.

Equation (18) is analysed transforming it into the subtraction of two phasors (as indicated in Figure IV.1) using:

$$Acos(wt + \theta) = Re\{Ae^{-i(wt+\theta)}\}$$

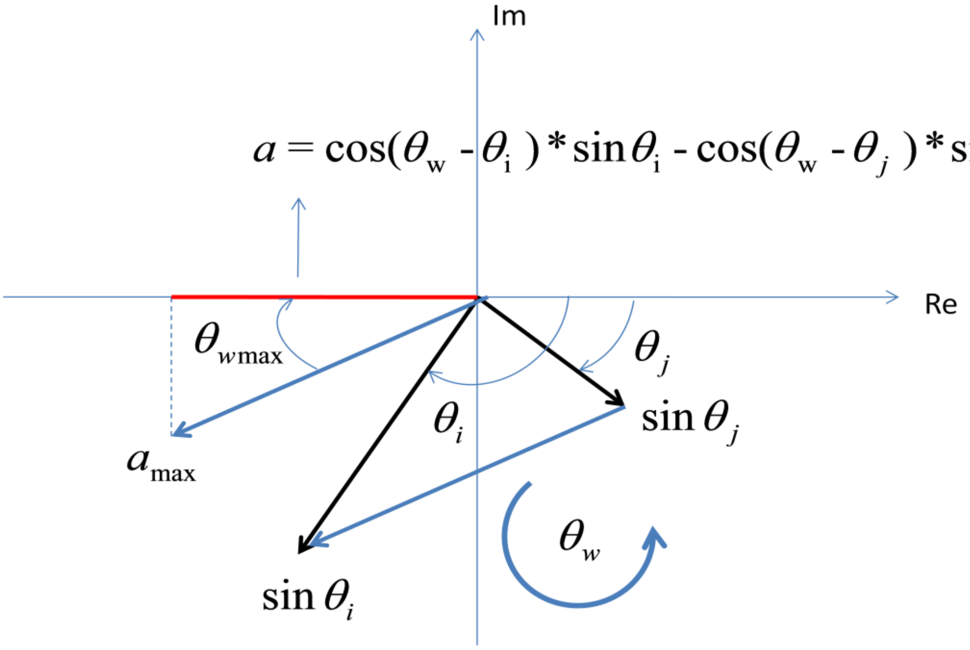

Figure IV.1. Phasors representation

$$a_{max} = \sqrt{(Re(a))^2 + (Im(a))^2}$$

$$\theta_{wmax} = atan\left[\frac{abs(Im(a))}{abs(Re(a))}\right]$$

$$\mathrm{Im(a)} = \sin^2\theta_i - sin^2\theta_j$$

$$\mathrm{Re(a)} = \sin\theta_i cos\theta_i - \sin\theta_j cos\theta_j$$

A matrix with 32 arrows (one for every θ_j) and 5 columns is calculated (θ_j, θ_i, $\boldsymbol{a_{max}}$, $\frac{\boldsymbol{a_{max}}}{\sqrt{2}}$, θ_w)

The values obtained are shown for three different speeds ratio (1, ½, 1/8).

At the end of the program the maximum and minimum values for $\boldsymbol{a}$ are calculated.

```
%First the speed ratio is settled
vj=1;
vi=1;
n=0;%counter
for c=10*pi/180:pi/80:80*pi/180 %tethaj variation
c=c;
n=n+1;

%Secondly, tethaj is settled and tetha i is calculated
tethaj=c;
tethai=pi-asin((vj/vi)*sin(tethaj));

%calculation of the maximum geometry factor a, and wind that produces
this maximum value

im=(sin(tethai))^2-(sin(tethaj))^2;
re=sin(tethai)*cos(tethai)-sin(tethaj)*cos(tethaj);
wmax=atan(abs(im)/abs(re));
amax=sqrt(re^2+im^2);

%calculation of the geometry factor variation with wind
i=0:pi/80:pi;
a=amax*cos(i-(pi+wmax));
dibujocero=i*0;

%calculation of the matrix containing all the needed data
matriz(n,1)=tethaj*180/pi;
matriz(n,2)=tethai*180/pi;
matriz(n,3)=amax;
matriz(n,4)=amax/sqrt(2);
matriz(n,5)=wmax*180/pi;

end
```

```
%calculation of the maximum and minimum values for amax
128áximo=matriz(1,3);
 for j=1:1:31

    if 128áximo<abs(matriz((j+1),3))
        maximo=abs(matriz((j+1),3));

    end
 end
minimo=matriz(1,3);
 for j=1:1:31

    if minimo>abs(matriz((j+1),3))
        minimo=abs(matriz((j+1),3));

    end
end
```

MATRIX ($\frac{v_j}{v_i}$ =1)

θ_j	θ_i	a_{max}	$\frac{a_{max}}{\sqrt{2}}$	θ_w
10.0000	170.0000	0.3420	0.2418	0.0000
12.2500	167.7500	0.4147	0.2932	0.0000
14.5000	165.5000	0.4848	0.3428	0.0000
16.7500	163.2500	0.5519	0.3903	0.0000
19.0000	161.0000	0.6157	0.4353	0.0000
21.2500	158.7500	0.6756	0.4777	0.0000
23.5000	156.5000	0.7314	0.5171	0.0000
25.7500	154.2500	0.7826	0.5534	0.0000
28.0000	152.0000	0.8290	0.5862	0.0000
30.2500	149.7500	0.8704	0.6154	0.0000
32.5000	147.5000	0.9063	0.6409	0.0000
34.7500	145.2500	0.9367	0.6623	0.0000
37.0000	143.0000	0.9613	0.6797	0.0000
39.2500	140.7500	0.9799	0.6929	0.0000
41.5000	138.5000	0.9925	0.7018	0.0000
43.7500	136.2500	0.9990	0.7064	0.0000
46.0000	134.0000	0.9994	0.7067	0.0000
48.2500	131.7500	0.9936	0.7026	0.0000
50.5000	129.5000	0.9816	0.6941	0.0000
52.7500	127.2500	0.9636	0.6814	0.0000
55.0000	125.0000	0.9397	0.6645	0.0000
57.2500	122.7500	0.9100	0.6434	0.0000
59.5000	120.5000	0.8746	0.6184	0.0000
61.7500	118.2500	0.8339	0.5896	0
64.0000	116.0000	0.7880	0.5572	0.0000
66.2500	113.7500	0.7373	0.5213	0.0000
68.5000	111.5000	0.6820	0.4822	0.0000

70.7500	109.2500	0.6225	0.4402	0.0000
73.0000	107.0000	0.5592	0.3954	0
75.2500	104.7500	0.4924	0.3482	0
77.5000	102.5000	0.4226	0.2988	0
79.7500	100.2500	0.3502	0.2476	0

MATRIX ($\frac{v_j}{v_i} = \mathbf{1/2}$)

θ_j	θ_i	$\boldsymbol{a_{max}}$	$\frac{a_{max}}{\sqrt{2}}$	θ_w
10.0000	175.0191	0.2585	0.1828	5.0191
12.2500	173.9101	0.3147	0.2225	6.1601
14.5000	172.8083	0.3696	0.2614	7.3083
16.7500	171.7149	0.4232	0.2992	8.4649
19.0000	170.6315	0.4751	0.3360	9.6315
21.2500	169.5592	0.5253	0.3715	10.8092
23.5000	168.4996	0.5736	0.4056	11.9996
25.7500	167.4540	0.6197	0.4382	13.2040
28.0000	166.4240	0.6636	0.4692	14.4240
30.2500	165.4108	0.7051	0.4986	15.6608
32.5000	164.4161	0.7441	0.5262	16.9161
34.7500	163.4412	0.7805	0.5519	18.1912
37.0000	162.4879	0.8142	0.5758	19.4879
39.2500	161.5575	0.8452	0.5976	20.8075
41.5000	160.6517	0.8733	0.6175	22.1517
43.7500	159.7720	0.8986	0.6354	23.5220
46.0000	158.9201	0.9210	0.6513	24.9201
48.2500	158.0975	0.9406	0.6651	26.3475
50.5000	157.3058	0.9573	0.6769	27.8058
52.7500	156.5467	0.9711	0.6867	29.2967
55.0000	155.8218	0.9822	0.6945	30.8218
57.2500	155.1326	0.9906	0.7004	32.3826
59.5000	154.4807	0.9962	0.7044	33.9807
61.7500	153.8677	0.9993	0.7066	35.6177
64.0000	153.2950	0.9999	0.7071	37.2950
66.2500	152.7641	0.9981	0.7058	39.0141
68.5000	152.2763	0.9941	0.7029	40.7763
70.7500	151.8329	0.9879	0.6986	42.5829
73.0000	151.4352	0.9797	0.6928	44.4352
75.2500	151.0843	0.9696	0.6856	46.3343
77.5000	150.7811	0.9577	0.6772	48.2811
79.7500	150.5265	0.9442	0.6677	50.2765

MATRIX ($\frac{v_j}{v_i} = \mathbf{1/8}$)

θ_j	θ_i	$\boldsymbol{a_{max}}$	$\frac{a_{max}}{\sqrt{2}}$	θ_w
10.0000	178.7562	0.1950	0.1379	8.7562
12.2500	178.4802	0.2380	0.1683	10.7302
14.5000	178.2065	0.2806	0.1984	12.7065
16.7500	177.9355	0.3225	0.2280	14.6855
19.0000	177.6676	0.3638	0.2572	16.6676
21.2500	177.4033	0.4043	0.2859	18.6533
23.5000	177.1430	0.4440	0.3139	20.6430
25.7500	176.8870	0.4827	0.3413	22.6370
28.0000	176.6357	0.5205	0.3680	24.6357
30.2500	176.3896	0.5572	0.3940	26.6396
32.5000	176.1490	0.5927	0.4191	28.6490
34.7500	175.9142	0.6271	0.4434	30.6642
37.0000	175.6857	0.6602	0.4668	32.6857
39.2500	175.4638	0.6920	0.4893	34.7138
41.5000	175.2489	0.7224	0.5108	36.7489
43.7500	175.0412	0.7514	0.5313	38.7912
46.0000	174.8411	0.7789	0.5508	40.8411
48.2500	174.6490	0.8049	0.5692	42.8990
50.5000	174.4650	0.8294	0.5865	44.9650
52.7500	174.2896	0.8523	0.6027	47.0396
55.0000	174.1230	0.8736	0.6177	49.1230
57.2500	173.9654	0.8933	0.6316	51.2154
59.5000	173.8170	0.9113	0.6444	53.3170
61.7500	173.6783	0.9277	0.6559	55.4283
64.0000	173.5492	0.9424	0.6663	57.5492
66.2500	173.4302	0.9554	0.6756	59.6802
68.5000	173.3213	0.9667	0.6836	61.8213
70.7500	173.2227	0.9764	0.6904	63.9727
73.0000	173.1346	0.9844	0.6961	66.1346
75.2500	173.0571	0.9907	0.7006	68.3071
77.5000	172.9903	0.9954	0.7039	70.4903
79.7500	172.9344	0.9985	0.7060	72.6844

PROGRAM 2: Geometry factor analysis: geometryfactor.m

The first part of the previous code is used to continue the analysis of the geometry factor. In particular, Figures 4.3, 4.7 and 4.11 show for each of the above speed ratios the three angles (θ_j, θ_i , θ_w) evolution for maximum geometry factor, whereas Figures 4.2, 4.6 and 4.10 show the maximum values for the geometry factor obtained for each

θ_j. Similarly, for every θ_j (and the correspondent θ_i), the curve followed by $\boldsymbol{a}$ when θ_w varies from 0 to 180 degrees is calculated and plotted in Figures 4.1, 4.5 and 4.9.

```
%First the speed ratio is settled
vj=1;
vi=1;
n=0;%counter
for c=10*pi/180:pi/80:80*pi/180 %tethaj variation
c=c;
n=n+1;
tethaj=c;
tethai=pi-asin((vj/vi)*sin(tethaj));

%calculation of the maximum geometry factor a, and wind that produces
this maximum value

re=(sin(tethaj))^2-(sin(tethai))^2;
im=sin(tethaj)*cos(tethaj)-sin(tethai)*cos(tethai);
wmax=atan(abs(re)/abs(im));
amax=sqrt(re^2+im^2);

%calculation of the geometry factor variation with wind
i=0:pi/80:pi;
a=amax*cos(i-(pi+wmax));
dibujocero=i*0;

%calculation of the matrix containing all the needed data
matriz(n,1)=tethaj*180/pi;
matriz(n,2)=tethai*180/pi;
matriz(n,3)=amax;
matriz(n,4)=amax/sqrt(2);
matriz(n,5)=wmax*180/pi;

%Figures 4.2,4.5 and 4.9 depending on the speed ratio
i=i*180/pi;
title('CALCULATION OF "Geometry Factor"')
xlabel('WIND ANGLE FROM THE RELATIVE SPEED VECTOR(degrees)')
if c<=30*pi/180
    plot(i,a,'b')
    hold on
elseif c <=60*pi/180
    plot(i,a,'g')
    hold on

else
    plot(i,a,'r')
    hold on
end
plot(i,dibujocero,'-')
title('CALCULATION OF "Geometry Factor"')
xlabel('WIND ANGLE FROM THE RELATIVE SPEED VECTOR(degrees)')

end

%Figures 4.3, 4.7 and 4.11 depending on the speed ratio
```

```
Figure
for x=1:n
plot(x,matriz(x,1),'rx')
hold on
plot(x,matriz(x,2),'bo')
hold on
plot(x,matriz(x,5),'g*')
end
title('Aircraft j, aircraft i, and wind angles evolution for maximum
"geometry factor"')
xlabel('Different geometry configurations')

%Figures 4.2, 4.6 and 4.10 depending on the speed ratio

Figure
for y=1:n
plot(matriz(y,1),matriz(y,3),'*')
hold on
end
title('Maximum values for "geometry factor"')
xlabel('Aircraft j angle')
```

PROGRAM 3: Distribution functions calculation: disfunctions.m

This program calculates sigma values obtained from (19):

$$\sigma = t_{CPA} \quad a \quad \sigma_w$$

and introduces them into equation:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-1}{2}\left(\frac{x}{\sigma}\right)^2}$$

This analysis is only made for $\frac{v_j}{v_i}$ =1, and the first 17 elements of the matrix calculated in program 1, as the results are symmetrical. For each of these 17 values for a_{max} obtained in the third column of the matrix calculated in program 1, the correspondent Gaussian function is plotted. As it is explained in the main text t_{CPA} is settled as 1 hour and σ_w as 6m/s.

```
%distribution functions calculation, Figure 28

matrixcal;
tcpa=60*60; *seconds
```

```
sigmaw=6/1852;%NM/s
Figure
for n=1:16
    sigma=matriz(n,3)*tcpa*sigmaw;
    x=-60:0.3:60;
    y=(1/(sigma*sqrt(2*pi)))*gaussmf(x,[sigma 0]);
    plot(x,y)
    hold on

end
```

PROGRAM 4: CPA variation calculation: CPAcal.m

From this program it is obtained the x coordinate from the integral:

$$Pconf(x) = \int_{-\infty}^{x} f(\tau)d\tau = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x} e^{\frac{-1}{2}\left(\frac{\tau}{\sigma}\right)^2} d\tau$$

taking into account: $\frac{v_j}{v_i}$ =1, t_{CPA} = 1 hour, σ_w = 6m/s, and the maximum and minimum a values obtained from program1 (called maximo and minimo) to calculate $\sigma_{max/min}$ from Equation (19):

$$\sigma = t_{CPA} \quad a \quad \sigma_w$$

The integral is solved considering the following[1]:

$$F(x, \sigma^2) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x} e^{\frac{-1}{2}\left(\frac{\tau}{\sigma}\right)^2} d\tau = \frac{1}{2}\left[1 + \text{erf}\left(\frac{x}{\sigma\sqrt{2}}\right)\right] \qquad x>0$$

Then, the probability P we are looking for is:

$$P = 1 - F(x, \sigma^2) = 1 - \frac{1}{2}\left[1 + \text{erf}\left(\frac{x}{\sigma\sqrt{2}}\right)\right] = \frac{1}{2}\left[1 - \text{erf}\left(\frac{x}{\sigma\sqrt{2}}\right)\right]$$

And, introducing the MATLAB erfc function:

[1] Barak, Ohad (2006). "Q function and error function". Tel Aviv University. http://www.eng.tau.ac.il/~jo/academic/Q.pdf. (Accessed January 2012).

$$2P = \text{erfc}(\frac{x}{\sigma\sqrt{2}})$$

As a conclusion, for a given probability P, the resulting x coordinate is:

$$x = \sigma\sqrt{2}\text{erfcinv}(2P)$$

It should be noted that in the program 5NM has been added to this distance as this is the minimum separation between two aircraft to be considered as not conflicted (Section 4.1.4).

Figures 4.16, 4.17 and 4.18 are obtained from this program.

```
matrixcal;
tcpa=60*60;%seconds
sigmaw=6/1852;%NM/s

sigma1=134áximo*tcpa*sigmaw;
sigma2=minimo*tcpa*sigmaw;
for b=1:500
y(b)=b*10^(-3)*2;
t(b) = erfcinv(y(b));
x1(b)=5+t(b)*sqrt(2)*sigma1;
x2(b)=5+t(b)*sqrt(2)*sigma2;
end

%Figures 4.16, 4.17 and 4.18

Figure
for m=1:b
plot( x1(m),m,'r*')
hold on
end

for m=1:b
plot( x2(m),m,'b*')
hold on
end
```

ANNEX V. PAPER PRESENTED IN THE SESAR INNOVATION DAYS. TOULOUSE 29th Nov / 1st Dec 2011

Flow management without en route capacity limitations by pre-tactical trajectory compatibility determination

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***Abstract*— Airspace capacity is limited by several inter-linked factors including controller workload, traffic distribution and procedures. Aircraft cannot always fly an optimal horizontal route or vertical profile and as traffic demand continues to increase then so do delays. Much of the controller's workload is spent on tactical actions related to conflict avoidance between two or more aircraft. If potential conflicts could be identified further in advance then controller workload would be reduced and less of a factor in limiting system capacity.**

This Paper discusses how future conflicts could be identified using Decision Support Tools (DST) in order to provide conflict-free trajectories in advance. Much of the research in this Paper deals with problems in estimating wind speed and direction and the impact of wind prediction errors on defining conflict-free trajectories.

To achieve this aim the Paper initially discusses lateral, longitudinal, and vertical uncertainties; the Paper then concentrates on the horizontal components (lateral and longitudinal uncertainties) and the influence of wind errors, both in direction and in speed, on defining conflict-free trajectories.

The Paper concludes, firstly, by expressing a minimum separation distance between two aircraft as a function of the angle between their tracks and an assumed wind speed prediction error, and assuming that both aircraft are at the same flight level and that lateral position errors are negligible. Secondly, the linkage between the prevailing wind direction and the relative speed vectors of the two aircraft, in terms of potential position errors, are demonstrated.

Keywords- ATM safety, ATM capacity, Trajectory Management, Decision Support Tools, Trajectories compatibility

I. INTRODUCTION

In spite of the fact that the airspace could be considered initially as an unlimited resource, this is not a true statement. For Air Traffic Management (ATM) purposes airspace is currently divided into different volumes, called Air Traffic Control (ATC) sectors, each of them controlled by an Air Traffic Controller (ATCO). The capacity of the ATM system is limited by the amount of simultaneous traffic inside each ATC sector that an ATCO is able to handle. This amount of traffic depends on a number of factors, including the physical pattern of air routes and airports, the traffic demand distribution (both geographic and temporal), the physical volume of the sector and the ATC working procedures designed to maximise the traffic throughput. As a result, airlines cannot fly the optimal route, but the available route which permits the balance between demand and capacity for that specific time.

The continuous increase on air traffic has determined a certain degree of saturation in both Europe and US, especially in high density traffic areas, where the limiting factor on capacity is, apart from the airports capacity, the controller tactical workload in the ATC sectors. Tactical actions, taken by controllers, to avoid conflict between aircraft, have been agreed as the main bottle neck for today's ATM system. These actions grow rapidly with traffic density, limiting the number of aircraft that can be safely attended. As an example, the proportion of ATFM delay in July 2011 (see Figure 1) shows that a 61.3% (46.4% en route capacity plus 14.9 en route ATC staffing) of the delay is due to a lack of en route capacity.

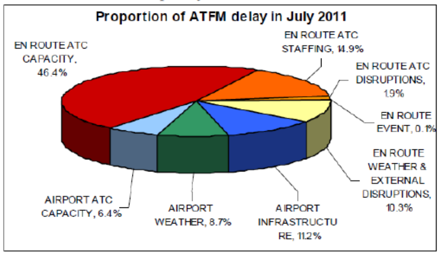

Figure 1. Proportion of ATFM delays as reported by Network Operations Report July 2011. Eurocontrol

Worldwide initiatives have been launched in order to reform the architecture of the current ATM in a way that:

- Allows airlines to decide its optimal route (operational cost reduction,
- Improves user satisfaction (predictability, overall travel time reduction)
- Reduces environmental impact (noise annoyance and air pollution)
- Improves safety (by pre-tactical compatibility among the different routes)
- Identifies possible route conflicts and could offer alternatives in the pre-tactical phase (capacity increase, delays decrease, ATC related cost reduction)

These statements constitute the goals and vision for the design of the future ATM System [1].

In order to minimise controller's tactical interventions, aircraft trajectory management shall be implemented to identify trajectories' incompatibilities in advance, proposing different alternatives to the airlines. Thus, airspace capacity will be closer to the unlimited capacity, and the ATCO work although still necessary, won´t be the system limiting factor. This philosophy, underlying the Trajectory Based Operations (TBO), is the basis for the work presented in this Paper.

Future ATM will require automated Decision Support Tools (DST) to provide quasi optimal conflict-free trajectories in advance, in order to minimise the ATCO tactical interventions. Whether trajectories' incompatibilities could be identified in advance (hours before the operation), and different alternatives would be proposed to the airlines, the efficiency of the whole system will be increased and the airlines will be close to decide its optimal route (cost reductions, lower environmental impact). The ability to predict accurate aircraft trajectories is one of the fundamental issues to tackle when developing these DST.

Wind prediction error has been identified as the greatest source of error for trajectory predictions on the order of 20 minutes time horizon. Flight tests have been conducted to better understand the wind-prediction errors, to establish metrics for quantifying large errors and to validate different approaches to improved wind prediction accuracy [2]. Therefore errors in the trajectory determination produced by wind uncertainties should be considered as critical when defining these conflict-free trajectories.

II. CAPACITY VERSUS PREDICTABILITY

Keeping in mind the Future ATM main goals, defined under the European initiative [3], as the following measurable outcomes:

- 3 fold increase in capacity
- 10 fold increase in safety
- 50% reduction in ATM cost per flight

If a conflict is defined as two or more aircraft coming within the minimum allowed distance and altitude separation of each other, the minimum separation between trajectories to be declared as compatible would be established as a trade-off between capacity and predictability. The capacity, based on ATCO workload is related to the number of tactical interventions required by aircraft, whereas the predictability is related to the probability of exposition to risk, and could be defined as the degree of compliance between planned and actual aircraft positions, affecting the total system safety.

A. *Predictability*

A critical enabler for TBO is the availability of an accurate, planned trajectory, providing valuable information to allow more effective use of the airspace. However, there are many definitions of a trajectory. The framework developed by the FAA/Eurocontrol R&D Action Plan includes definitions of "trajectory" and "trajectory predictor" (TP) [4]: "the Predicted Trajectory describes the estimated path a moving aircraft will follow through the airspace. The Trajectory can be described mathematically by a time-ordered set of Trajectory Vectors".

There are many different stakeholders in the transition to a TBO environment, and there are many different time frames over which TBO may operate—from strategic capacity management operating on the time frame of years to short-term collision avoidance, operating up to over fraction of minutes. Therefore, it is very important to reduce the uncertainty associated with the prediction of an aircraft's future location through use of an accurate 4D Trajectory in space (latitude, longitude, altitude) and time. Trajectory uncertainties can be divided into three groups: lateral deviation uncertainties, vertical deviation uncertainties and longitudinal deviation uncertainties.

The **lateral uncertainties** are already defined within the Performance Based Navigation (PBN) Manual of ICAO, in which the Total System Error (TSE), for some specific aircraft navigation system requirements, operating in a particular airspace, supported by the appropriate navigation infrastructure, is settled. As an example, during operations in airspace or on routes designated as RNP1, the lateral system error must be within ±1NM for at least the 95% of the total flight time. The TSE has a standard deviation composed of the standard deviation of the three errors: path definition error (PDE), Flight Technical Error (FTE), and Navigation System Error (NSE).

In order to analyse the **vertical uncertainties** two different cases should be brought into consideration. When the aircraft is establish at a defined flight level, the approach is similar to the one shown when explaining the horizontal uncertainties, as for the operations in Reduced Vertical Separation Minimum (RVSM) is defined a total vertical error of 200ft, being in this case the accuracy requirements of 3 sigma. On the other hand, when aircraft are climbing or descending vertical uncertainties are much greater as climbing rate varies with aircraft performance and the atmospheric air speed, temperature and density.

When analysing **longitudinal uncertainties** it must be considered that aircraft use to fly most of the time at a constant airspeed of Mach number rather than at a constant ground speed and, as a consequence, the effects of wind modeling and prediction errors accumulate with time. Airlines use the wind estimation to minimise flight costs by appropriate choice of a route, cruise level and by loading the minimum necessary fuel on board. In spite of the fact that wind-field accuracy is sufficient on average, large errors occasionally exist and cause significant errors in trajectory prediction. The performance of ATM DST depends on the accuracy of the wind predictions. Studies have shown a predominant daily value for RMS vector difference of about 6m/s and large errors of 10m/s are 3% overall [2].

B. Capacity

Nowadays, for ATC purposes, the airspace is divided into sectors that are three dimensional volumes with specific dimensions and procedures depending on the type of traffic that goes through them and its physical characteristics. Each of these sectors is handled by an executive ATCO, and has a previously established capacity defined as the maximum number of aircraft that can be inside the sector within an hour. This capacity depends on the specific characteristics of each sector and it is considered as the maximum number of aircraft that the ATCO can manage keeping the safety margins applied.

As a result, a bottleneck could be identified: the ATCO is able to control a limited number of aircraft, and although the number of available sectors could be increased to cope with an increase of air traffic demand, this has a clear limitation as tiny sectors cannot be properly managed and coordination workload will increase as a consequence.

Current ATFM considers "conflict free" trajectories in an strategic/pretactical level if they do not exceed capacity at any involved "ATC sectors". ATC sector capacity is mainly limited by ATCOs conflict resolution workload for a given aircraft population.

As an example, some results providing a relative value of the risk for a given scenario have been obtained using real radar data in Maastricht UAC [5]. After processing 31 days of radar data (600 flights per sector a day) more than 45.000 proximate events were identified in the en-route airspace assigned to the Maastricht UAC, which involves approximately a 50% of conflicted aircraft. Considering the total number of ATC sectors, the conclusions obtained show about 75 potential conflicts per sector a day.

A potential conflict is nowadays identified when the minimum distance between two aircraft is, or is going to be in the short term, lower than an established minimum separation standard defined by two values, the minimum horizontal and vertical separations. During the en route phase of flight, in the ECAC airspace, these values are 5 nm horizontal distance and 1,000 ft in height.

However, these current minimum separation standards were determined many years ago and they are used to facilitate conflicts resolution in an ATC environment. Trajectories compatibility should not be based in minimum separation standards but in probability of conflicts that finally would require tactical ATCO intervention. This compatibility should be established based on trade off between false alarm and misdetection probabilities.

This assumption is also made in [6] where a method of estimating conflict probability is developed in order to analyse medium term conflict detection and the implications for conflict resolution. However, if aircraft trajectories could be deconflicted time in advance the real time operation takes place, the ATCO workload per aircraft would be significantly reduced and the global system capacity and safety could be increased. This is the purpose for conflict probability analysis within this Paper.

III. HORIZONTAL MOVEMENT UNCERTAINTIES

If the aircraft kinematics is split into horizontal and vertical movements, the horizontal movement and the influence of wind errors on trajectory uncertainties are analysed in this Paper as independent from the vertical movement, taking as starting point the model presented in [7]. In order to model the aircraft kinematics the following parameters are defined:

- $\boldsymbol{v_{ij}}$ is the relative velocity vector between the two aircraft i and j involved in a proximity event.
- Intruder aircraft (ACj) will be represented as a point and its speed will be the relative velocity vector.
- Reference aircraft (ACi) will be stationary.
- The impact plane is defined as a generic projection plane containing the centre of ACi (assumed as static) and perpendicular to v_{ij}. This plane is represented in Figure 2.

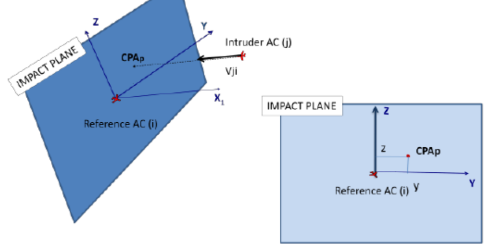

Figure 2. Impact Plane definition

Considering that the coordinates of the Closest Point of Approach (CPA) are directly related to the relative speed v_{ji}, the expression for the CPA coordinates could be calculated as the intersection of the straight line (defined using the position of aircraft j and whose direction is the same as v_{ji}) and the impact plane. The straight line equations are the following:

$$(x, y, z) = (x_j, y_j, z_j) + \lambda(v_x, v_y, v_z) \tag{1}$$

The CPA coordinates will be given as the intersection between this line and the impact plane. That involves the following condition:

$$x = x_j + \lambda v_x = 0 \tag{2}$$

As the impact plane is perpendicular to the relative speed direction (impact plane definition), it can be stated that $v_x = -v_{ji0}$ (encounter relative speed), and then:

$$\lambda = \frac{x_j}{v_{ji0}} = time\ to\ CPA = t_{CPA} \tag{3}$$

So, the estimated coordinates of the CPA are:

$$\begin{aligned} \hat{y} &= y_j + t_{CPA} v_y \\ \hat{z} &= z_j + t_{CPA} v_z \end{aligned} \tag{4}$$

The true coordinates differ from the estimated ones due to the existence of some uncertainties affecting both to the calculated position of aircraft j and to the calculated relative speed. Likewise, the true coordinates are:

.

$$\begin{aligned} y &= y_j + \varepsilon_{yj} + t_{CPA(}v_y + \omega_y) \\ z &= z_j + \varepsilon_{zj} + t_{CPA(}v_z + \omega_z) \end{aligned} \tag{5}$$

Where:

- $\varepsilon_{y,zj}$ is the y or z component of the aircraft j initial position coordinates uncertainty
- $\omega_{y,z}$ is the y or z component of the relative speed coordinates uncertainty

Using the covariance matrix for estimation error, given by the following expression:

$$Q = E[(\hat{x} - x)(\hat{x} - x)]^T \tag{6}$$

In this case it is obtained:

$$\hat{y} - y = -\varepsilon_{yj} - t_{CPA}\omega_y$$

$$\hat{z} - z = -\varepsilon_{zj} - t_{CPA}\omega_z \tag{7}$$

$$Q = E\begin{bmatrix} (\varepsilon_{yj} + t_{CPA}\omega_y)^2 & (\varepsilon_{yj} + t_{CPA}\omega_y)(\varepsilon_{zj} + t_{CPA}\omega_z) \\ (\varepsilon_{yj} + t_{CPA}\omega_y)(\varepsilon_{zj} + t_{CPA}\omega_z) & (\varepsilon_{zj} + t_{CPA}\omega_z)^2 \end{bmatrix}$$

The resulting general expression for covariance matrix will be simplified considering the following assumptions:

- Horizontal movement assumption: only horizontal speed components are initially considered (this imply all z components equal to zero),
- Aircraft position lateral error is considered negligible: the navigation performance proposed by PBN concept specifies that aircraft navigation system performance requirements, defined in terms of accuracy, integrity, availability, continuity and functionality required for the proposed operations, when supported by the appropriate navigation infrastructure may give values as low as a lateral deviation of 0.1 nautical miles 2-sigma. A PBN 0.1 implies that the aircraft lateral deviation is confined within 0.1NM at both sides of the track a 95% of the time (this imply $\varepsilon_{yj} \approx 0$). (1)

Under these assumptions covariance matrix is reduced to:

$$Q = E\begin{bmatrix} (t_{CPA}\omega_y)^2 & 0 \\ 0 & 0 \end{bmatrix} \tag{8}$$

Taking into account that w_y is the y component of the relative speed coordinates uncertainty due to the influence of the wind error, it can be stated in terms of the angular deviation resulting:

$$\omega_y = v_{ji0} * \delta\theta \tag{9}$$

And then,

$$Q = E\begin{bmatrix} (t_{CPA} v_{ji0} * \delta\theta)^2 & 0 \\ 0 & 0 \end{bmatrix} \tag{10}$$

$$Q_{11} = t_{CPA}{}^2 v_{ji0}{}^2 * E(\delta\theta^2)$$

Where $\delta\Theta$ was obtained in [8] as:

$$\delta\theta = atan\frac{a}{r+b} \tag{11}$$

Being:

$$\boldsymbol{a = cos(\theta_j - \theta_w) * \sin(\theta_{ji} - \theta_j) - cos(\theta_i - \theta_w) * \sin(\theta_{ji} - \theta_i)}$$

$$\boldsymbol{b = cos(\theta_j - \theta_w) * \cos(\theta_{ji} - \theta_j) - cos(\theta_i - \theta_w) * \cos(\theta_{ji} - \theta_i)}$$

$$\boldsymbol{r = \frac{v_{ji0}}{w}}$$

Where:

- $\Theta_{i,j,w}$ are the angles measured from the North for aircraft i, aircraft j and wind direction respectively.
- Θ_{ji} is the angle measure from the north for the relative speed vector.
- w is the magnitude of wind error

Considering (11), it is shown that $\delta\Theta$ depends on the geometry of the encounter and the wind error direction through the different angles $\Theta_{i,j,w}$. Likewise, it depends on the ratio between the relative speed and the wind error.

On the other hand, it would be desirable to express $\delta\Theta$ in relation to δw, which can be obtained using the first component of the Taylor Series development (component higher than first term are assumed negligible):

$$\delta\theta \approx f'(0)\delta w \tag{12}$$

Where the derivative at zero point is:

$$f'(0) = \frac{\partial}{\partial w}\left[\frac{a}{r+b}\right]_{w=0} =$$

$$\left.\frac{a * v_{ji0}}{w^2(r^2+b^2+2rb)}\right|_{w=0} = \frac{a}{v_{ji0}} \tag{13}$$

And then

$$\delta\theta \approx f'(0)\delta w = \frac{a}{v_{ji0}}\delta w \tag{14}$$

Therefore, the expression for variance calculation results:

$$Q_{11} = t_{CPA}{}^2 v_{ji0}{}^2 * E\left[\left(\frac{a}{v_{ji0}}\delta w\right)^2\right] =$$

$$t_{CPA}{}^2 a^2 * E[(\delta w)^2] = t_{CPA}{}^2 a^2 \sigma_w^2 \tag{15}$$

Where:

- t_{CPA} is the time for the conflict to happen, or time to CPA
- σ_W is the root mean square vector difference for wind error estimation
- a is a geometry factor which expression is (taking as reference axis and the origin for angles the direction of v_{ji0}):

$$a = cos(\theta_w - \theta_i)sin\theta_i - cos(\theta_w - \theta_i)sin\theta_j \tag{16}$$

As a conclusion, the probability distribution for CPAy coordinate determination is determined by:

$$\sigma = t_{CPA} \;\; a \;\; \sigma_w \tag{17}$$

It can also be initially assumed for the wind statistical model to respond to a modeled bias, introduced as aircraft ground speed into the flight plan, plus a Gaussian distribution $N(0,\sigma_w)$. This consideration has also been made by other authors [9,10], according to whom the along track error at a time for aircraft in level flight is well modeled by a normal distribution.

Each of the factors composing Equation (17) will be analysed and some initials considerations and results shown.

A. Time to CPA (t_{CPA})

Once a potential conflict is detected, and segments of the trajectories involved are modeled, the t_{CPA} is defined as the time for the conflict to happen. To determine its value it must be considered the predicted trajectories definition and the normal time horizon that is currently used by the prediction tools.

Network Management tools will typically work with the flight profile for the whole flight (that is an average of two hours). Whereas tactical tools may predict the flight only with regard to the current ATC sector, being the looking ahead time less than 20 minutes.

As trade-off between expected trajectories accuracy and look-ahead time must be established, it will be settled an intermediate value of **1 hour** for the calculations presented in this paper.

B. Wind error estimation: σ_w

Taking into account previous sections of this document, it will be considered an initial wind error RMS value of **6 m/s** (12kt) [2]. This value has been obtained under the following assumptions:

- A predominant daily value for RMS vector difference is of 4.5-5.5 m/s range. This value was obtained taking into account all possible forecast projections (from 0 to 6 hours).
- The forecast errors grow with the time in advance of the forecast projection, being the RMS vector difference values increase of about 1.5 m/s from 1 to 6 hours.

As it is considered that the RBT will be presented at least, about 6 hours before the operation time, a value for the RMS vector difference of 5.5m/s plus a 0.5m/s increment is settled (because most of the measures in the referenced study have been done for projections less than 6 hours in advance).

This value is very similar to the one obtained in other analysis of level flights [10], in which a rate of growth of along-track r.m.s error of 0.22NM per minute is reported.

C. Geometry Factor: a

Considering the expression obtained for the geometry factor calculation (17), and that dependence between Θ_i and Θj is:

$$\boldsymbol{\theta_i = \pi - arcsin\left[\frac{v_j}{v_i} sin\theta_j\right]} \qquad (18)$$

Taking into account that the angles are referenced to the direction of v_{ji0} it must be highlighted that there are some geometries that are not possible and therefore are being ignored in the analysis. These configurations are the following (remember that the origin of angles has been settled in v_{ji0} direction):

- $\boldsymbol{\theta_i or\ \theta_j = 0, \pi}$ This would assume two aircraft flying a track with the same heading (under the same speed assumption, conflict no possible) or opposite heading. Although some studies [11] consider the user preferred trajectories as a total removal of the current flight level constraints based on the east/north west/south flying routes, this Paper still considers the current segregated cruise altitudes. Taking this into account, this is operationally only possible if one of them is climbing or descending. This case is not considered as only the horizontal movement is being under analysis.
- $\boldsymbol{\theta_i or\ \theta_j = \pi/2}$ It is not possible due to obvious geometrical reasons.

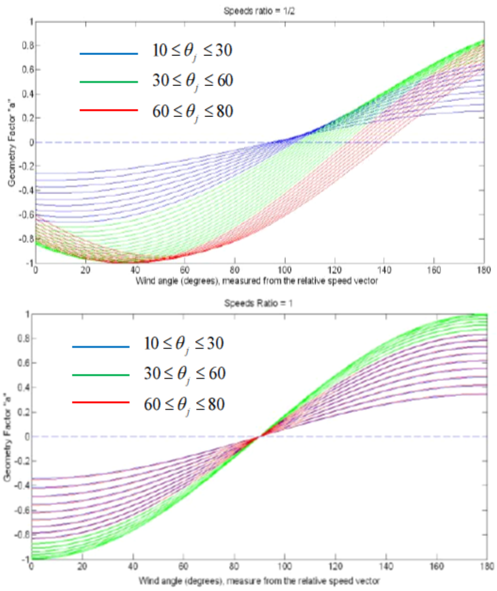

Figure 3. Geometry Factor

Figure 3 presents the calculation of the geometry factor "a" increasing Θj from 10 to 80 degrees (colour legend is explained), Θw from 0 to 180 degrees and for speeds ratio ½ (upper part) and ratio 1 (lower part).

One of the most interesting results to analyse is the geometry of the encounter for which the geometry factor "a" reaches its maximum value. Increasing Θj from 10 to 80 degrees, the correspondent Θi angle, and the calculated Θw for which "a" is maximum is presented in Figure 4. From it can be learnt that if both aircraft have the same speed and the wind direction is the same of the relative speed vector (Θw=0), "a" reaches its maximum value. On the other hand, if the speed ratio is ½ the worst configuration (a maximum) is produced when the wind direction is close to the aircraft whose speed is minor (in this case aircraft j).

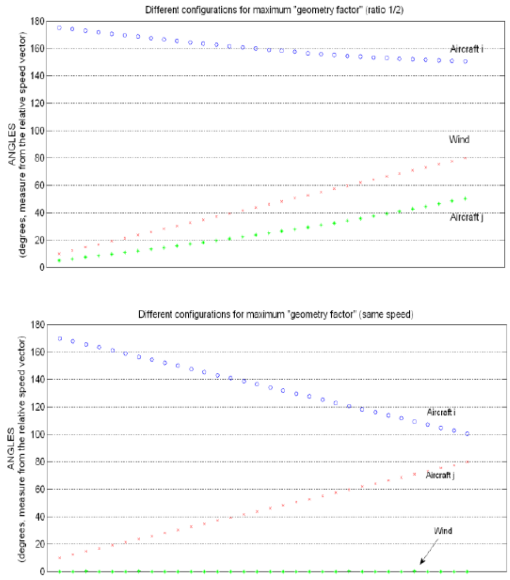

Figure 4. Encounter geometry for "a" maximum. Same speed

As the speed range for turbojets is very similar in the enroute phase of flight, from now on a ratio between aircraft speeds equal to 1 will be considered.

From the above presented results it could be calculated the "a" value for every specific wind angle knowing the aircraft speeds and the encounter angles for both aircraft (data obtained from the flight plan).

Whether the prevailing winds in the airspace where the encounter is to happen could be known in advance, an accurate value for the geometry factor "a" could be calculated. If no previous information about the wind field is available, the wind angle that produces the higher error should be chosen in order to be conservative.

Figure 5 shows the maximum "a" values for the above presented encounter configurations.

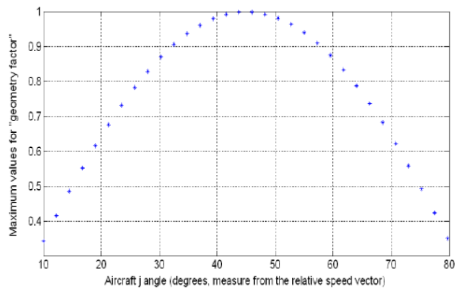

Figure 5. Maximum "a" values. Same speed

IV. TRAJECTORY COMPATIBILITY DETERMINATION

Figure 6 shows the different distribution functions obtained setting the following values for the parameters determining σ (17):

- t_{CPA} = 60 min
- σ_w = 6 m/s
- a = maximum values obtained for the different geometry configurations (see Figure 5)

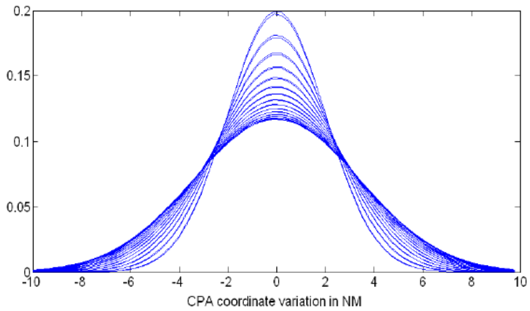

Figure 6. Probability density functions for maximum "a" values.

This functions show the probability distribution of the CPAy coordinate due to the wind error effect on the aircraft speed.

It is now to be considered that the minimum separation between the aircraft involved in the encounter must be, at least, equal to the current minimum standard separation, which is 5 NM. Furthermore, it must be settled the probability for a conflict to happen that is going to be assumed.

Based on this probability, the extra distance to be added to determine compatibility between trajectories will be calculated. Figure 7 shows the distance calculation graphically.

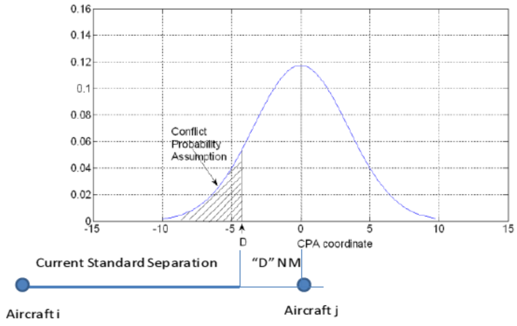

Figure 7. Probability of conflict and extra distance calculation

When analysing the reduction of separation standards using automation tools some studies [11] show a concept which uses predicted conflict uncertainty as a decision aid for traffic controllers. The medium term conflict probability assumed is 5.10^{-2}, since a reasonable level of missed detection is allowed, whereas the probability of conflict for short term separation assumed is 10^{-3} since the sector controller is responsible for assuming the final separation.

If we assume a threefold increase in the future air traffic demand [1], [5], the total number of flights per sector and per day could reach 1800 (same number of sectors has been assumed). As an example, the planned probability for a conflict to happen in the future ATM scenario would involve up to 6 conflicts a day to be solved by the ATC, which results in $3*10^{-3}$, which would reduce significantly the ATC workload for conflict resolution.

Figure 8 shows the minimum distance between two trajectories for them to be considered as compatible for different geometrical configurations, and always for the wind error vector angle that produces the maximum deviation.

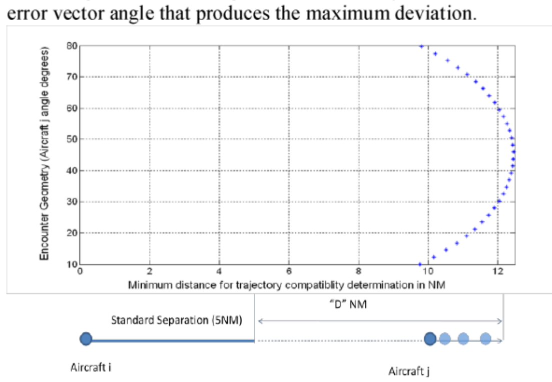

Figure 8. Extra distance calculation for trajectory compatibility.

V. CONCLUSIONS

The main initial conclusion obtained and presented in this Paper is that the minimum distance between two trajectories to be declared as compatible varies between **10** and **12 NM** depending on the encounter geometry configuration, considering a time to CPA equals to **1 hour**, and a RMS value for wind error of **6m/s** and a controller workload in the future ATM limited to **6** conflicts a day (if any other type of contingencies does not take place).

The assumptions made include the consideration that both aircraft are flying established at the same flight level and the aircraft lateral position error is negligible. The three factors affecting probability distribution for CPA coordinates determination are described in the table below.

As the range of speed for turbojet aircraft is very similar, it is considered for the final calculations that $|\vec{v_j}| = |\vec{v_i}|$.

TABLE I. FACTORS AFFECTING PROPABILITY DISTRIBUTION

t_{CPA}	a			σ_w
1 hour	Dependant on the encounter geometry ($\vec{v_j}$,$\vec{v_i}$, Θ_w)			6 m/s
	$\vec{v_j}$	$\vec{v_i}$	Θ_w	
	Known through the Flight Plan (see Figure 9)		As unknown the "worst case" has been chosen for the analysis (see Figure 10). Prevailing winds could be used if any	

The encounters geometries that provides a maximum and a minimum value of "a" are shown in Figure 9. As can be seen, an angle between tracks of 90 degrees provides the maximum value, whereas angles near 180 degrees or near 0 degrees provides a minimum.

On the other hand, Figure 10 shows the wind angle that produces maximum and minimum deviation for angle between tracks of 90 degrees. The maximum wind influence happens when the wind direction is parallel to the relative speed vector, whereas the contrary takes place when the wind direction is perpendicular to it.

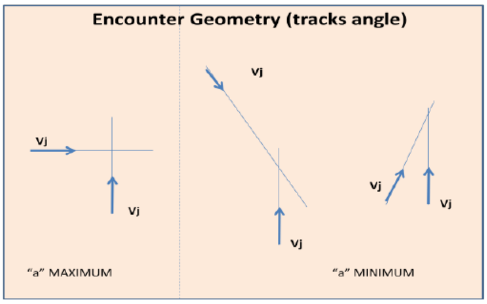

Figure 9. Different encounters geometry for maximum and minimum deviation.

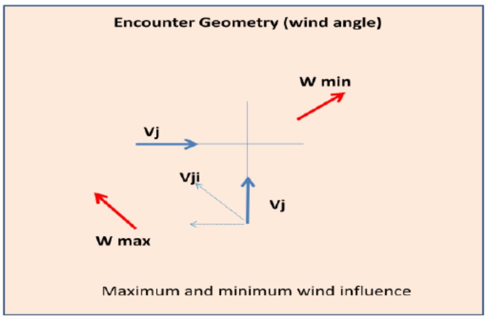

Figure 10. Wind angles for maximum deviation

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ANNEX VI. QUESTIONNAIRES

QUESTIONNARIE

Clarifications: A 4-Dimensional trajectory is considered as the line that the aircraft follows in the space and time, that is the position given with **three special coordinates** and the correspondent **time**. The foreseen trajectory normally differs from the real flown due to certain factors, such as wind, or changes in the estimated take off time among others.

1. Which of the following Air Traffic Controllers tasks you consider that involves a **higher workload?**
- Conflicts detection and resolution
- Traffic monitoring
- Both require a similar workload

2. Could **workload** be a reason for operating **less efficiently?**
- YES, Why? ___________________________________
- NO, Why? ___________________________________

3. If the ATCO's **future job** would involve mostly monitoring and supervision (assuming a dramatic conflict reduction), do you think that the current **sector capacity** could be increased?
- YES, Why? ___________________________________
- NO, Why? ___________________________________

4. If only aircraft whose trajectories were de-conflicted in advance were allowed into the future system, do you think the **ATCO's job** will be different in the future?
- YES. Explain briefly the difference ___________________________________
- NO, I CAN NOT SEE ANY DIFFERENCE

5. Under your point of view and under **normal** circumstances (no disruptive events), which of the following factors make an aircraft planned trajectory differs from the real flown trajectory **the most?**
- Wind
- Variations in the estimated take off time
- Pilot performance
- Q4 Aircraft performance (Airline performance)

6. Which of the following events that could make a planned route to differ from the real flown route is under your opinion the most **likely** to happen during a **whole year** operation scheme?
- Weather disturbances
- On ground system disruptions (ej. Radar or communications failure)
- Aircraft equipment/structural failures

Current perception of their job:

1. Which of the following Air Traffic Controllers tasks you consider that involves a **higher workload?**

TASK	No. Answers (26)	Percentage
Conflicts detection and resolution	20	77%
Traffic monitoring	1	4%
Both	5	19%

2. Could **workload** be a reason for operating less **efficiently**?

	No. Answers (26)	Percentage
YES	26	100%
NO	0	0%

The reasons given can be summarised as follows:

- Less time to efficient solutions evaluation
- Less time to be spent on each traffic
- More time spent on conflict resolution involves less time to do another tasks
- Mistakes are more likely
- Fatigue

Perception of their future job:

3. If the ATCO's **future job** would involve mostly monitoring and supervision (assuming a dramatic conflict reduction), do you think that the current **sector capacity** could be increased?

	No. Answers (26)	Percentage
YES	15	58%
NO	7	27%
No answer	4	15%

Positive answers justification and concerns:

- Less time spent in communications
- Less workload, less concentration needed
- Current sector capacity is nowadays higher in "less conflicted sectors"
- How much can it be increased? Only a slight increase foreseen (about 5 answers).

Negative answers justification and concerns:

- Risk factor increase
- Other factors such as weather, wind...to be taken into account
- Lack of trust on the system

4. If only aircraft whose trajectories were de-conflicted in advance were allowed into the future system, do you think the **ATCO's job** will be different in the future?

	No. Answers (26)	Percentage
YES	15	58%
NO	10	38%
No answer	1	4%

Positive answers justification and concerns:

- Mainly monitoring, less conflicts resolution
- Contingencies and emergencies mainly
- Less workload, potential risk increase due to under work and complacency

Negative answers justification and concerns (most of them without any justification):

- ATCO remains as the main supervisor. Lack of trust in the system performance.

Perception of the factors hindering TBO:

5. Under your point of view and under **normal** circumstances (no disruptive events), which of the following aspects make an aircraft planned trajectory differs from the real flown trajectory **the most?**

Factors	No. Answers *(35)	Percentage
Wind	17	48%
Variations in the estimated take off time	16	46%
Pilot performance	1	3%
Airline performance	1	3%

*It should be taken into account that some of the responses include two aspects from the list instead of one, this is the reason why the number of total answers considered to calculate the percentages are 35 instead of 26.

6. Which of the following events that could make a planned route to differ from the real flown route is under your opinion the most **likely** to happen during a **whole year** operation scheme?

Events	No. Answers (26)	Percentage
Weather disturbances	25	96%
On ground failures	1	4%
On board failures	0	0%