

**CRANFIELD UNIVERSITY**

MICHAEL F BESSANT

**LIGHTWEIGHT AVIONICS PLATFORM TO ACCESS  
ATMOSPHERIC ENVIRONMENTAL SCIENCE**

SCHOOL OF ENGINEERING

MSc BY RESEARCH THESIS

Academic year: 2012-2014

Supervisor: David C Cullen

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## **ABSTRACT**

There is a region of the atmosphere between approximately 10-40 km above the Earth's surface that is inaccessible to most winged aircraft and that rockets visit only fleetingly, but where small unmanned balloons are increasingly being used to carry lightweight (<5 Kg) scientific payloads. A major disadvantage of using these inexpensive 'weather' balloons is that researchers often have to develop telemetry and support avionics in addition to the core experiment. The aim of this thesis project was to significantly reduce this challenge by developing a Lightweight Avionics Platform (LAP) that would be able to support a wide range of experiments by providing data from a suite of sensors and a GPS receiver, together with an Iridium satellite link for communicating with internet enabled ground stations. The LAP also provides non-volatile storage for the sensor, GPS and experiment generated data.

The LAP design is based on a low power consumption microcomputer that is compatible with the Arduino Integrated Development Environment (IDE) and its associated open-source communication and sensor interface libraries. Modular systems architecture was employed as an aid to rapid hardware development. A major design goal was to allow researchers to interface their experiments without affecting the integrity of the LAP's embedded operating software. A dedicated Science Interface Port (SIP) is provided for this purpose that allows experiments to be powered and data exchanged, via a single electrically robust connector. This part of the project was completed with the construction and testing of a flight-capable LAP that weighs less than 0.2 Kg.

In order to ascertain the reliability of the above platform when subjected to the low temperatures and pressures expected during stratospheric flight, the project included the development of an environmental test chamber and associated monitoring/logging system. A unique feature of this low cost chamber is that it is both portable and transparent to satellite communications' signals. Finally, design details for a proposed atmospheric dust sampling experiment are provided as an example LAP application.

## **ACKNOWLEDGEMENTS**

With grateful thanks for the enthusiastic help of my supervisor, Prof. David Cullen, and the unstinting support and advice from my family

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## ACRONYMS

ADC	Analogue to Digital Converter
AML	Automatic Monitoring and Logging
ASCII	American Standard Code for Information Interchange
AT	Attention Modem
BEXUS	Balloon Experiments for University Students
CAA	Civil Aviation Authority
CASS-E	Cranfield Astrobiological Stratospheric Sampling Experiment
CNSP	Californian Near Space Project
CSV	Comma Separated Values
CUSF	Cambridge University Space Flight
DSE	Dust Sampling Experiment
EEPROM	Electrically Erasable Programmable Read Only Memory
FAT	File Allocation Table
FET	Field Effect Transistor
GHOST	Global Horizontal Sounding Techniques
GPS	Global Positioning System
HASP	High Altitude Student Platform
I2C	Inter-Integrate Circuit
IBM	International Business Machines
ICP	In Circuit Programmer
IDE	Integrated Development Environment
LAP	Lightweight Avionics System
LEO	Low Earth Orbit
LIDAaR	Laser Imaging Detection and Ranging
LSA	Logic State Analyser
MOSFET	Metal Oxide On Silicone Field Effect Transistor
MS	MicroSoft
NASA	National Aeronautics and Space Administration
NMEA	National Marine Electronics Association
NOTAM	Notice to Airman
NTC	Negative Temperature Coefficient
OEM	Original Engineering Manufacturer
PC	Personal Computer
PPS	Pulses Per Second
PROM	Programmable Read Only Memory
RC	Resistor Capacitor
REXUS	Rocket Experiments for University Students
RH	Relative Humidity
RISC	Reduced Instruction Set Computing
RPV	Remotely Piloted Vehicle
RTD	Resistive Temperature Detector
RXD	Receive Data
SBD	Short Burst Data
SCL	Signal Clock
SCP	Satellite Communications Port
SD	Secure Digital
SDA	Signal Data
SH	Systems Harness
SIP	Science Interface Port
SMA	Sub Miniature A
SRAM	Static Radom Access Memory
TXD	Transmit Data
UK	United Kingdom
USB	Universal Serial Bus
XPS	Extruded Polystyrene Foam

## 1. INTRODUCTION

Of the many areas of atmospheric research, dust transportation, is particularly relevant to human health whether directly by disease transmission or indirectly by impacting nutrition. An increasing number of scientists are beginning to appreciate the influence that escalating amounts of atmospheric dust are having on climate and on ocean and forest fertilization [1]. The majority of airborne soil and mineral dust present in the Northern Hemisphere is produced in Africa and transported, in plumes hundreds of kilometres wide, to land on the other side of the Atlantic. The number of publications on the subject of Saharan dust alone has risen sharply since the 70s [2]. Much of the early research relied on ground-based LIDaR (Laser Imaging Detection and Ranging) [3] with remote satellite observation making a growing contribution [4]. Data from remote sensing platforms are often complemented by in-situ measurements that are made from a range of atmospheric vehicles, including unmanned balloons [5]. At the altitudes of interest, balloons are uniquely efficient platforms from which to undertake in-situ dust measurements and collection.

An illustration of the important contribution balloon-borne instruments can make to science relates to the influence that electrical charge has on dust particles. Remote sensing observation has repeatedly detected the transportation of large ( $8\mu\text{m}$ ) particles over significantly greater distances than had been predicted by atmospheric models that had assumed randomly aligned particles. This anomaly was recently explained when in-situ measurements showed that the influence of electrical charge can cause dust particles to become predominantly vertically aligned and larger ones effectively levitated within a dust plume, beyond the point where existing models had predicted gravitational settling [6]. A similar mechanism has been shown to affect the transportation of electrically charged volcanic ash [7]. It is interesting to note that such a fundamental discovery was made possible with the aid of small disposable ‘weather’ balloons and lightweight payloads that cost only hundreds of pounds to launch [8]. In order to better exploit these low cost research tools, it was proposed to develop a lightweight avionics

platform that could support a range of scientific experiments and this will be the subject of this thesis.

## **2. PRESENT STATE OF TECHNOLOGY**

Three types of vehicle that provide access to high altitudes are: rockets, winged aircraft and balloons. The following brief comparison of these technologies summarises the unique advantages that balloons offer in many areas of atmospheric research. The three main balloon technologies are described together with example research applications.

### **2.1 High Altitude Atmospheric Research Vehicles**

#### **2.1.1 Rockets**

Sounding rockets are an established high altitude research tool. One example used by researchers and students is the REXUS unguided solid fuel rocket [9]. It is able to carry a payload to a maximum altitude of over 90 km, but offers only a few minutes of experiment time. The high speeds reached during ballistic flight can make the integration of some types of instrument an aerodynamic challenge [10]. Additional payload design constraints include having to withstand rapid temperature and pressure changes together with high levels of acceleration and vibration. Therefore the entire development process requires access to a wide range of specialised test facilities. Sounding rockets may often be a prohibitively expensive means of undertaking research at altitudes that can be more easily accessed by the vehicles described below.

#### **2.1.2 Winged Aircraft**

At the time of writing the highest altitude reached by a winged aircraft is 29 km. The NASA Helios remotely piloted vehicle (RPV) managed to maintain this altitude for 40 minutes during its maiden flight but disintegrated early into the second flight [11]. A more practical vehicle for stratospheric sampling is the manned NASA ER-2 version of the Lockheed U2 reconnaissance aircraft, which is able to cruise at altitudes of over 20 km [12]. However, research projects that require routine access must rely on commercial jet aircraft that normally operate at altitudes of less than 10 km but even their use for monitoring/collecting sample

materials, e.g. volcanic ash and radioactive particles, may be prohibited on safety grounds.

### 2.1.3 Large Zero-Pressure Balloons



**Figure 1: Partially inflated zero pressure balloon before launch of the CASS-E payload (D.Cullen)**

A zero-pressure balloon, of the type shown by Figure 1, is usually fabricated of polyethylene and designed to attain specific altitudes. When the expanded gas has extended the envelope to its maximum size the gas is vented to prevent bursting. The largest zero-pressure balloons can be up to 17 million cubic metres in volume and lift 1,000 kg payloads to an altitude of 45 km. A near constant altitude can be maintained, for several hours or days, by releasing ballast to compensate for reduced lift after sunset. These unmanned flights are primarily undertaken on behalf of scientists to transport a single heavy instrument (e.g. cosmic ray

detector) into the stratosphere [13]. However, a number of zero-pressure balloon programmes are specifically aimed at providing teams of university students with a practical and low cost means to fly their experiments. The main feature that these programmes have in common is the use of a flight proven avionics platform that can support multiple instrument payloads. The example described below is the joint Louisiana State University/NASA High Altitude Student Platform (HASP) zero-pressure balloon programme [14].

The HASP platform currently supports eight small (3 kg) and four large (20 kg) student payloads. A standard interface port is provided for each payload that provides power supplies, serial communications and discrete input/output lines. HASP is able to archive payload data on-board as well as transmitting to a ground station via a radio telemetry link. The telemetry data rate for small and large payloads is 1200 bps and 4800 bps respectively. Radio commands issued by the ground station are able to control discrete output lines on individual payloads. The HASP-Student Payload Interface Manual [15] includes information on the discrete interface lines and serial communications protocol to aid the development of experiments.

Such large balloons require extensive ground support facilities and the weight of fully populated avionics platforms restricts the areas where they can be safely launched, flown and recovered. These operational limitations, together with the number of participants involved, can lead to up to a year elapsing between NASA issuing a 'Call for Payloads' and the actual flight.

#### 2.1.4 Super-pressure Balloons

Super-pressure balloon technology enables long duration flights at a predetermined altitude without recourse to flight duration limiting gas and ballast expenditure. This is achieved by constructing a sealed envelope from material that is less yielding than that used by zero-pressure balloons. A super-pressure balloon's internal gas expands during ascent until the limit of the envelope's displacement is reached and a float condition is established. This is normally at a lower altitude than the maximum reached during zero-pressure and extensible

balloon flights. Changes in temperature mainly affect the balloon's internal pressure, whilst displacement remains relatively stable and a near constant atmospheric density altitude can be maintained over many diurnal cycles. For example, a super-pressure balloon, launched in 1968 as part of the US Air Force's Global Horizontal Sounding Technique (GHOST) research programme [16], repeatedly circumnavigated the southern hemisphere during a flight lasting over two years. More recently, a small ( $< 0.2$  cu m) super-pressure balloon, similar to the one shown in Figure 2, was launched from the UK on the 12<sup>th</sup> July 2014 and circumnavigated the northern hemisphere three times in 59 days at an approximate altitude of 12 km whilst carrying an 11 gram solar powered GPS receiver and radio transmitter.



**Figure 2: Super-pressure pico balloon made from heat sealed mylar sheets (L.Bodnar)**

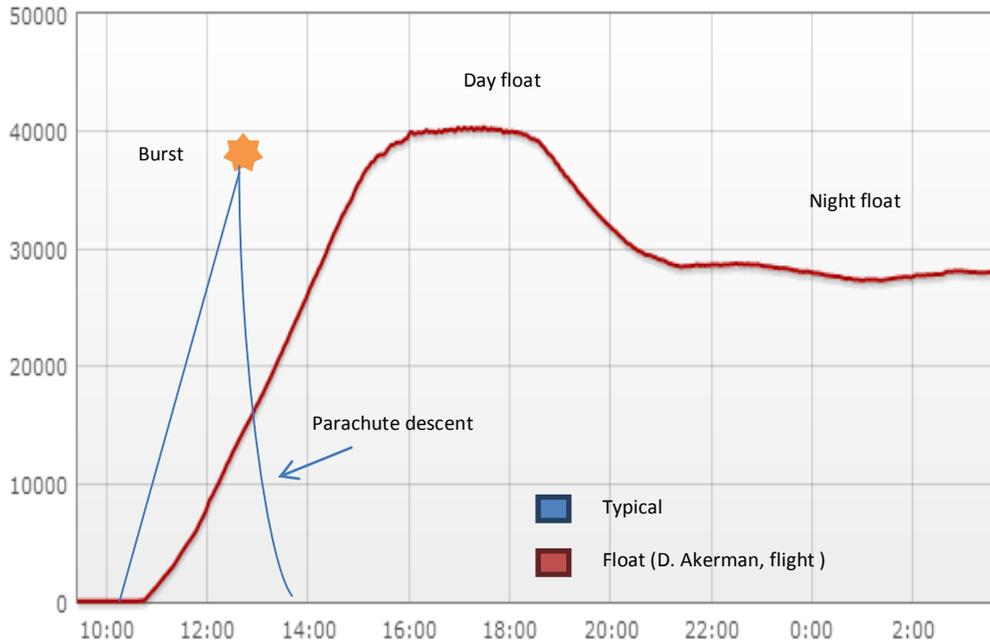
### 2.1.5 Extensible Latex Balloons



**Figure 3: Cambridge students prepare to a launch latex balloon carrying a Cranfield bio-sampling experiment (D.Cullen)**

An extensible latex balloon, shown in Figure 3, has an envelope that typically contains a few cubic metres of helium (or less commonly hydrogen) and is usually made of latex. When released these balloons normally rise and expand until bursting. They are routinely used by meteorologists to carry radiosonde instruments, weighing a few hundred grams, into the stratosphere to obtain vertical profiles of atmospheric conditions. This type of balloon is variously referred to as ‘weather’, ‘sonde’ or ‘latex’ (only the latter will continue to be used in this document). Many thousands of disposable meteorological radiosonde payloads are released throughout the World each year and this has led to latex balloons becoming low cost commodity items. They are available in a range of sizes/weights having different lift capacity and burst diameters [17]. The typical flight profile of a 1600 gram balloon and 2 kg payload combination is a 7 metres/second ascent to a burst altitude of over 32 km, within about 80 minutes

[18]. Figure 4 shows typical and extended flight profiles for small latex balloons. The difference in day and night float altitudes is caused by the balloon expanding under the influence of solar heating.



**Figure 4: Typical weather balloon and float flight profiles for latex balloons**

Automatic altitude control systems could be used to extend the flight duration but the combined weight of ballast and the venting valve would reduce the lift available for payloads [19]. However, a simpler passive approach was successfully used in 2012 by the amateur Californian Near Space Project (CNSP) to fly a 1600 gram latex balloon from California to Morocco covering a distance of 9,804 km in 55 hours at an altitude of approximately 31 km. CNSP claim this feat was made possible by proprietary software that predicts the volume of helium required to float a specific balloon/payload combination at a predetermined cruise altitude [20]. A practical disadvantage of this technique is that the marginal lift required to obtain a float condition makes the balloon difficult to handle and vulnerable to ground damage at launch.

### 2.1.6 Latex Balloons: Research Applications

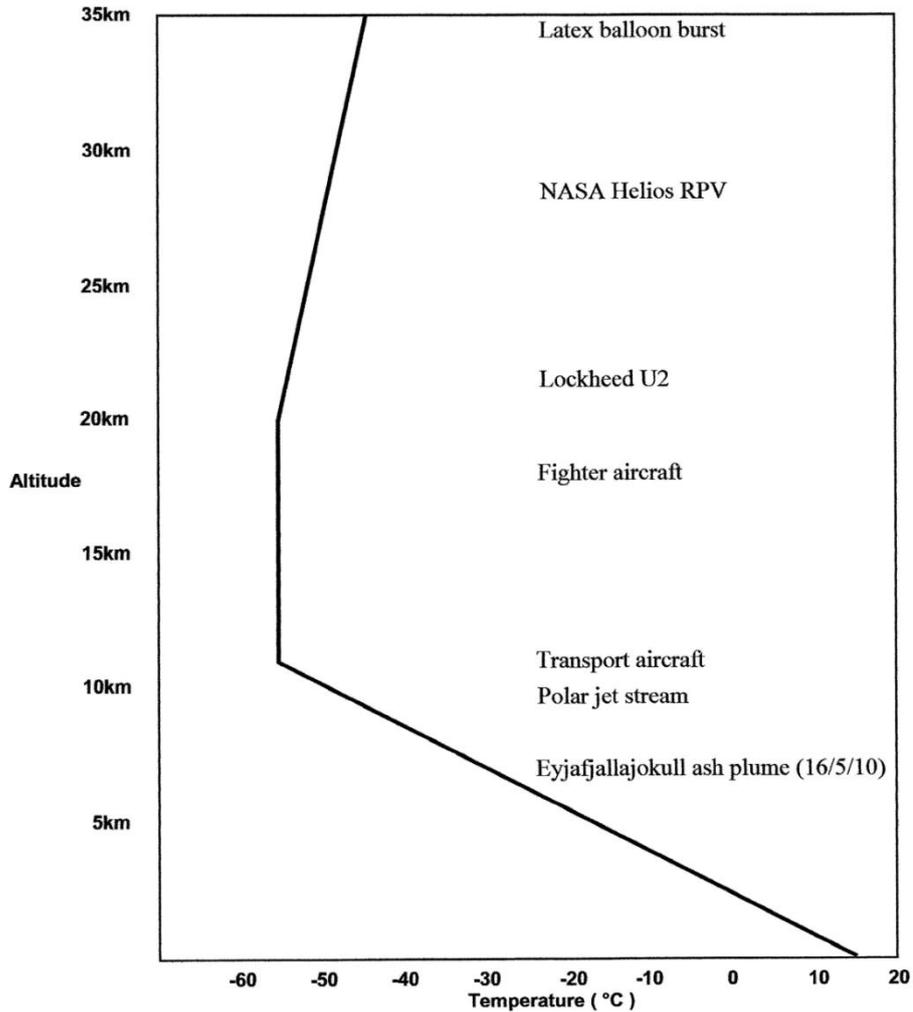
The global demand for intelligent mobile products has led to a rapid reduction in the size and cost of low power electronics, including wireless devices and sensors. The increased availability of these components has enabled research teams to produce novel scientific instruments specifically designed to be carried by latex balloons [21, 22, 23]. Recent examples include aerosol particle spectrometers and atmospheric electrical charge sensors [24]. Using latex balloons enabled such instruments to be deployed in response to the Eyjafjallajokull volcanic eruption of 2010 [25].

An impediment to rapid balloon deployment in the UK is the need to gain launch permission from the Civil Aviation Authority (CAA) for balloons that exceed 2 metres in any dimension. An application with details of the payload (normally restricted to <5kg) and launch location must normally be made 28 days before the event. If the application is successful the CAA will email permission and also issue a NOTAM (Notice to Airmen). Fortunately it is possible to obtain permanent NOTAM clearance that may allow launches to be undertaken at shorter notice. Cambridge University Spaceflight (CUSF) [26] has a permanent NOTAM for the Churchill College sports field and they regularly make this launch facility available to other organisations.

A further legal constraint involves the use of radio transmitters for telemetry and command. No radio equipment may be installed or operated in the UK except under the authority of a licence granted by, or otherwise exempted by, regulations made by Ofcom [27]. In practice these restrictions have resulted in the 433 MHz license exempt band being used for most airborne telemetry applications in the UK. Even though the maximum permitted output power for this band is only 10 mW the inherently good line-of-site conditions offered by balloon platforms enable data to be received over hundreds of kilometres, providing the data rate is limited to a few hundred bits per second (bps) and the ground station is equipped with a sensitive radio receiver and high-gain antenna.

One university group avoids the need to set-up and operate ground stations by employing modified radiosonde transmitters that use the standard meteorological receiving network [28]. However, this approach is only able to monitor a few channels at low data rates. At the time of writing few UK operators have developed a legal means of sending commands to latex balloons and therefore they are not able to remotely control instruments or flight duration.

### 3. AIMS AND OBJECTIVES



**Figure 5: Summary of platforms that could be used for atmospheric research**

Figure 5 shows that a region of the Earth's atmosphere, between approximately 10 km to 40 km above the surface, is essentially uninhabitable to all but the most exotic winged aircraft, and where sounding rockets visit only fleetingly. Unmanned balloons routinely carry payloads into this region on flights that last hours or even months to provide a relatively economical means of gaining information that would otherwise be inaccessible.

Users of large zero-pressure balloons already have access to established facilities in Europe and North America. Examples are the BEXUS and HASP programmes that provide flight-proven avionics platforms and extensive ground support, but their inherently long lead-times and launch/recovery safety considerations make it difficult for them to be rapidly deployed in response to environmental events.

Although the above operational constraints need not apply to latex balloon payloads of less than a few kilograms, researchers may be obligated to develop avionics and ground support facilities in addition to the core experiment.

This project aims to reduce this challenge by developing, and environmentally testing, a Lightweight Avionics Platform (LAP) (<200g) that will support a wide range of balloon-borne experiments. The availability of this reference LAP design should allow researchers to concentrate more time on the development and testing of unique experiments. The main tasks required of the LAP are listed below:

- Acquire GPS position data for tracking
- Acquire local environment data that may complement the experiment
- Exchange experiment and local environment data via interface port
- Transmit avionics and experiment data to a ground station
- Receive commands from a ground station
- Store avionics and experiment data on-board
- Condition battery supply to power the avionics and experiment.

The LAP must perform a similar role to the HASP zero-pressure balloon platform but, due to the smaller lift capacity of latex balloons, it will support a single experiment payload. Unlike the heavier and well supported platforms that utilise radio telemetry, LAP telemetry data will be received, and commands issued from an internet equipped ground station using the commercial Iridium satellite network [29]. This approach will avoid international radio restrictions and the burden of ground station logistics, thus facilitating the rapid global deployment of atmospheric experiments in response to environmental events.

Since high altitude balloon payloads must operate reliably when subjected to low temperatures and pressures, a significant portion of the project will be devoted to the development of environmental test facilities and procedures. These should not only be useful for proving the LAP design but also for students and researchers involved in future experiment development. This aim is particularly relevant because commercially available environmental chambers tend to be large, expensive and employ metal enclosures that inhibit GPS reception and satellite communications.

Finally, the project will endeavour to prove the basic LAP concept by designing a compatible science experiment. The proposed Dust Sampling Experiment (DSE) will collect samples by means of a number of inertial impact filters placed in the air flow created by a single diaphragm pump. The electromechanical part of the experiment will be developed by another researcher (Professor David Cullen, Cranfield University) whilst the work of this thesis will be responsible for designing the associated microcontroller board. Microcontroller-operated solenoid valves will route the air flow through selected filters. The DSE microcontroller circuitry and operating software could also act as a reference design for future experiment developers.

#### 4. IMPLEMENTATION AND REFINEMENT

For ease of assembly and modification the LAP design employs a modular architecture and through-hole components. Devices that are only available in surface-mount packages were purchased pre-mounted on modules that plug into the LAP mother board. The target footprint for the prototype board (6 x 9.5 cm) was dictated by the size of the companion satellite transceiver and the availability of a suitable lightweight electromagnetically screened plastic enclosure. The main functional blocks outlined in Figure 6 are described in detail below.

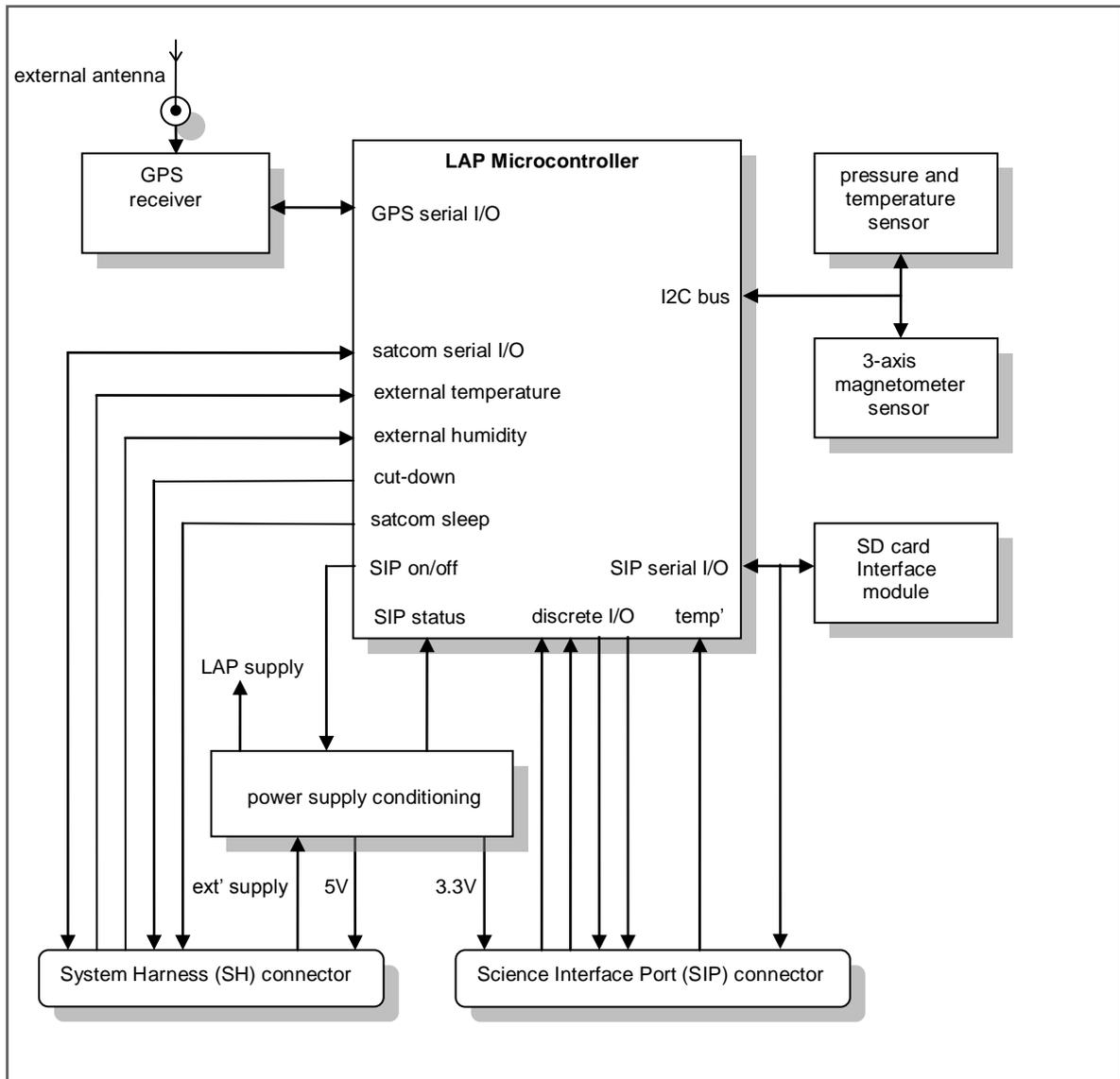


Figure 6: Functional blocks of the Lightweight Avionics Platform (LAP)

## 4.1 LAP Microcontroller

The main role of the LAP microcontroller is to format and route data between subsystems via four serial interfaces. The modest data rates involved enable low power 8-bit architecture to meet the combined processing demands of GPS reception, satellite communications, sensor monitoring and science experiment interfacing. The choice of the LAP microcontroller was strongly influenced by the availability of stable development tools and open source applications software. As a consequence the design is based on a member of the low power Atmel AVR microcontroller family [30] that is pre-programmed with an Arduino boot-loader utility that enables code from a PC resident Integrated Development Environment (IDE) software package to be programmed into an area of the microcontroller's embedded Flash memory. The Arduino IDE was derived from a set of tools developed at the Massachusetts Institute of Technology for developing code in the Processing language [31] and includes a text editor with features such as colour syntax highlighting, automatic indentation and brace matching. It is also able to compile C++ like programs and transfer them directly to an Arduino microcontroller over a standard PC serial port. The Arduino (IDE) was originally developed for the 8-bit Atmel AVR series but has subsequently been extended to support microcontrollers from a wide range of manufacturers including 32-bit devices from ARM and Microchip, which offer a choice of performance and chip packages. There is now an abundance of open-source Arduino libraries that perform a range of embedded tasks, together with many well documented example applications programs [32, 33, 34]. Easier to learn languages (e.g. Python and Basic) were briefly considered as an alternative to C++ but were found to lack many of the libraries needed for this project.

The member of the Atmel AVR family selected to meet the performance, size and power demands of the LAP requirement was the ATmega 328. This low power microcontroller employs RISC architecture to achieve throughputs approaching 1 MIPS per MHz [35]. The 28-pin dual in line package option was used for ease of assembly. This version has 23 programmable I/O lines, many of which can be configured as Analogue-to-Digital Conversion (ADC) and serial interfaces. User

programmable internal storage consists of 32 Kbytes of Flash program memory, 1 Kbyte of EEPROM and 2 Kbytes of volatile SRAM for working space. A small protected area of Flash memory is occupied by the Arduino boot loader utility. By operating the microcontroller at 3.3 volts it is possible to interface with a wide range of peripheral devices without level translation circuitry. The only peripheral that does not operate at 3.3 volts is the Iridium satellite transceiver that requires a 5 volt supply, but its digital I/O lines are still compatible with 3.3 volt logic levels

The ATmega 328 is specified to operate at a clock speed of 13 MHz when operated at a supply voltage of 3.3volts over the temperature range -40°C to +85°C. However, the Arduino boot loader program contains the following anomaly. The internal brown-out detector issues a reset when the supply drops to 2.7 volts, at which level the microcontroller is only specified to operate at 10 MHz. To ensure reliable operation down to the Arduino's obligatory reset voltage threshold, the LAP design operates the ATmega 328 at a clock speed of 8 MHz. Timing compatibility with the IDE is achieved by selecting the '*Arduino Pro or Pro mini (3.3v, 8MHz) w/ATmega 328*' option using the Tools and Board tabs.

## **4.2 Watchdog Recovery**

Of course, the LAP must be able to recover from code errors without human intervention. A simple and effective method of achieving this is to use a watchdog circuit that automatically generates a system reset if not cleared within a predetermined timeout period. Therefore, no system reset will be generated if a correctly functioning main program loop is able to continuously clear the watchdog within this timeout period (see Figure 7). In common with many microcontrollers, the ATmega328 has an integrated programmable watchdog. However, as it would be theoretically possible for a corrupted program to change setup registers and disable or reprogram the internal watchdog, the LAP design employs an external circuit. This independent approach also complies with the general recommendations of insurance and regulating bodies that dedicated watchdog circuitry be used to reduce the risk of system failures in safety critical

applications (e.g. IEC 61508 and ISO 26262 standards). Even for LAP operating software that was totally free of errors, a hardware watchdog would be required to protect against code that has been corrupted by power supply or electromagnetic interference. Although well designed circuitry and board layout should minimise the former source of errors and the screened enclosure the latter, this still leaves the problem of ‘soft errors’ [36]. Amongst the most common sources of soft errors is cosmic ray strikes that flip the state of bit locations stored in semiconductor memory. The problem of soft error induced failures has become more significant with advances in semiconductor fabrication density and the lowering of operating voltages. Based on results for 1990’s semiconductor technology, IBM found that a typical office computer experienced about one error due to cosmic radiation every month per 256 MB of RAM [37] and that this figure can be fourteen times higher at an altitude of 3 km due to the greater exposure. The intensity of cosmic radiation increases rapidly with altitude until reaching a peak at about 15 km before starting to decrease again [38]. Therefore, depending on the operating altitude and flight duration, balloon avionics may be uniquely vulnerable to cosmic radiation induced failures.

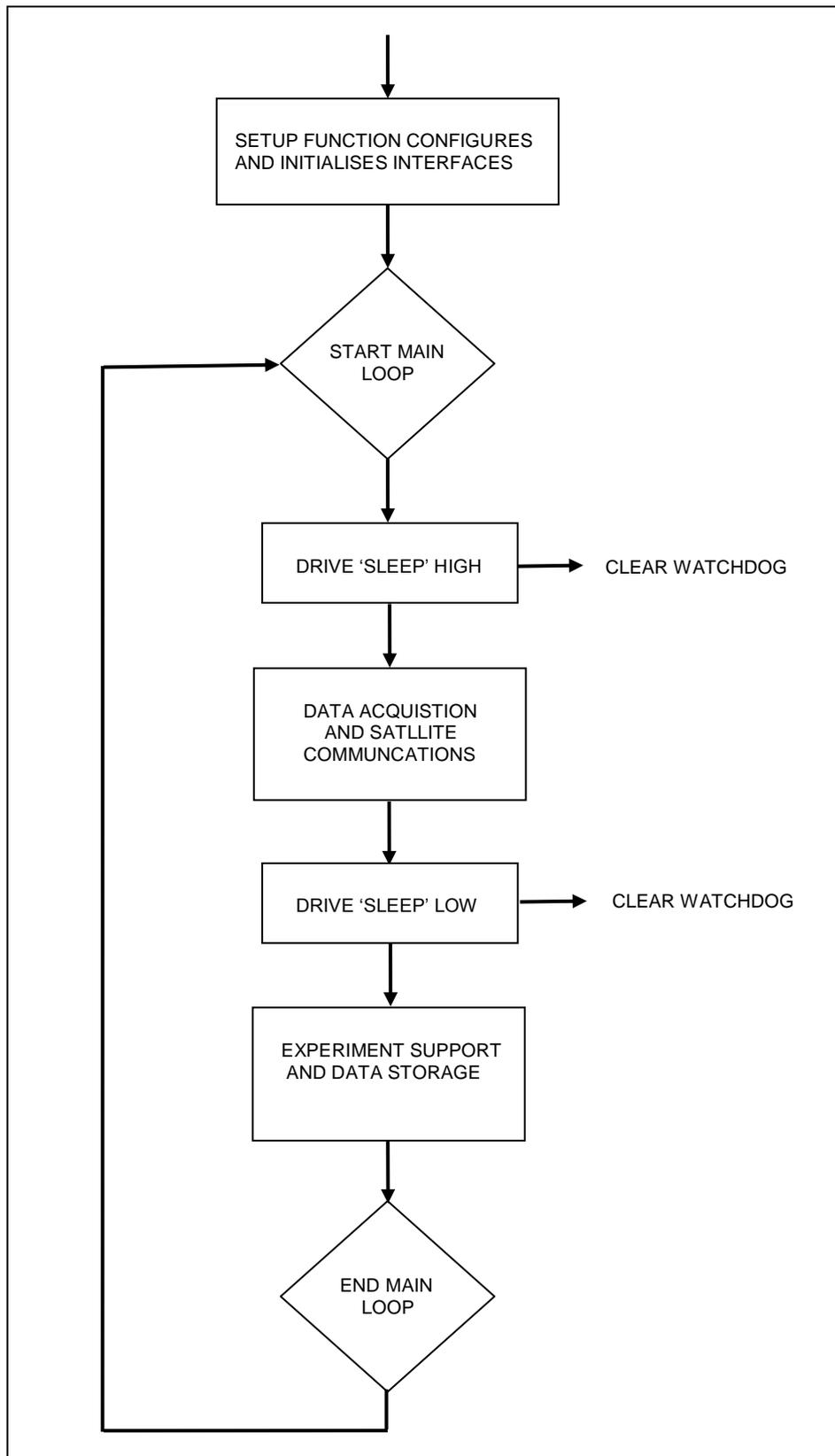
Most watchdog integrated circuits have timeout settings of less than a few seconds, which would be too short a period for dealing with the LAP main program loop. This is because, although the flight version of the operating software will sample all input channels at a rate of 1Hz, the timing of the main loop must be aligned with the Iridium communications sessions that are undertaken every minute. Therefore it was necessary to use the Maxim Integrated MAX6301 capacitor adjustable watchdog IC that can have timeout periods of many tens of seconds [39]. Figure 8 is a schematic of the MAX6301 watchdog circuit. The duration of the reset pulse (300 mS) and the timeout period (200 seconds) are set by capacitors C5 and C14 respectively. The open-collector output is connected to the reset pull-up resistor that is shared by the microcontroller and SD Card interface. A reset can also be generated if the voltage at the junction of a potential divider, connected between the Vcc and GND, indicates that the supply has dropped near to the ‘brown out’ level where reliable microcontroller operating cannot be guaranteed. This feature was inhibited (thus saving two resistors) by

connecting the RESET IN pin directly to Vcc and using the microcontroller's internal brown out reset circuit.

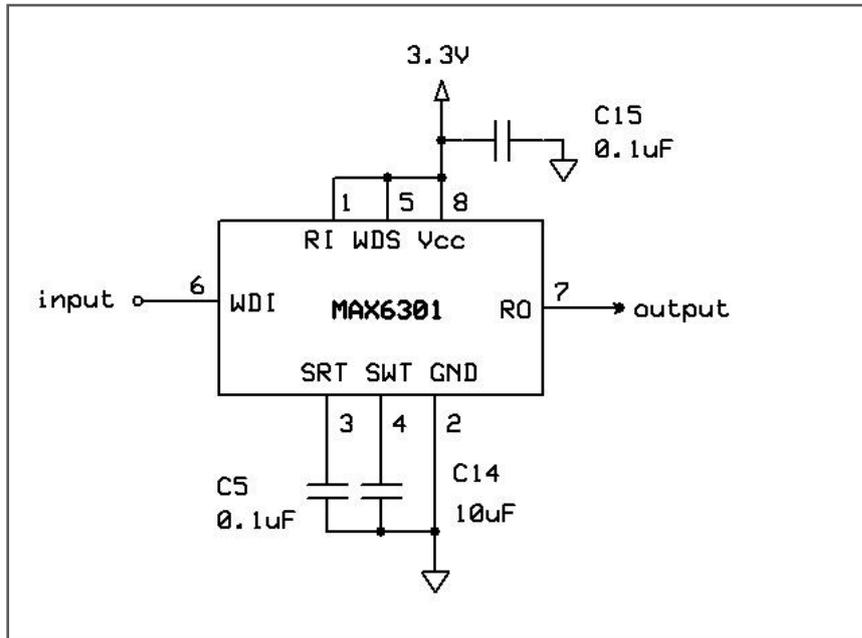
The watchdog is cleared whenever there is a rising or falling transition on the sleep line to the Iridium transceiver (e.g. when the transceiver is being powered up and down). Figures 9a and 9b show an oscilloscope trace of this activity.

Because the clear input receives a rising edge at one point in the main loop and a falling edge at another there is less possibility (compared with simply generating a pulse) of a program that is stuck in a short parasitic loop from continually clearing the watchdog. The transceiver sleep/wake control cycle must, of course, be of shorter duration than the timeout period.

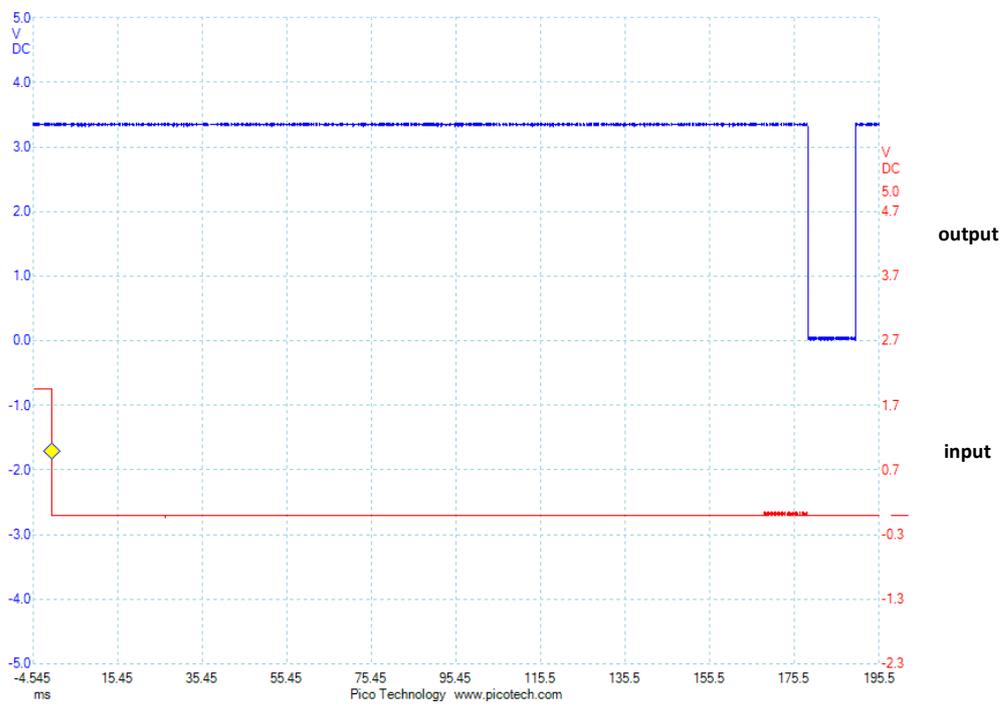
As a corrupted programme may have time to issue disruptive commands to peripherals before the watchdog times out, it is desirable to reset these devices at the same time as the microcontroller. This is not possible on the prototype LAP because the only module equipped with a reset input is the SD card Interface. It is anticipated that a surface mount version of the LAP would have the smart sensor chips and GPS receiver mounted directly on the main board, with their resets driven from the watchdog circuit.



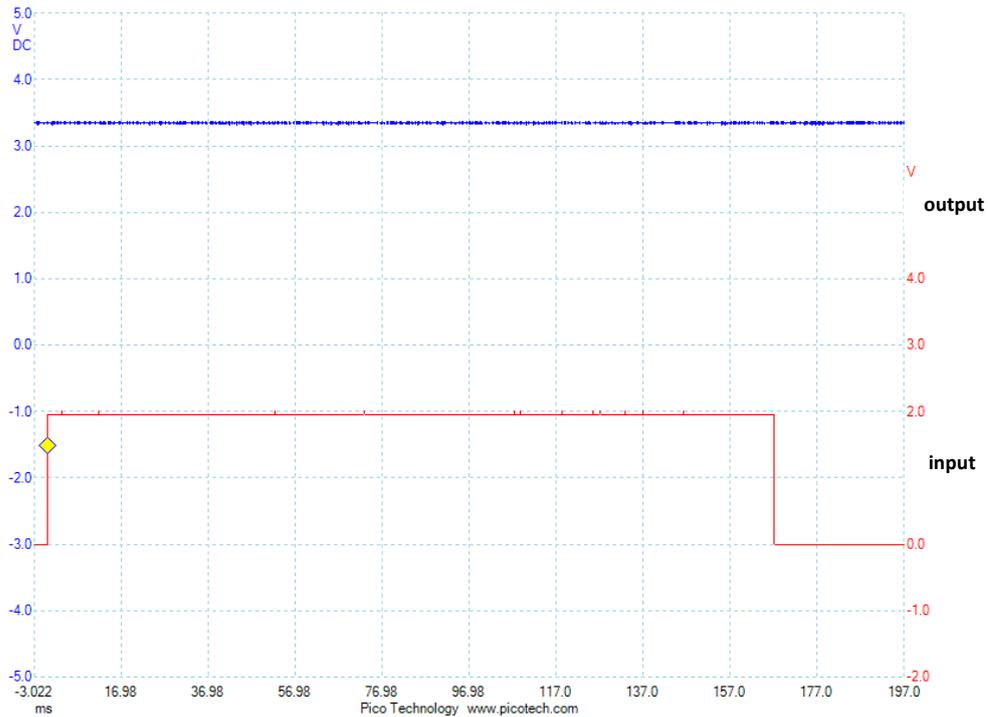
**Figure 7: Recommended program flow with the watchdog cleared within main loop**



**Figure 8: Independant watchdog circuit**



**Figure 9a: Watchdog times out and generates a reset pulse**



**Figure 9b: Watchdog receives clear input within timing out period and does not generate a reset pulse**

### 4.3. The I2C Bus

The prototype LAP board has two sockets that accept magnetometer and pressure/temperature sensor modules. Sensor ICs are used on the modules interface with the ATmega 328 via an Inter-Integrated Circuit (I2C) serial bus [40]. The I2C bus is able to transfer data between a number of different types of device using only two common lines. The bidirectional SDA line is used to carry data and the SCL line a 100 KHz bus clock. The ATmega 328 can be configured to make the SDA and SCL lines available on pins 27 and 28 respectively. The LAP microcontroller is considered the master device, that initiates all bus activity, and all other devices on the I2C bus are considered slaves. Each slave has its own hexadecimal address that allows the microcontroller to communicate only with selected devices. Part of the address is assigned by the manufacturer to identify the device type (memory, ADC etc.) with the remainder normally assigned by the user via chip input pins. The open-drain bus lines rely on resistors to pull them HIGH when their outputs are in a high impedance state. Each sensor module has a

set of ‘pull-up’ resistors fitted and these must be removed or disabled so as not to appear in parallel with those already mounted on the LAP board.

The synchronous bus technique used by the I2C standard normally offers a very robust means of communicating over sub-metre distances [41]. However, it is possible for slave devices to malfunction in such a way as to disable the entire bus and halt all inter-IC communications. Therefore, no I2C devices are mounted outside the LAP enclosure where they might be exposed to electromagnetic interference or extremes of environment. The Arduino IDE includes the standard ‘wire’ library for I2C communications, which does not include any form of time-out recovery, but an alternative will be evaluated [42]. However, in the unlikely event of a ‘hung’ bus the LAP microcontroller will eventually be reset by the watchdog circuitry describe above.

#### **4.4. Serial Communications**

Returning to Figure 6, we see that the LAP employs three serial ports to communicate with the GPS receiver, the Iridium transceiver and the Science Interface Port (SIP). All three of these peripherals have asynchronous serial interfaces that use separate lines to send and receive data, but no independent clock line [43]. The rate that bits are sent must be matched between the sender and receiver and clocked independently at each end of the link. Therefore reliable communications depends on achieving mutually accurate timing and the most critical link in this respect is between the LAP and the GPS receiver. The most accurate timing is achieved by the ATmega 328s only hardware ‘Serial’ port (TXD and RXD) and this is used to receive data from the GPS receiver at a rate of 9600 bps. As the Arduino IDE also expects to communicate via the Serial port, a mechanical switch is provided on the LAP board to change between ‘development’ and ‘flight’ modes.

The Arduino IDE includes the ‘SoftwareSerial’ library for asynchronous communications and this is used to implement the two 19,200 bps serial ports required by the Iridium transceiver and SIP. Although offering less accurate

timing than the hardware port, no SoftwareSerial communications problems were observed during many hours of LAP development and environmental testing. However, in the event of a hung serial port the watchdog circuitry will reset the LAP microcontroller.

The GPS receiver outputs serial data that is formatted in the alphanumeric ASCII format [44]. Whilst a less efficient format than binary for transmitting numerical data, ASCII has the advantage of being easily read by users of standard communication devices. As the Iridium satellite transceiver also communicates using ASCII, it was decided to use the same serial standard for communicating with the experiment via the SIP, making all three LAP microcontroller serial ports directly compatible with the multiple PC based terminal emulators used during development and testing.

#### **4.5. Analogue to Digital Converter (ADC)**

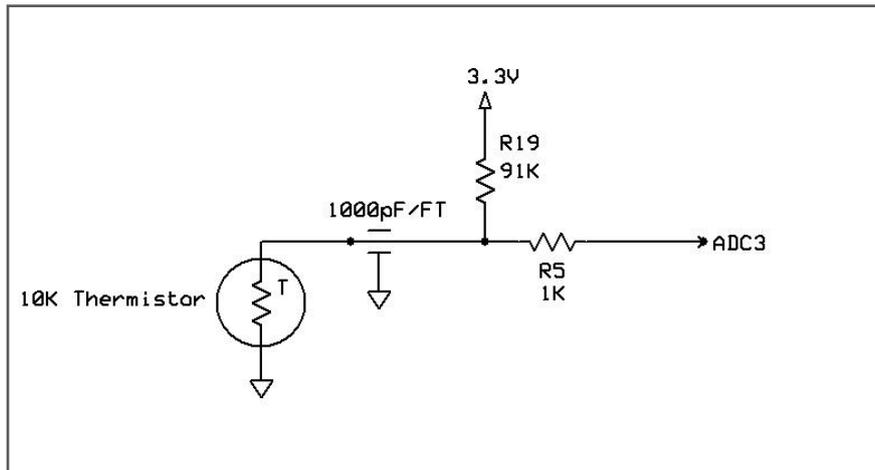
As a consequence of the I2C bus being confined to the inside of the LAP's screened enclosure, it is not available to interface with externally mounted smart digital sensors. As a consequence, analogue temperature and humidity sensors are used for these external measurements and are connected to the microcontrollers Analogue -to- Digital Converter (ADC) input channels via resistors that offer protection against over/reverse voltages [45]. The ADC is referenced to the regulated microcontroller supply and has a resolution of 10-bits. Therefore it is able to distinguish 1024 different levels between 0 and 3.3 volts that correspond to a full scale resolution of better than 0.1%. Although this exceeds the accuracy of the sensors, the level of dynamic range provided circumvents the need for analogue offset and gain circuitry at the ADC inputs. For example, a directly connected sensor with an output range of only 1.65 volts can still be measured to a resolution of 0.5%. Once digitized, offset and gain scaling can be performed in software by the microcontroller. This approach allows external humidity and temperature plus battery voltage measurements to be made without active

analogue signal conditioning. Only simple and reliable resistive potential dividers are required at the relevant ADC inputs.

## **4.6 Sensors**

### **4.6.1 External temperature**

In addition to providing potentially useful information for experiments, measuring the external temperature helps in assessing the effectiveness of the enclosures thermal insulation during the balloon's passage through the troposphere, where temperatures can drop below  $-60^{\circ}\text{C}$ . Available sensor technologies for this task include semiconductor, thermocouple, resistive temperature detector (RTD) and negative temperature coefficient (NTC) thermistor [46]. Thermocouple and RTD sensors were rejected because they require relatively complex analogue signal conditioning circuitry and semiconductor sensors having integral circuitry are not normally specified to operate below a temperature of  $-40^{\circ}\text{C}$ . A thermistor was initially selected because it can be interfaced by placing a fixed resistor in series with the sensor to form a potential divider at an ADC input [47]. The temperature response of the thermistor is inherently non-linear but the resultant error can be minimised by making the value of the series resistor equal to that of the thermistor at the centre of the chosen  $-60^{\circ}\text{C}$  to  $+20^{\circ}\text{C}$  measurement range (e.g. 91 Kohm). Nonetheless, the simple circuit shown in Figure 10 is still only able to yield a near linear temperature response with the aid of post-processing. The thermistor was connected between ground and a System Harness (SH) input pin that has an integral 1000 pF feed-through capacitor for interference suppression. Resistor R5 is included to protect the ADC input from potentially damaging external voltages.



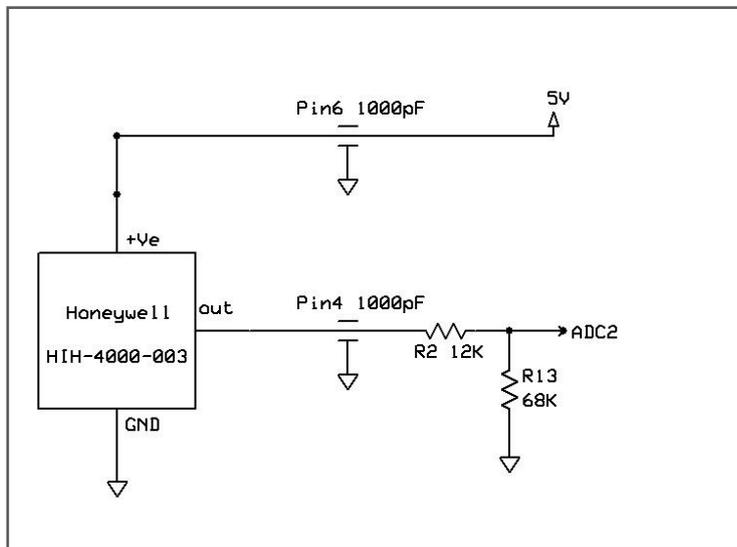
**Figure 10: Thermistor based external temperature interface**

#### 4.6.2 Relative Humidity:

By measuring external Relative Humidity (RH) it should be possible to detect when the sensor is passing through cloud. This could be useful to certain science experiments and for monitoring the effects of moisture on balloon and recovery parachute performance [48]. Smart RH sensors having an integral digital interface are not suitable for this application because of their inability to operate below  $-40^{\circ}\text{C}$ . As it would have had to share the same I2C bus as used by the internally mounted temperature/pressure sensor and magnetometer, a digital RH sensor malfunction at low temperature could also disable communications with these internal devices.

In the absence of a suitable smart device, a Honeywell HIH-4000 analogue sensor was selected to measure RH [49]. Its voltage output can be connected to an ADC input via a simple potential divider. The HIH-4000 is claimed to produce a 'near linear' voltage output -v- %RH when powered from a 5 volt supply and have a typical response time of 5 seconds. It is fitted with a hydrophobic filter allowing it to be used under condensing conditions. Although it is only specified to operate from over the range  $100^{\circ}\text{C}$  to  $-40^{\circ}\text{C}$ , the low temperature failure mode is non-destructive and will not affect LAP microcontroller operation.

The typical output voltage -v- relative humidity graph shown in the HIH-4000 series data sheet gives an output range of 0.5 to 3.75 volts for a corresponding range of 0 to 100% RH. The potential divider circuitry shown in Figure 11 was employed to better match this output to that of the 0 to 3.3 volts ADC input range. The value of the potential divider resistors R2 and R13 were calculated (using the formula  $ADC_{in} = (R_{13} / (R_2 + R_{13})) * RH_{out}$ ) to produce an ADC2 input range of 0.42 to 3.19 volts whilst adhering to 80K Ohm minimum output load specified for the HIH-4000. The resultant 2.76 volt ADC input range corresponds to a measurement resolution of better than 0.2 %. This is more than adequate given that the specified accuracy of the HIH-4000 is +/- 3.5% RH. However, this figure can be improved by using the unique Factory Calibration Data supplied with each device (see Figure 12) for post-processing. The HIH-4000 should be mounted in a short open-ended tube protruding downwards from the payload gondola and powered from and interfaces to the LAP via the Systems Harness (SH) connector. Each pin on this 9-pin connector has interface suppression in the form of a 1000pF feed-through capacitor to ground.



**Figure 11: External humidity interface**

MODEL: HIH-4000-003  
Channel: 233  
Serial Number: 14134300229  
Wafer Number: 22429C24  
MRP Number: 99405931  
Calculated Values at 5V  
Vout @0%RH: 0.819550 V  
Vout @75.3%RH: 3.162728 V  
Accuracy@25 C 3.5 %RH  
Zero Offset: 0.819550 V  
Slope: 31.117901 mV/%RH  
Sensor RH:  $(V_{out}-0.820) / 0.031$   
Ratiometric Response  
for 0 to 100% RH  
 $V_{out} = V_{supply} (0.164 \text{ To } 0.786)$

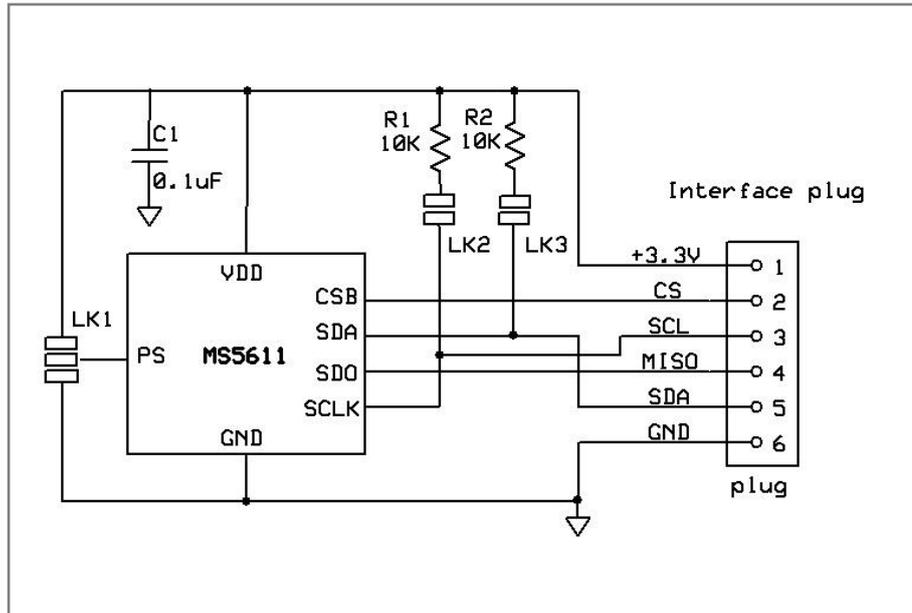
**Figure 12: Manufacturer’s calibration sheet for the relative humidity sensor used during environmental tests**

#### 4.6.3 Pressure and Internal temperature

In the event of a GPS receiver failure it will be possible to derive balloon altitude from on-board atmospheric pressure and temperature measurements. The LAP sensor suite includes a ‘smart’ pressure and temperature sensor. The manufacturer terms the product smart because it provides signal conditioning, a 24-bit ADC and an I2C serial bus interface on the same integrated circuit. The Measurement Specialities’ MS5611-01BA03 [50, 51] was chosen because it is one of the few smart pressure sensors that are specified to operate down to a minimum pressure of 10 mbar. The 8-pin surface mount package is mounted on an Embedded Adventures breakout module (see Figure 13) that is plugged into a socket on the LAP main board. The LAP enclosure has atmospheric venting to allow the sensor to measure pressure to a maximum altitude of approximately 28 km.

The MS5611-01BA03 is also able to measure the internal temperature of the LAP enclosure, over the range  $-40^{\circ}\text{C}$  to  $+85^{\circ}\text{C}$ , to a specified accuracy of  $\pm 0.8^{\circ}\text{C}$ . For optimum accuracy each sensor is individually factory calibrated and the coefficients necessary to compensate for pressure and temperature measurement errors are stored in PROM, and may be accessed via the same I2C interface that is used for measurements. Solder link LK1 has been configured to select the higher of the two available I2C address options. As pull-up resistors for the SDA and SCL bus lines are provided on the main LAP board, links LK2 and LK3 have been left open.

The environmental test version of the LAP operating software employs the MS5611 interface library for the Arduino. The free software was developed by Fabio Varesano of the Department of Computer Science, Università degli Studi di Torino, Italy and distributed under the terms of the version 3 GNU General Public License.



**Figure 13: Embedded Adventures MOD-1009 pressure/temperature sensor module**

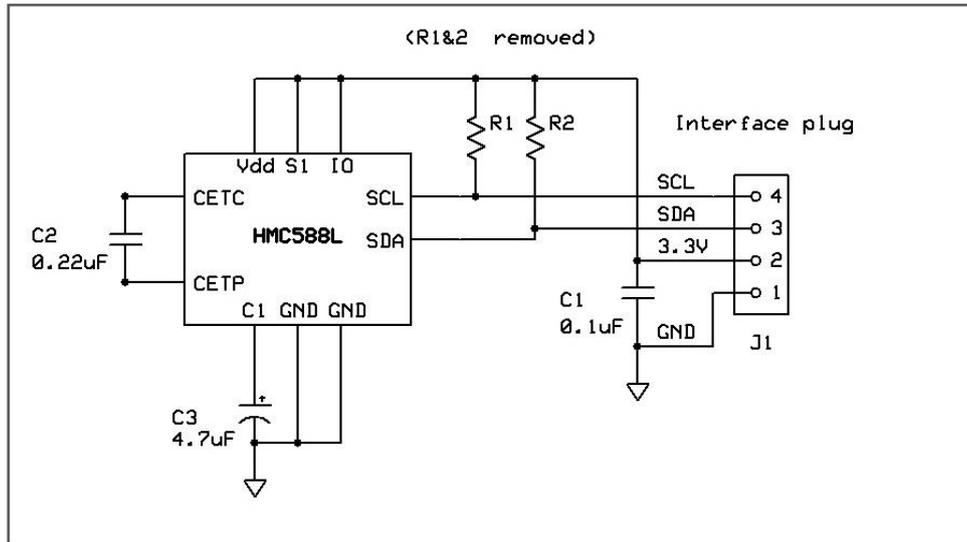
#### 4.6.4 Magnetometer

The usefulness of data obtained from certain science experiments may be enhanced by knowing their attitude at the time of sampling. Tilt and azimuth information can be derived by measuring the vertical and horizontal components of the terrestrial magnetic field using a 3-axis magnetometer. This information is also able to provide an indication of the level of atmospheric turbulence experienced during the flight [52]. The Honeywell HMC5883L ‘smart’ triple-axis magnetometer [53] is therefore included as part of the LAP sensor suite. This 16-pin integrated circuit contains three magneto-resistive sensors plus low-level signal conditioning, automatic degaussing straps, an ADC and an I2C serial bus interface. Many of the HMC5883L’s operating parameters may be programmed via the I2C interface, including sampling mode and sensitivity.

At the maximum sensitivity range of +/- 0.88 Ga, the internal 12-bit ADC is able to adequately resolve the terrestrial magnetic field of 0.3 to 0.6 Ga [54]. The HMC5883L surface mount package is mounted on a SparkFun Electronics SEN-10530 breakout module that plugs into a socket on the LAP board. The location of the magnetometer socket was chosen to minimise the effects of local ferrous materials. However, to achieve absolute attitude measurements it will be necessary to calibrate the magnetometer with the LAP, the experiment and battery

mounted in the final payload gondola configuration. Figure 14 shows a circuit schematic of the SEN-10530 module. Components R1 and R2 were unsoldered from the module so as not to appear in parallel with the I2C bus pull-up resistors provided on the LAP board.

The environmental test version of the LAP operating software employs the HMC5883 interface library for the Arduino that was developed by Love Electronics Ltd. The free software is distributed under the terms of the version 3 GNU General Public License.



**Figure 14: SparkFun Electronics 3-axis magnetometer module**

#### 4.6.5 GPS Receiver

Position data from a GPS receiver is sent over the telemetry link to allow ground based tracking of the balloon's flight path and to help predict the recovery site. In addition to latitude and longitude position fixes the GPS serial output stream includes altitude data that may be of use to many types of science experiment. The choice of GPS receiver is constrained by governmental security restrictions that relate to their export and operation. These dictate that receivers must not function whilst travelling faster than 1,000 knots at an altitude exceeding 18 km. Some manufacturers interpret this to mean the receiver must be disabled when both

limits are reached but others disable when only a single limit is reached. The uBlox 6 receiver [55] was selected because it can be software configured to disable the speed or altitude limit. This capability has enabled uBlox 6 receivers to operate routinely on balloon flights exceeding 30 km in altitude [56].

The uBlox 6 chipset is mounted on a Revelation Education Ltd (REL) GPS 010 module (see Figure 15) that plugs into a socket on the main LAP board. The module has a SMA socket that protrudes through the screened LAP enclosure. During the development and environmental testing phase this socket was connected to an REL supplied GAAC7-A active antenna via a 2 metre long co-axial cable. Reliable GPS reception was achieved when operating in locations that could only provide a limited view of the sky. As the active antenna weights 110 grams and is 49 x 39 x 14 mm in size, a much lighter and smaller passive antenna would be connected directly to the SMA socket for the flight configuration, with the LAP enclosure oriented to give the attached antenna an adequate view of the sky. An additional reason for not retaining the GAAC7-A antenna for the flight configuration is that it failed when subjected to temperatures in excess of +65°C during environmental testing (but recovered when the temperature was lowered).

The uBlox GPS receiver used by the GPS 010 module supports both the National Marine Electronics Association (NMEA) standard for serial data communications and a proprietary message format. The more widely accepted NMEA standard automatically broadcast a set of ‘sentences’ at regular intervals (typically 1 Hz). The standard defines the contents of each type of sentence and specifies that ASCII coded data within sentences must be separated by commas. The choice of the comma separated variable (CSV) format enables data to be read manually using a PC terminal emulator and selected data parsed (extracted) from strings of sentences [57]. When connected to the output of a GPS receiver, a PC terminal emulator displays the example sub-set of NMEA formatted sentences shown below:

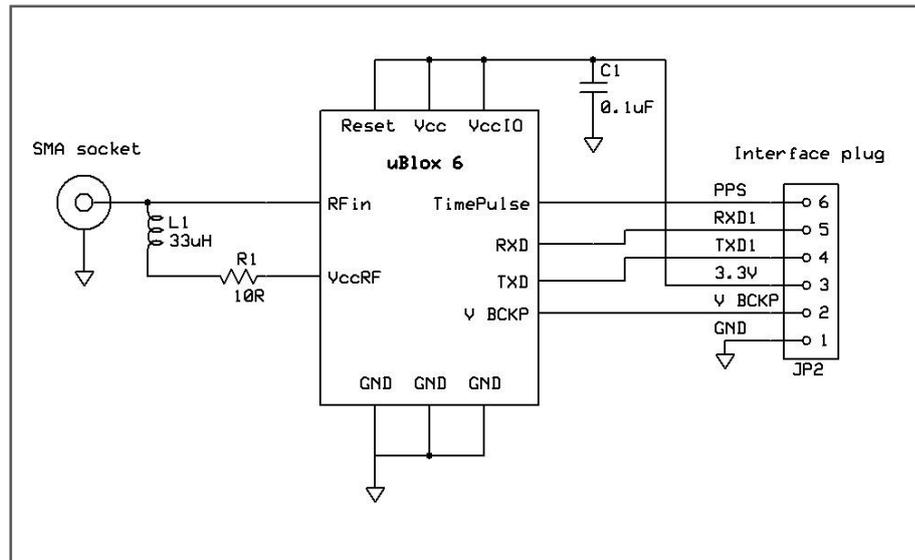
```
$GPRMC,225316.000,A,3003.9040,N,10512.5782,W,0.09,144.75,141112,,*19
$GPGSA,A,3,22,18,21,06,03,09,24,15,,,,,2.5,1.6,1.9*3E
$GPGGA,225317.000,3003.9039,N,10512.5783,W,1,08,1.6,1587.5,M,-20.7,M,,0000*5F
```

The sentence starting with the header label ‘\$GPGGA’ is the most useful for balloon tracking because it contains the following data:

- Time: **22:53** and **17** seconds UTC
- Longitude: **3003.9039,N** (in degrees.decimal minutes, North)
- Latitude: **10512.5793,W** (in degrees.decimal minutes, West)
- Number of satellites in view: **08**
- Altitude: **1587.5** metres.

The LAP microcomputer communicates with the GPS receiver via the serial port that is labelled according to the Arduino convention as ‘TXD’ and ‘RXD’. Being a hardware port makes it better able to meet the tight timing stability demands of uBlox 6 than would have been possible using a software implementation of a serial port. The environmental test version of LAP operating software employs the TinyGPS Arduino library to parse time data from the \$GPGGA sentence. Time was selected as being the most appropriate GPS information to obtain from a static test. This compact library is widely used for remote GPS tracking applications because it demands few resources and minimum processing from the host microcontroller. The free TinyGPS library was developed by Mika Hart and distributed under the terms of the version 3 GNU General Public Licence.

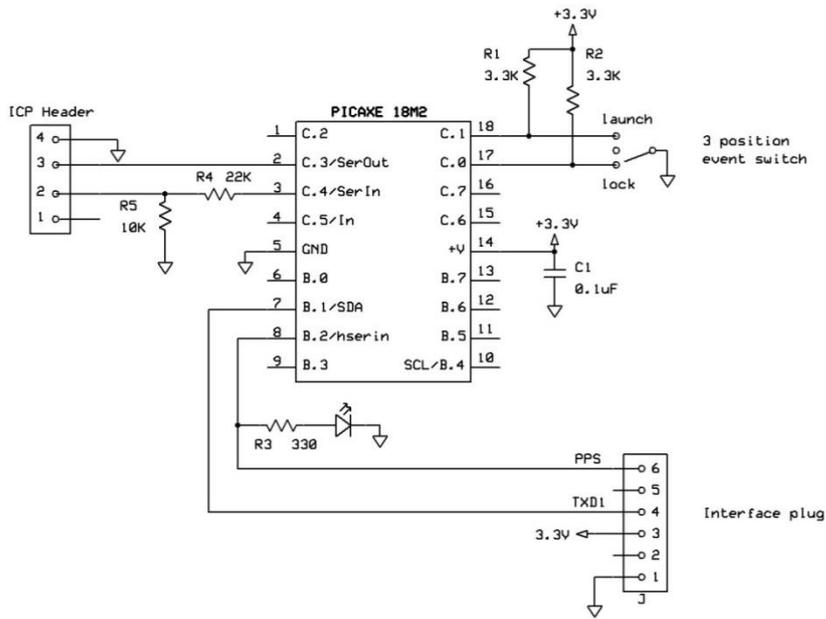
The flight version of the LAP operating software will employ a version of the above library that has been adapted to use the UBlox 6 proprietary message format. The proprietary format is similar to the NMEA standard but allows selected data from different sentences to be available on demand, rather than automatically generating the complete set of sentences at regular intervals. This will further reduce the already light processing load on the LAP microcomputer.



**Figure 15: Revelation Education GPS 010 uBlox receiver module**

#### 4.6.6 GPS Receiver Simulator

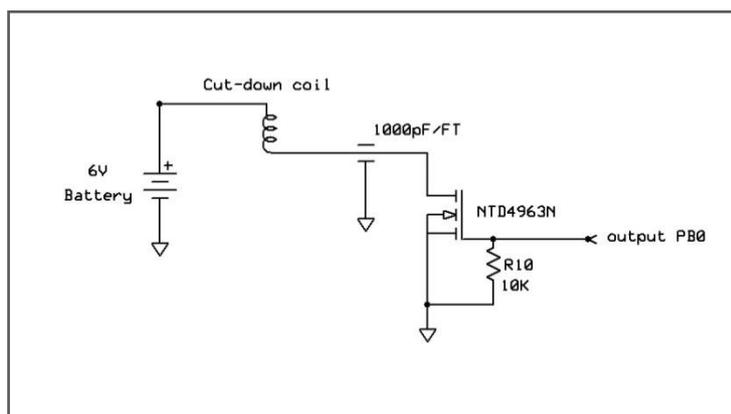
When equipped with an active antenna the uBlox receiver is normally able to obtain a fix when operating in my laboratory but static GPS data are of limited use during development and testing. Therefore test equipment was constructed that simulates the serial data output from a GPS receiver travelling on board a typical latex balloon flight. This plug-in substitute for the Revolution Education GPS 010 module is able to generate simulated NMEA sentence having realistic levels of random fluctuations. Simulated balloon launch and loss of GPS lock can be activated by push buttons. A range of simulator parameters can be individually programmed from a PC, including ascent rate, launch/landing site altitude and float/burst altitude. The simulator schematic shown in Figure 16 is a modified version of a design by Dr. Paul Verhage. In addition to making it compatible with the GPS 010 socket, the original simulator program was edited to produce a nominal 1 Hz PPS output. The PICAXE-18M2 [59] cannot be operated with an external crystal oscillator but the microcontroller's internal RC oscillator maintained sufficient accuracy to provide reliable serial communications when operated in my laboratory environment.



**Figure 16: LAP compatible GPS simulator module**

#### 4.6.7 Balloon Cut Down Switch

The only actuator directly controlled by the LAP Microcontroller is the balloon cut down wire. This will consist of a 30 cm length of nichrome wire coiled around the nylon cord that connects the top of the recovery parachute to the neck of the balloon. When supplied from the 6 volt battery pack the cut down wire will briefly draw approximately 2 amps and become sufficiently hot to sever the nylon cord and allow the payload gondola to descend under the recovery parachute. The open-drain of an ON Semiconductor NTD4963N N-channel power MOSFET [60] is used to switch the cut-down current, under the control of a LAP microcontroller digital output. A resistor is placed between the MOSFET gate and ground to ensure that it is not inadvertently turned on during system power-up or reset, when the microcontroller's digital lines temporarily default to high impedance inputs.



**Figure 17: MOSFET Cut-down circuit**

#### 4.7 On-board Data Storage

To provide the option of sampling at higher rates than can be handled by the satellite telemetry link, and to provide a backup in the event of communications failure, data are stored on-board for post flight retrieval. It was initially planned to provide the LAP with fixed non-volatile storage that could be interrogated via a detachable cable, after a few hour duration latex balloon flight. However, for super-pressure flights lasting several weeks it might take an inconveniently long time to transfer data serially to a PC for archiving. Therefore it was decided to use a removable SD card [61] to provide up to 32 Mbytes of non-volatile storage. Not only does this Flash based memory technology provide storage but data can be rapidly accessed by physically transferring the SD card from the LAP to a laptop mounted memory card slot.

Continuously writing incoming serial data to an SD memory card in a PC compatible file format can be processor intensive and resource hungry. Although well proven Arduino libraries exist for directly interfacing with SD memory cards [62], it was decided not to burden the LAP microcontroller with this complex task but to use a dedicated interface controller that offers a potentially higher level of reliability. The OpenLog module shown in Figure 18 employs an ATmega 328 microcontroller to write incoming serial data to a microSD memory card in the PC compatible FAT16/32 file format. OpenLog makes few demands on the system, having similar weight and dimensions to a basic microSD card compatible socket. It draws only 6 mA during the instant of writing and 2 mA during standby. A

passive adaptor is used to plug the smaller form factor microSD card into the standard SD card slot found on modern laptop PCs.

Referring once more to the system overview, shown by Figure 6, it can be seen that the OpenLog module does not demand a dedicated serial port but intercepts data packets being broadcast by the LAP microcontroller to the experiment via the Science Interface Port (SIP). In addition to the basic GPS and sensor data, the flight version of the LAP operating software will include telemetry commands in these data packets (together with previously sent experiment data that are ignored when subsequently received via the SIP). In the absence of an experiment the environmental test version of the LAP operating software broadcasts basic data packets via the SIP, using the format shown in Figure 19. This format was developed to be compatible with the StampPlot real-time PC display and logging software described later. Throughout environmental tests the OpenLog module recorded serial data packets as a backup to PC logging. Each packet consumes a maximum of 121 bytes of storage and is sent at a rate of 1 Hz. Therefore, even a modest 1 Gbyte capacity SD card would be capable of recording over 2,295 hours of environmental test data. The flight version of the LAP operating software will employ similar size packets, with experiment data and additional GPS fields taking the place of StampPlot commands.

The OpenLog module can only use microSD cards that have been pre-formatted by a PC. After a logging session the card can be removed from the LAP and interrogated via a compatible PC socket using a basic editor like MS Notepad. This application can also be used to configure OpenLog operating parameters, including the serial communications rate and operating mode by writing to assigned areas of the micro SD card. (This feature could be used to set the LAP sample rate.) The LAP uses the NewLog operating mode, which creates a new file on power-up/reset and then automatically starts logging the incoming serial data. This feature is useful for indicating the number of erroneous system resets that may have occurred during a flight.

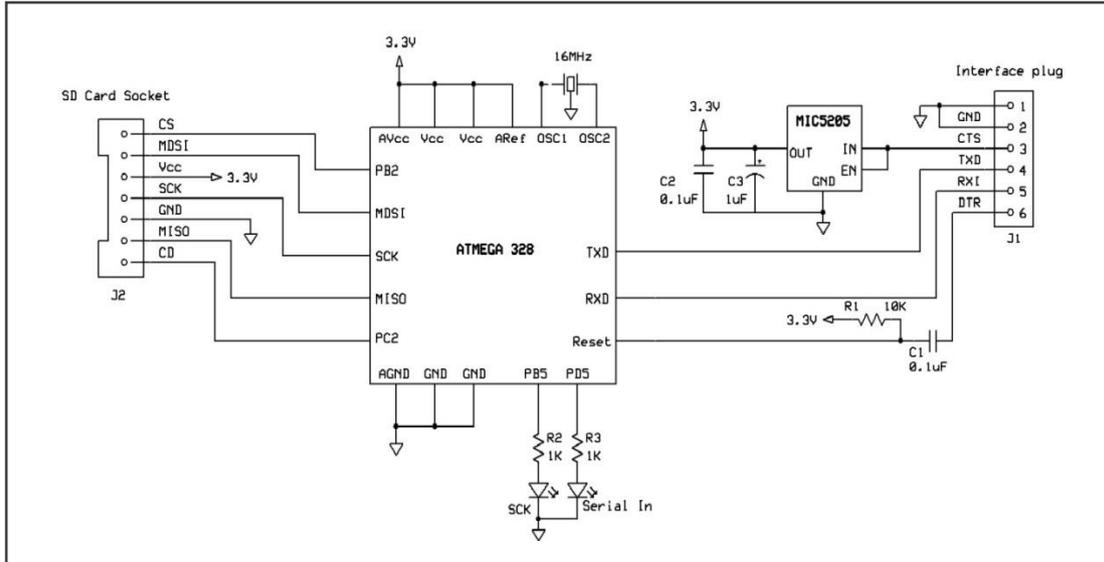


Figure 18: SparkFun Electronics OpenLog micro SD card interface module

```

ISTAT 24.11 C: 10 mbar: GPS 13102100 // !:STAT command display in status window
: DATA 24.11 C: 10 mbar: GPS 13102100 //!:DATA command display in message window and log
10,641,263,913,625,62,26,444,338,270 // No command means plot and log raw CSV data
%100 // '% command plot/log as digital data

The format of raw CSV analogue data sentence is as follows:
Pressure, internal temp,RH,external temp,batt volts, battery volts/10, RH/10,mag X,magY,magZ.
All channels are scaled from 0-1023 (10-bit) but magnetometer channels have an offset of 512 .

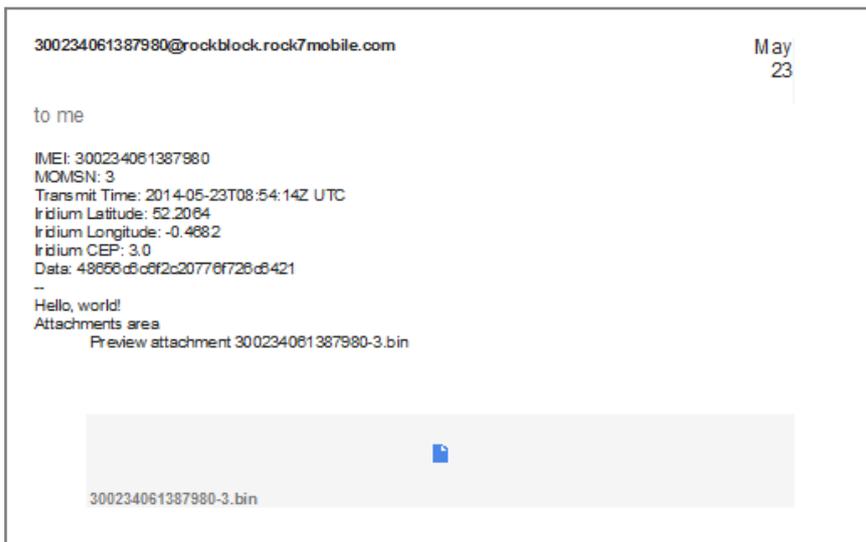
```

Figure 19: Data packet broadcast via the SIP and stored on the SD card

## 4.8 Satellite Communications

The commercial satellite communications services considered for airborne telemetry and command included: OrbComm, Globalstar and Iridium [64]. It was decided that the Iridium network offered the best compromise of affordability, coverage and message latency. The Iridium transceiver sends telemetry data directly to a satellite that is in view, which in turn passes the data to other Iridium satellites via cross-links until it arrives at one that can communicate with a ground station that is in view. Once at the ground station, telemetry data can be emailed to an internet connected PC. Commands emailed from a PC follow a reverse communications path from the Iridium ground station to the balloon borne transceiver. With the excellent level of satellite acquisition expected during high altitude balloon flight, latency in either direction should only be in the order of

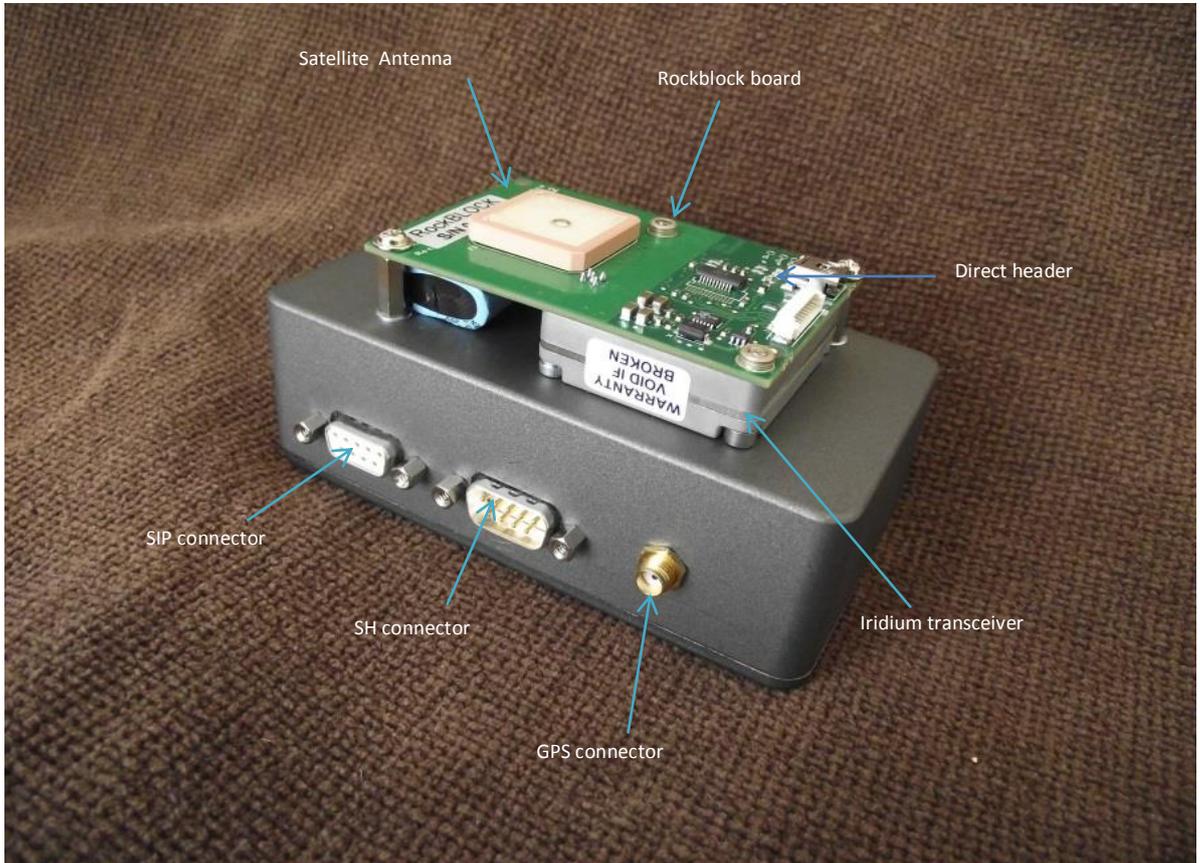
seconds. In addition to sensor and experiment data, each telemetry email distributed by the ground station will include a time-of-acquisition timestamp and a rough Iridium position fix [65]. Although the accuracy of this fix is typically in the order of several km, it could provide backup for tracking the balloon in the event of a GPS failure. Figure 20 shows an example email received during ground tests at location Latitude: 52.206588, Longitude: -0.550199.



**Figure 20: Example email from Iridium Transceiver Ground Test**

The Iridium consortium supply transceiver modules to OEM partners (e.g. Rock7Mobile) who integrate the hardware into a board level product known as Rockblock [66] which, at the time of writing, comes bundled with a monthly ‘line-rental’ of £8 plus data transmission charges of £2 per Kbyte. Rockblock is effectively a breakout board for the Iridium 9602 Transceiver Module that supports the Short Burst Data (SBD) mode [67]. The digital-only SBD service allows messages of 340 characters to be transmitted from the module and 270 characters to be received by the module. The LAP telemetry and command rate is a compromise between response time and operating costs, but will initially be in the order of one SBD session per minute. A basic feature of the Rockblock is that it automatically looks for incoming Iridium messages during each SBD session. Operating costs can therefore be minimised by aligning telemetry and command

events within the same SBD session, rather than being charged separately for both of these functions.



**Figure 21: The Rockblock Iridium satellite transceiver board mounted on 3.5x6.5 x12 cm screened LAP enclosure.**

Figure 21 shows the Rockblock board mounted on the exterior of the screened LAP enclosure. This configuration dictates that the enclosure be positioned within the payload gondola to give the Iridium antenna an unrestricted view of the sky. The Rockblock board supports the option of interfacing directly with the transceiver module or via a USB adaptor. The least complicated ‘direct option’ is used to interface to a LAP microcontroller serial port. Appendix A gives details of the cable wiring between the Rockblock Direct header and the LAP System Harness (SH) connector.

It can be seen from Appendix A that, in addition to serial communications, this cable is also used to supply power to the Rockblock. The current demand from the LAP mounted 5 volt regulator drops from a maximum of 470 mA, following the

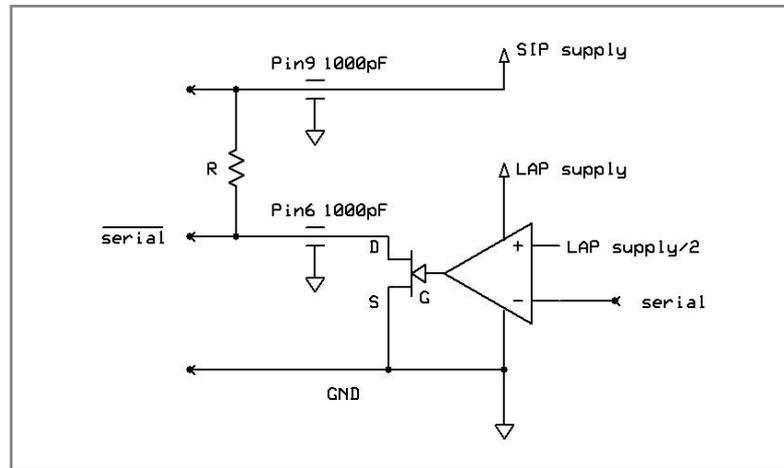
initial application of power, to an average of 50 mA during standby. The LAP can evoke the sleep command to reduce this further (to 20  $\mu$ A) between communication sessions. The Rockblock employs a local super capacitor to accommodate the transitory current demands of these short sessions. The supply is constantly available to maintain the charge and make the Rockblock ready to operate almost instantly on being wakened from sleep.

The Rockblock communicates using the AT protocol standard and appears similar to a legacy dial-up modem serial interface. In addition to the complexity associated with modem interfacing, the nature of low Earth orbit (LEO) satellite communications is such that it is difficult to predict the time required to establish a link (again, like a dial-up modem). Under the less than ideal line-of-sight conditions experienced during ground operation it can take an indeterminate number of tries before contact is made with a suitably positioned satellite. Therefore the LAP must initiate a series of retries whilst waiting for a satellite to appear that is able to accept telemetry data and download commands. As a consequence satellite communications may have to be performed as a background task. The Iridium SBD library [68] for the Arduino was developed specifically to undertake this function and was therefore used during ground tests of the Rockblock board and will be included in the flight version of the LAP operating software. The free Iridium SBD library by Mika Hart is distributed under the terms of the version 3 GNU General Public Licence.

#### **4.9 Science Interface Port (SIP)**

A SIP connected experiment will receive information and commands from the LAP and return science data using a bidirectional asynchronous serial interface. The table listed in Appendix B shows that, in addition to the two lines used for serial communications, the SIP connector provides two discrete digital inputs and outputs, plus a single analogue input. The discrete inputs and outputs can be monitored and controlled directly without using the serial interface. The status of the National Semiconductor LP3872 low-drop linear regulator [69] that conditions

the SIP supply is monitored and controlled by the LAP microcontroller. Its 3.3 volt output can be switched on and off in response to ground station commands to conserve power or to isolate a faulty experiment. However, powering-down only one side of an interface has the potential to permanently damage or temporarily latch-up electronic circuitry. To protect against this eventuality the three digital output lines on the SIP are of the open-drain configuration. The open drain outputs are part of the circuitry included in the Microchip Technology Inc. MCP6549 quad comparator package [70]. The operation of the SIP digital outputs is explained with the aid of the simplified schematic shown by Figure 22.



**Figure 22: LAP serial output circuitry to SIP**

Serial data from the LAP microcontroller arriving at a comparator's (-) inverting input transits the 1.65 volt threshold set by the voltage at the non-inverting (+) input, to produce inverted serial data at the output of the open-drain FET. This data polarity was chosen to be compatible with the serial port of the PC used during development and environmental testing. Normally, the resistor shown in the above schematic would form part of the SIP connected experiment circuitry. The resistor is necessary to pull the serial output line up to the SIP supply voltage when the comparator's open-drain FET is turned off. When the SIP supply is removed no unwanted parasitic current is available from the resistor or the FET, to power the experiment circuitry.

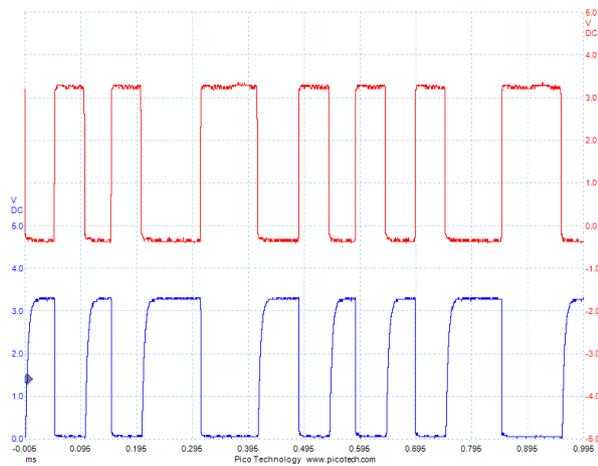
The same level of protection is not required in the reverse direction because the LP3872 regulator is configured (using another open-drain comparator) to switch off the SIP supply when the LAP microcontroller supply is absent. However, series resistors have been included to protect LAP microcontroller inputs from over/reverse voltages that may be inadvertently applied during development. Such abuse does not always lead to immediate failure but can reduce longer-term reliability [71].

Although it should be possible to power many types of experiment from the SIP supply, the digital outputs are able to interface with circuitry operating from other voltages. For example, the open-drain outputs can be made compatible with legacy logic levels simply by powering the pull-up resistors from a 5 volt supply, rather than to the 3.3 volt SIP supply. The SIP has a single analogue input that connects via a series protection resistor to a LAP microcontroller ADC channel. This input will normally be used to measure the temperature of the experiment's separate enclosure. This could be useful in determining if a SIP communications failure was caused by the experiment being subjected to extremes of temperature.

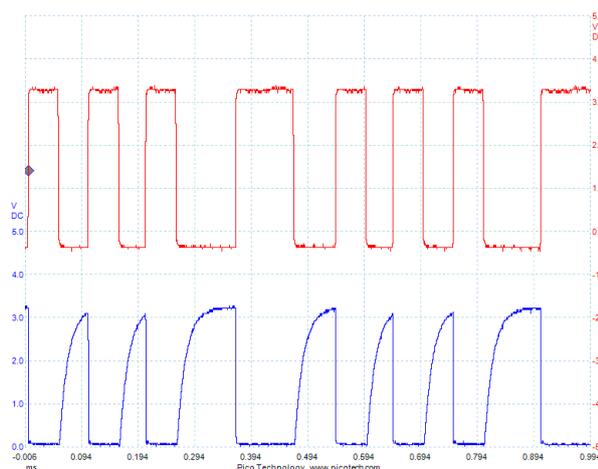
All wires entering and exiting the LAP screened enclosure must pass through interference suppression connectors that have integral capacitors fitted to each pin. This feature provides the LAP with a high level of immunity to Iridium radio transmission and experiment generated electromagnetic interference (from electromechanical actuators) but also complicates the transmission of serial data, in that the value of the series protection and pull-up resistors associated with passing streams of data through the SIP and SH connectors must be carefully chosen.

This issue can be illustrated by referring again to Figure 22, where the value of the pull-up resistor is a compromise between current consumption and serial data rate. A minimum resistor value of 120 Ohms could be used, without exceeding the comparator's maximum specified output current limit of 30 mA, but at the expense of high power consumption. Whilst the maximum value is constrained by the 1000 pF feed-through capacitors fitted to each pin of the SIP connector, because the time required for the voltage across this capacitor to charge to a

logical '1' level after the FET switches off is determined by the pull-up resistance. Figures 23a & b show the effect that two values of pull-up resistor on an ASCII character (HEX55) being fed through the SIP connector at a data rate of 19.2 kbps. It can be seen that the possibility of corrupting characters increases with the value of the resistor and that 15 Kohm should be considered the maximum to use at this transmission rate. The two discrete digital outputs also employ comparators but the values of their pull-up resistors are less critical because they are not required to transmit serial data.



**Figure 23a: Digital oscilloscope display of waveform at SIP pin 6, for R = 3.3 Kohm**



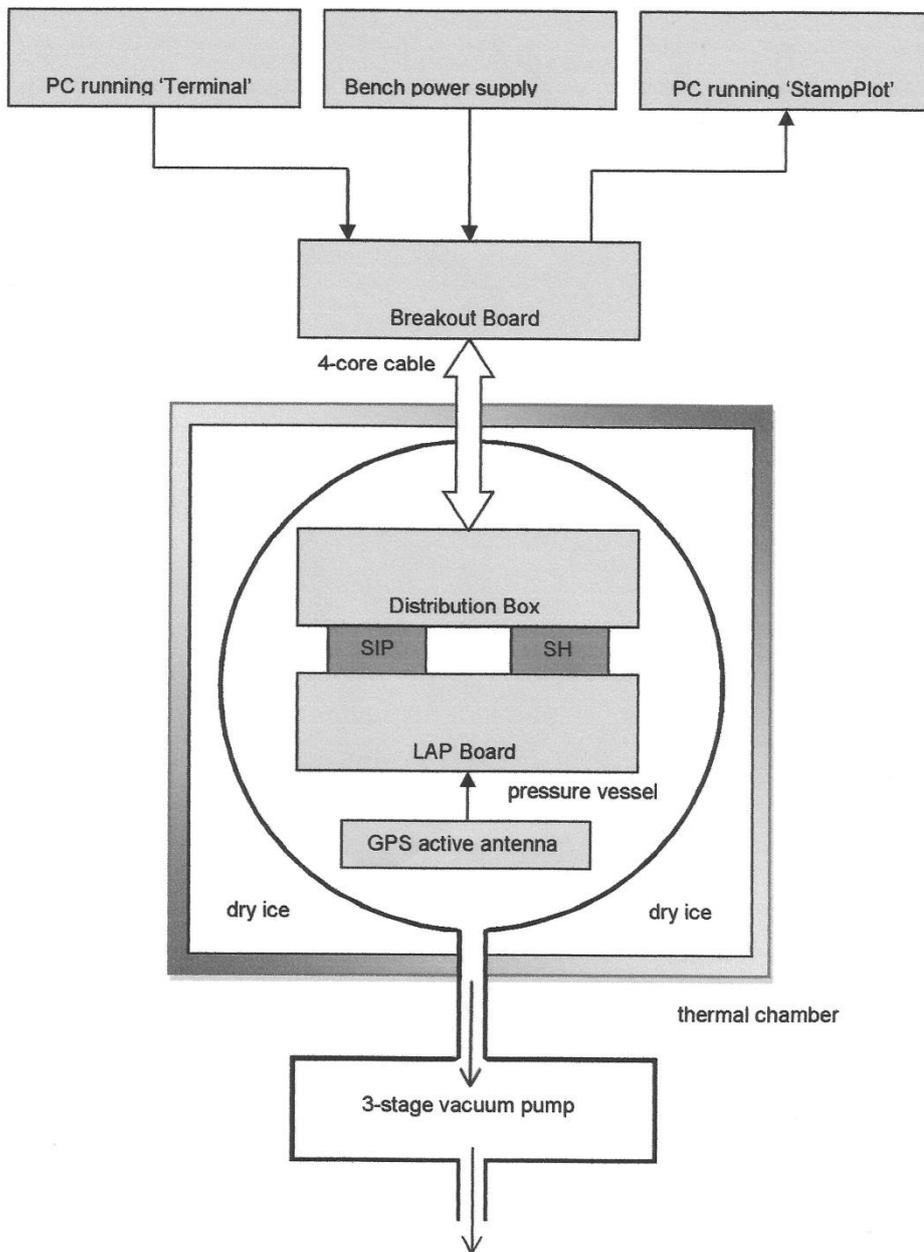
**Figure 23b: Digital oscilloscope display of waveform at SIP pin 6, for R = 15 Kohm**

## 5. ENVIRONMENTAL TESTING

Balloon avionics must operate reliably whilst subjected to a unique combination of low pressures and temperatures. Therefore environmental testing forms an essential part of the avionics development process in order to reduce the possibility of costly in-flight failures. However access to test chambers that can operate over the required environmental range may be prohibitively expensive for many research projects and their construction (and interior location) could screen satellite communications during testing. Therefore it was decided to investigate the feasibility of using lower cost and portable test equipment that also offered the advantage of good satellite communications. The resultant test facility was constructed from available items of laboratory equipment, mainly comprising of vacuum pumps and a pressure vessel that could be mounted in a thermally insulated enclosure together with a layer of dry ice.

Using this basic equipment it was possible to subject an operational LAP board to temperatures over the range  $-37^{\circ}\text{C}$  to  $+62^{\circ}\text{C}$ , at pressures from ambient down to 10 mbar. The main limitation of this low cost approach was that the chamber lacked independently certifiable sensors and the internal environment was only measured by the LAP mounted MS5611-01BA03 pressure/temperature sensor. This smart sensor has a specified accuracy of  $\pm 0.8^{\circ}\text{C}$  over the temperature range  $-40^{\circ}\text{C}$  to  $+85^{\circ}\text{C}$ , and an accuracy of  $\pm 2.5$  mbar over the pressure range 1200 to 10 mbar. However, this information did allow the basic operation of the LAP to be explored when subjected to the pressures and temperatures expected within a payload gondola during a typical latex balloon flight.

## 5.1 Automated Monitoring and Logging (AML) System.



**Figure 24: Overview of Automatic Monitoring and Logging (AML) System**

Operating pumps, administering dry ice and monitoring readings from all LAP sensor channels could have proved demanding during environmental tests of several hours duration. An Automated Monitoring and Logging (AML) system,

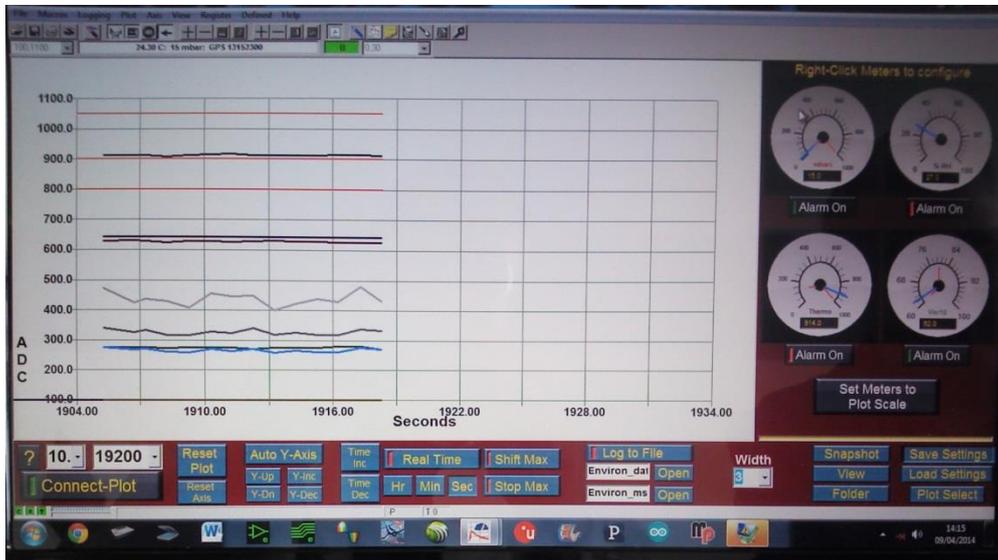
outlined in Figure 24, was therefore developed to assist manual control and reduce the risk of overlooking significant events or losing valuable test data. The aim was to present the operator with real-time information in the most appropriate form for observing trends and monitoring alarm limits, at a higher update rate than would have been possible using the flight version of the LAP operating software.

The AML employs the StampPlot application that was developed by Associate Professor Martin Hebel of Southern Illinois University as a user configurable PC software tool for research and education. StampPlot communicates with remote microcontrollers via a PC serial port using the standard ASCII character format. It was initially free to download for educational use but morphed into the commercial MakerPlot product [72]. The user is able to construct a display screen from a range of plotting tools, virtual dials and text windows, and select how the incoming serial data are routed to them.

Figure 25 shows the StampPlot screen layout used during all environmental tests. The main display area is dedicated to plotting trends using a different colour for each channel. All the channels shown are analogue, with the exception of the three red traces used to indicate the digital status of the SIP supply regulator and two sets of discrete I/O lines. An inherent plotting limitation is that the most appropriate label (excluding the digital channels) for the common Y-axis is 'ADC readings'. Therefore, those channels that are essential for manual environmental control are also assigned individual engineering units and displayed in the text window at the top left of the screen.

The example shows that when the image was taken the GPS derived time is 13:15:52, the 'internal' temperature was +24.30°C and the pressure 15 mbar. As an additional aid to efficient monitoring, the pressure, 'external' temperature, % RH and supply voltage channels are displayed on the four virtual meters to the left of the screen. Each meter has a user selectable maximum and minimum audible alarm setting, which proved helpful in avoiding dangerously low pressures and damagingly high temperatures, during testing. StampPlot can display incoming serial data and simultaneously archived it in spreadsheet compatible txt and csv files for subsequent analysis. Although this AML feature provided storage back-

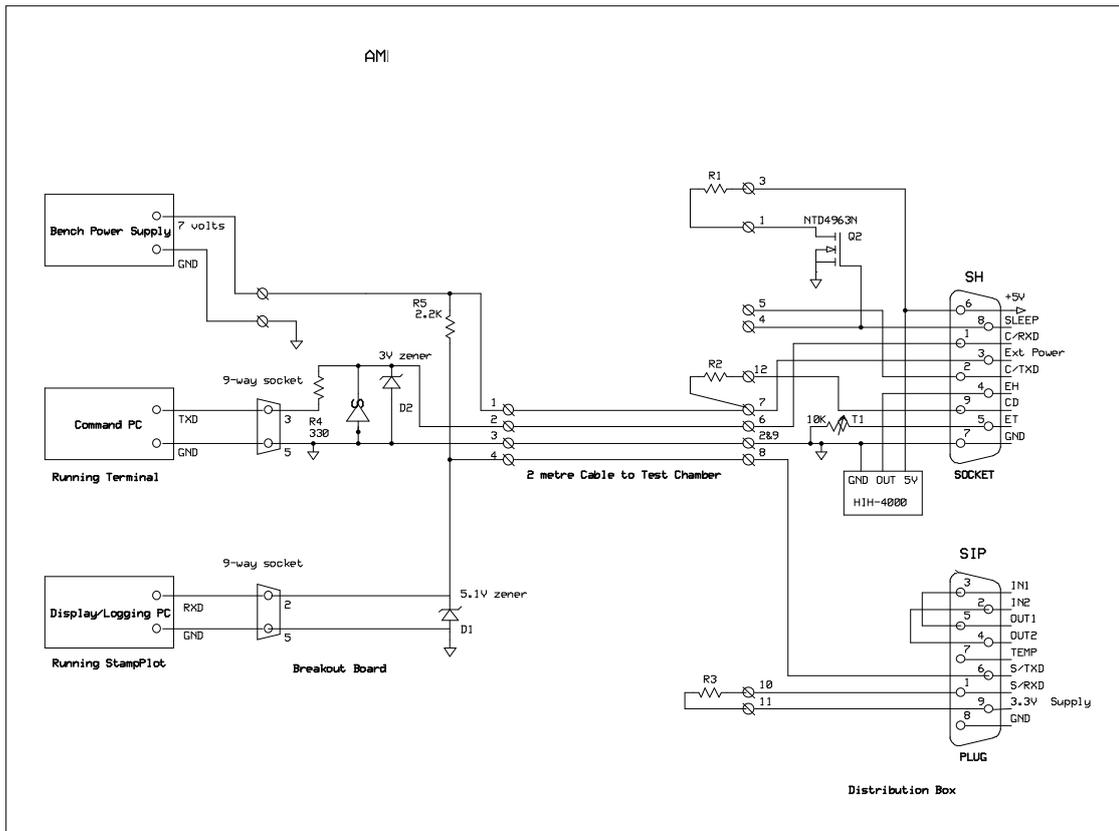
up during all environmental tests, the LAP's on-board data storage operated reliably to yield the data presented in the Final Discussion and Conclusions section.



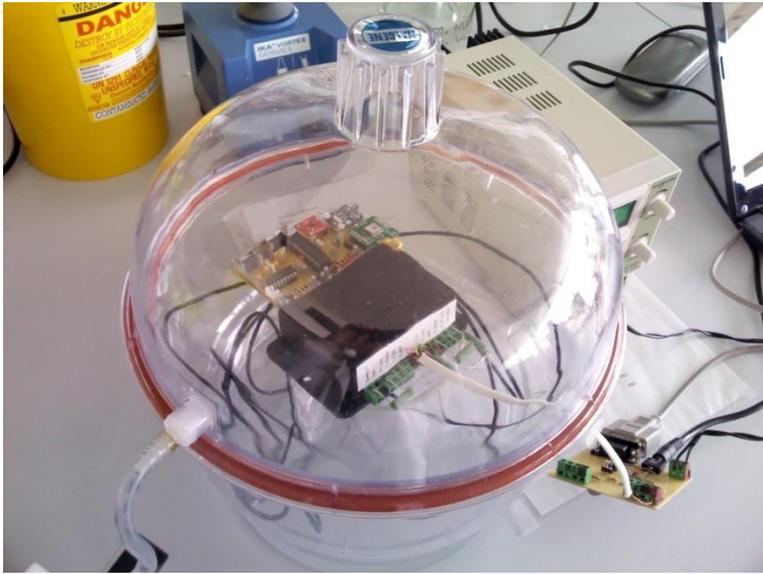
**Figure 25: Scrolling StampPlot display from pressure test at ambient temperature**

The architecture of the AML is markedly different from that proposed for the flight system, with the SIP and telemetry serial ports being connected to test PC's. As the cabling available for these connections was constrained by the need to test the LAP in a pressure vessel, it was necessary to construct the Distribution Box and Breakout Board shown by schematic Figure 26. These units reduced, to four, the number of wires that need pass through a pressure seal to the LAP. The pressure vessel mounted Distribution Box was also used to house the 'external' temperature and RH sensors, in addition to providing screw terminals for connecting the dummy load resistors for the 5 volt and 3.3 volt power supplies and the cut-down output. The FET switch Q2 is included on the 5 volt supply to simulate the telemetry transceiver being powered on and off by the sleep control output. Figures 27 and 28 show the Distribution Box, LAP and GPS antenna mounted in the pressure vessel and being removed following a low temperature soak test.

The main task of the bench mounted Breakout Board is to make the two LAP serial interfaces compatible with the +/- 5 volt levels used by the two PC serial ports. The standard RS-232 output from the 'Terminal' PC to the LAP is clamped between + 3 volts by the zener diode (D2) and - 0.3 volts by diode (D3). The open-drain LAP output to the 'StampPlot' PC has a pull-up resistor (R5) to the 7 volt supply line, but is clamped at a maximum level of +5 volts by the zener diode (D1). A pull-up resistor value of 2.2 K was found capable of driving the SIP connector, plus the capacitance associated with 2 metres of interconnecting cable (between the Breakout Board and the Distribution Box), at a data rate of 19.2 kbps. StampPlot displayed occasional interference during tests that were not present on the SD card record. The cause may have been electromagnetic interference, corrupting data being transmitted over the unscreened interconnecting cable. This type and length of cable is not representative of the proposed flight configuration.



**Figure 26: Automatic Monitoring and Logging (AML) wiring schematic for environmental test.**



**Figure 27: LAP, Distribution Box and GPS antenna in pressure vessel, with external Breakout Board**



**Figure 28: LAP board being removed from thermal chamber after -36°C soak test , frost covered but fully functional**

## 5.2 LAP Operating Software for Environmental Tests

The proposed flight version of operating software for the LAP microcontroller will be developed around the dual tasks of receiving commands and transmitting succinct packets of data during satellite communication sessions, scheduled at a rate of once per minute. This operating mode could not provide the command latency or data rate required for controlling and monitoring LAP during environmental tests. As a consequence, the Rockblock module could not be included in these tests and it was necessary to develop a specialised version of LAP software to work in conjunction with the AML system described previously.

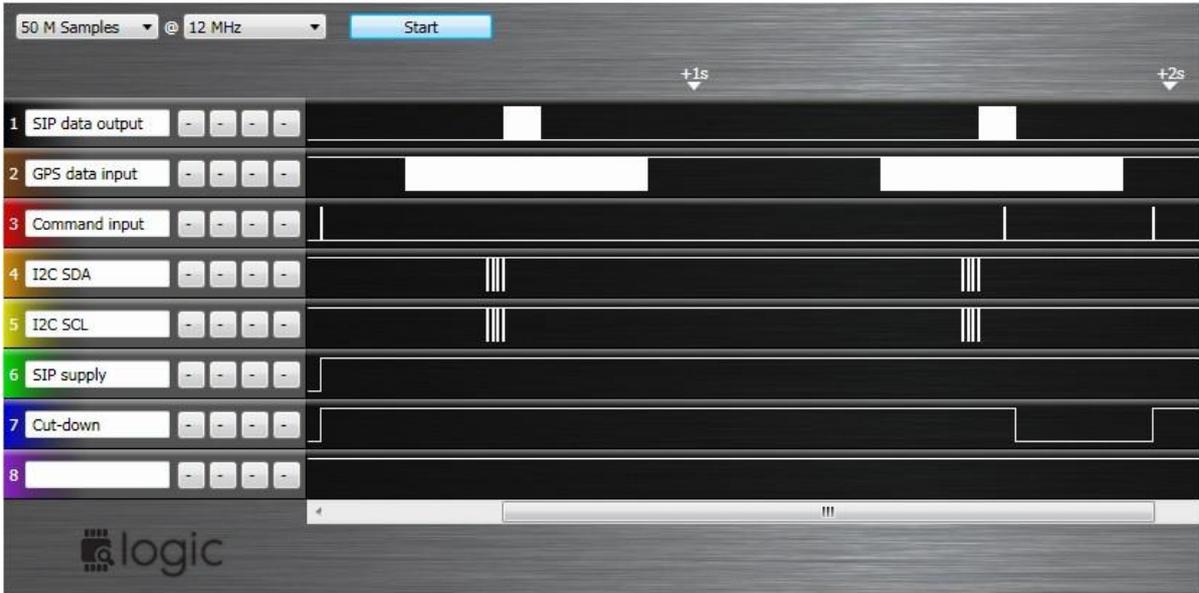
To respond more rapidly to commands and increase the data transmission rate, the ‘test’ version of the operating software lacks satellite communications features, with serial commands being received from the terminal PC via the SCP and serial data packets being transmitted to the StampPlot PC via the SIP at a rate of once per second. The outgoing packets are intercepted by the OpenLog module and written to a SanDisk 2 Gbyte micro SD card for on-board data storage. The existing ‘test’ and proposed ‘flight’ versions of operating software will share many similarities, most notably in the way they interface with sensors and format data.

The embedded operating software developed for the environmental tests is listed in Appendix D. The function of code segments may be understood by referring to the associated comments. The structure of an Arduino program dictates three distinct sections of code. The first informs the compiler about the libraries that must be installed, plus details about interface and the memory requirements. Starting at the *void setup()* function, the second section initialises interfaces and undertakes other tasks that need only be performed once at power-up or following a system reset. The main program does not start until reaching the *void loop()* function. The code in this loop runs continuously until power is removed or a system reset generated. The main program loop appears deceptively brief, because the listing does not show details of the complex work undertaken by the libraries, but is nonetheless responsible for performing the following tasks:

- Monitor the serial Satellite Communications Port (SCP) input and execute commands from a PC terminal
- Monitor the serial input from the GPS receiver and parse NMEA sentences
- Read value of four analogue and the status of three digital inputs
- Read data from the pressure and temperature sensor via the I2C bus
- Read data from the 3-axis magnetometer via the I2C bus.
- Format the above data into StampPlot compatible packets
- Broadcast packets to the SD card interface and to a PC via the SIP.

The sequences of events that are performed during the main loop are discernible in the screenshot shown by Figure 29. This was obtained from a Logic State Analyser (LSA) that captured activity from two main program loops over a two second period. The highly compressed nature of the resultant LSA display portrays data packets as solid blocks and groups of bytes as individual spikes, with only the two lower traces being true representations.

In the example shown, the first event displayed is an incoming command that turns on the SIP power and cut-down output. A relatively long packet of GPS sentences is then received. Parsing is completed part way through the GPS packet and sensor interrogation starts, as indicated by I2C bus activity. Finally, a packet containing all the above data is transmitted to the SD card interface and the SIP. The sequence of events in the second loop shown to the left of the screen-shot differs, in that a command is received during the transmission of a data packet. However, the command is not discarded but stored in the SCP input buffer until it can be executed by turning off the cut-down output. The last event is the reception of another test command to turn the output on again (not representative of cut-down operation during flight). The proposed flight version of the embedded LAP operating software will have a similar structure but the duration of the timing loop will be dictated by Iridium satellite communications.

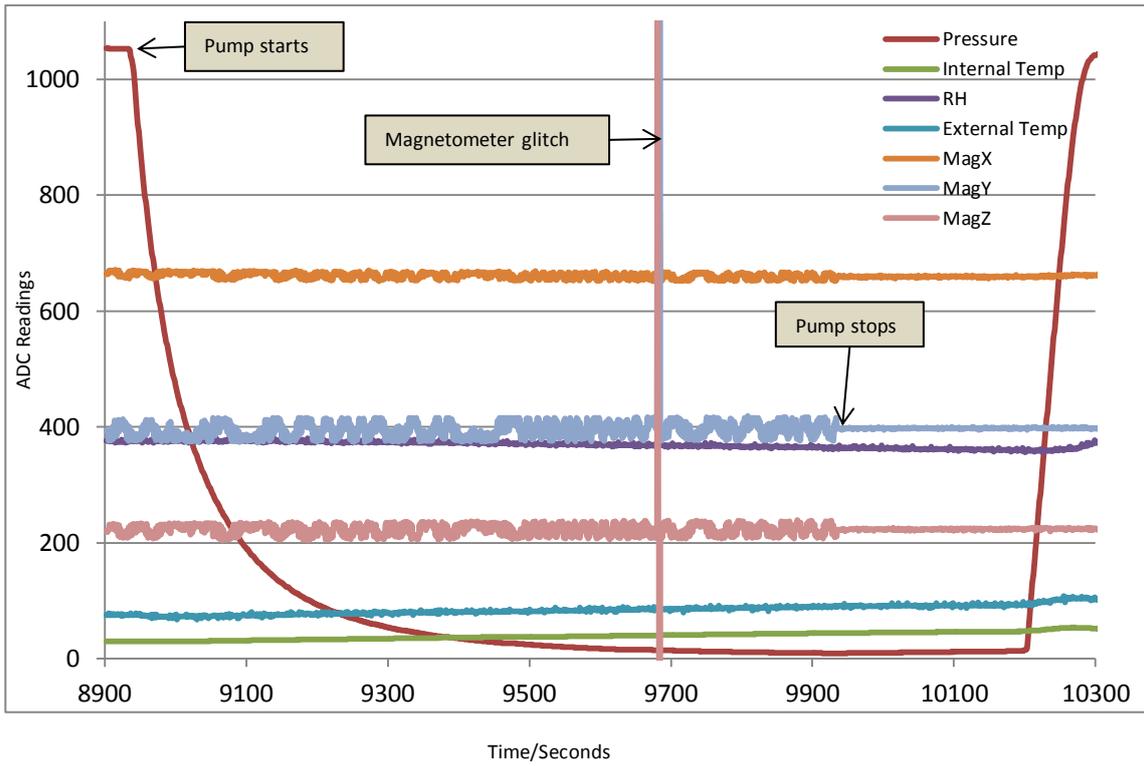


**Figure 29: Logic State Analyser display of two main program loops**

## **6. ENVIRONMENTAL TEST RESULTS**

### **6.1 Data processing**

During the many hours of environmental testing all LAP inputs were sampled once per second. Although this resulted in a large amount of stored data, it allowed relatively short duration anomalies to be observed and investigated. Figure 30 has been included as an example of the information that can be gleaned by using a 1 Hz sample rate. Electromagnetic interference can be seen on all three magnetometer axes when the ganged vacuum pumps, were operated. These pumps were mounted less than a metre from the unscreened LAP board. The fundamental frequency of the interference is 50 Hz (UK mains) but the effects of aliasing [73] makes it appear much lower on the plot. Also apparent is a short duration glitch on all magnetometer axes just before 9700 seconds. It was not possible to identify the cause but it may have been interference from other nearby electrical equipment. As these were the only type of high frequency anomalies found, it was deemed acceptable to decimate and average data to produce MS Excel plots with 1 minute time increments. Imputation was also applied to the magnetometer glitches in the interest of presentational clarity.

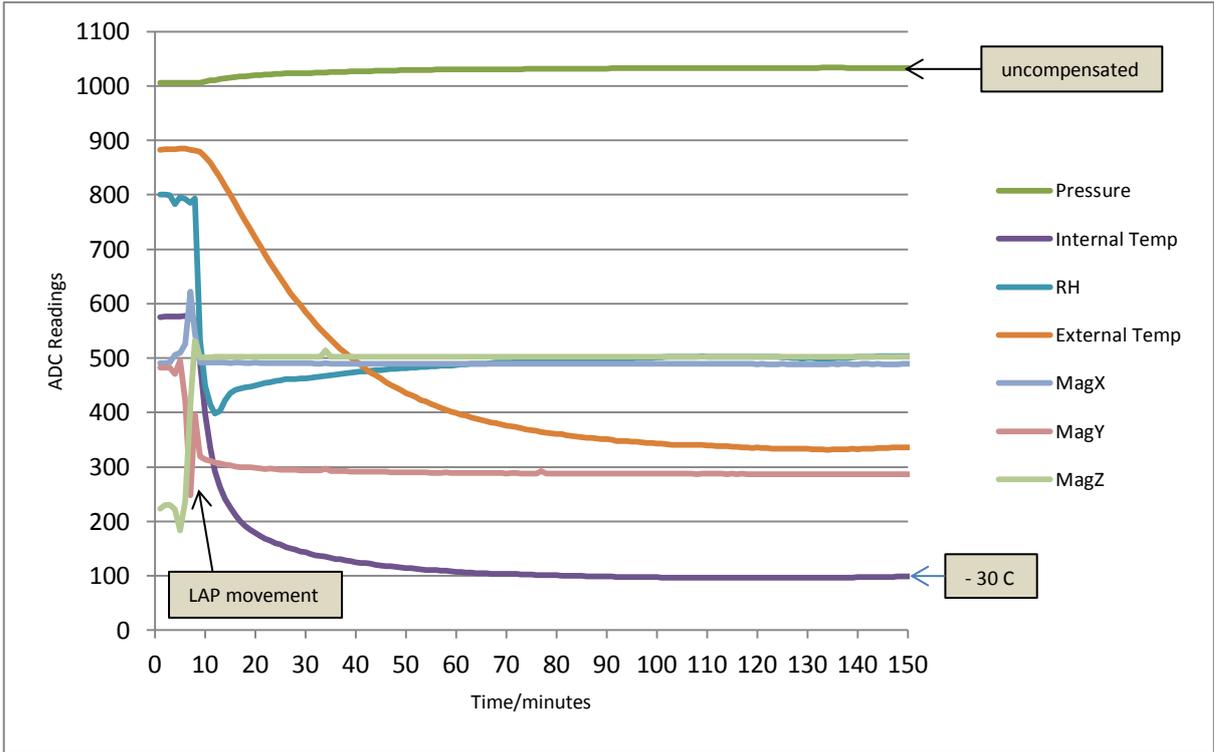


**Figure 30: Raw LAP sensor data sampled at 1 Hz during an environmental test**

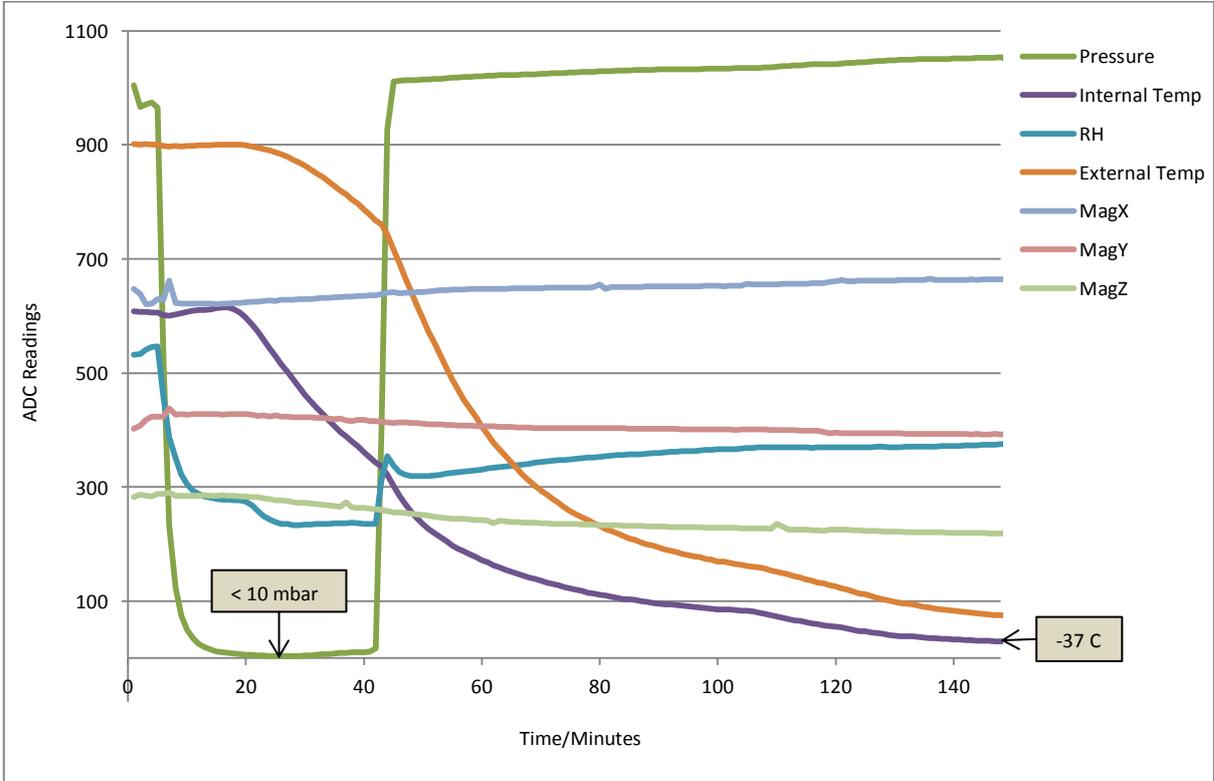
## 6.2 Example Plots

The aim of the environmental test programme was to evaluate the reliability of a LAP when subjected to temperatures near the specified limits (-40°C to +85°C) of its electronic components and to the pressures at an altitude of 25.6 km. A specialised atmospheric test chamber would be able to simulate the external environment, including solar heating, and enable the sensors to be calibrated. However, the chamber constructed for this project is unable to maintain selected pressure and temperature points due to the use of dry ice for cooling and the unreliable restart characteristics of the diaphragm pumps at low pressure. Therefore, the results in Figures 31 – 34 were obtained using dynamic tests that were only made practicable by the supporting AML system. The example plots presented below were chosen because they cover the following main environmental contours.

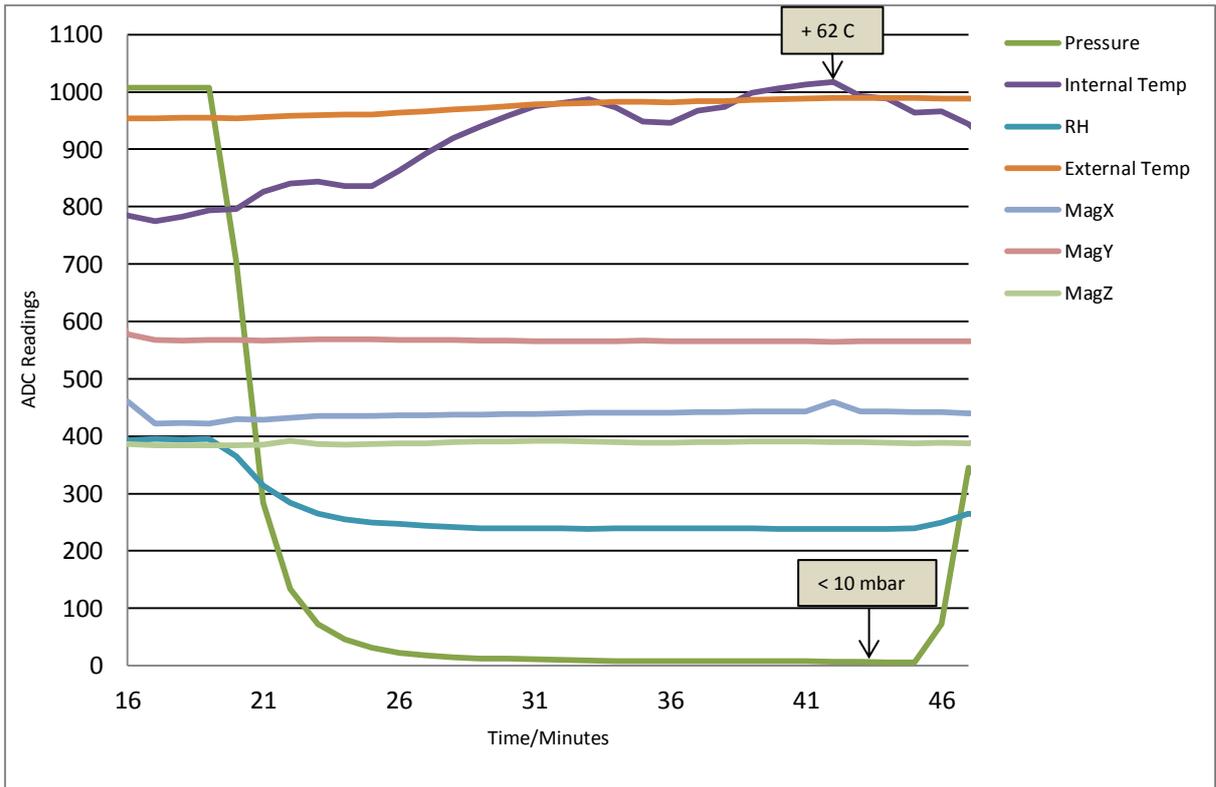
- Decreasing temperature at ambient pressure
- Decreasing pressure and temperature
- Decreasing pressure and increasing temperature
- Decreasing pressure at ambient temperature.



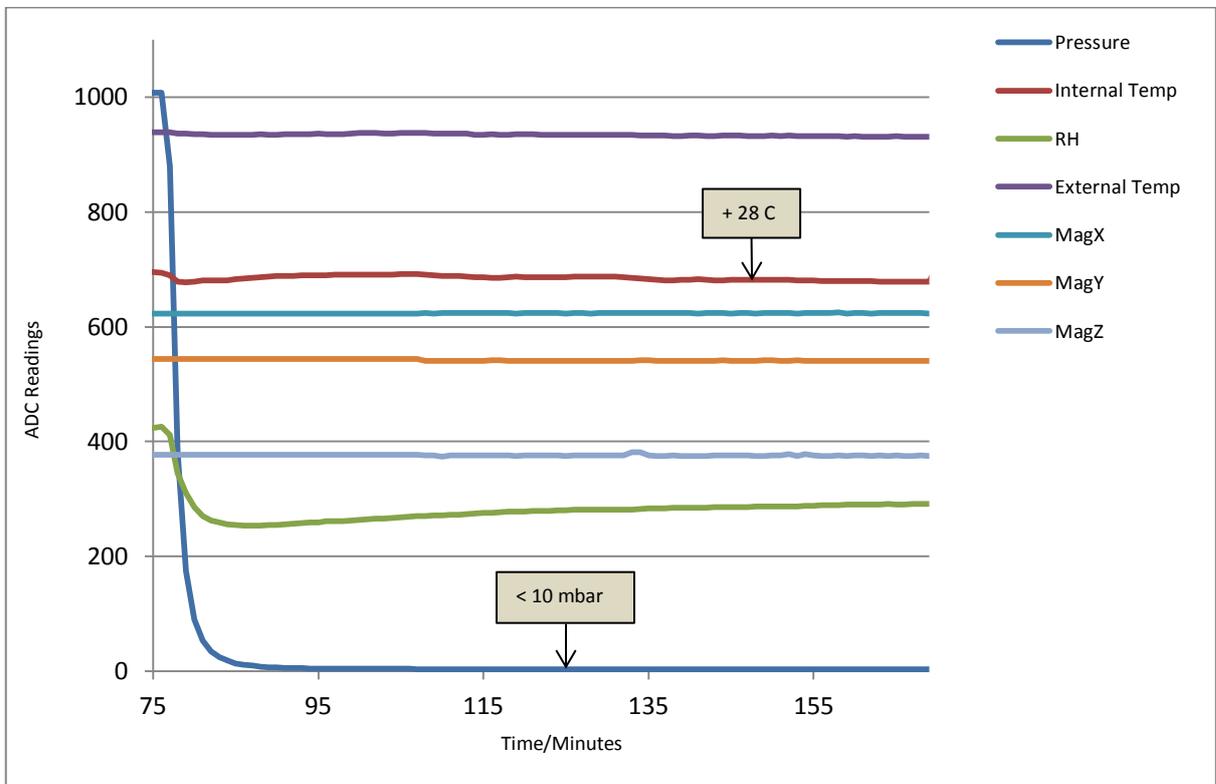
**Figure 31: Decreasing temperature at ambient pressure**



**Figure 32: Decreasing pressure and temperature**



**Figure 33: Decreasing pressure with increasing temperature from solar heating**



**Figure 34: Decreasing pressure at ambient temperature**

No system malfunctions are evident from the above results. The only failure experienced during testing was that of the active GPS antenna, at temperatures above approximately +65°C. This type of antenna will be replaced with a more reliable passive version during flights. The above Excel graphs were produced from data stored on the SD card in StampPlot compatible format. The LAP environmental test software applied basic offset, scaling and inversion to certain sensor channels to improve presentation. Whilst the flight version of the software will apply temperature compensation, where appropriate, and convert data to engineering units for ease of real-time assimilation when receiving emails on mobile devices.

## 7. FLIGHT PLANNING

When planning a balloon flight the procurement of, and compliance with, an insurance contract is a major consideration. The follow extract from the document “*Cranfield University framework for the launching, flights and recoveries of lightweight tropospheric and stratospheric balloons*” (see Appendix D) was prepared as part of an application for insurance cover and therefore contains all pertinent planning details:

Details for typical flight

- Avionics / payload features
  - Two way communication to balloon
  - Ability to real-time track
    - Via two-way communication (GPS)
    - Radar reflector as established by the HAB community (for warning of radar equipped aircraft and ground-based radar)
  - Ability to remote terminate flight if flight path is predicated to deviate to an safe area by use of a cut-down mechanism to cut tether between balloon and payload
  - Ability to have a watchdog capability such that if two-way communication is lost, system will cut-down
  - All radio communication is performed within the local (national) approved guidelines for licensing / frequency / broadcast power / duty cycle
  - Mass typically of payload  $\leq 3\text{kg}$
  - Altitude of flights up to 40 Km
  - Size / volume of payload such that peak impact force per unit area on landing is minimised (i.e. no “sharp pointy bits”)
  - Parachute used (sized) to have descent velocity close to ground of  $\leq 7\text{ m/s}$  for payload mass

- Chemical hazard minimised – e.g. for lithium-based batteries, choose format with appropriate case strengths – e.g. standard domestically common formats - AAA, AA, B, C, D
  - Only use non-flammable lifting gases (e.g. helium not hydrogen)
- Pre-flight planning
  - Use of community established predictive flight path planning software
  - Assessment of flight path – only fly when predicated flight path avoids large urban areas and airfields
  - Duration of flights – typically 2-3 hrs (balloon ascends until burst and then descent under parachute)
  - Flight distance typically 100 miles
- Pre-flight approval
  - Will use the established UK CAA NOTAM route to inform CAA of planned balloon flight (unusual activity - see <http://www.ukra.org.uk/notam>)
- Launch
  - For Cranfield University launches, launch locations will be one of (and with approval from location owner):
    - Cranfield sports-field (preferred option)
    - Cranfield airfield when non-operational
    - Launch site of the East Anglian Rocketry Society (Ellsworth, Cambridgeshire)
    - Other local launch sites
    - Launch sites to be assessed for risk of hitting power and other overhead line and other structures
  - Assess low level weather conditions – wind, rain, etc.

- Appropriate control of pressurised gas containers
- A Cranfield employee will be nominated as the launch, flight and payload recovery manager and be responsible for health and safety aspects
- The launch, flight and payload recovery crews will be briefed by the launch, flight and payload recovery manager
- No balloon will be flown with a lifting capability of  $>1/5$  (a safety factor of 5) of the weight of a typical UK adult (all launch crew to be adults) – i.e. minimised risk of crew being lifted off the ground
- Flight
  - The flight will be monitored continuously to assess the current and updated predicted flight path to minimise the chance of landing in urban and other high risk areas via ability to remotely terminate flight using cut-down mechanism
  - To guide the recovery crew to the predicted landing location
- Recovery
  - Payload recovery crew will use appropriately insured vehicles to travel to and from the landing site and will have the necessary driving credentials
  - Payload size and mass and use of parachute (landing velocity) is designed to minimise impact damage to objects / property at the landing site
  - If the landing location is not publically accessible, the recovery crew will make contact with the owner and agree a means of accessing the landing site to allow payload recovery
  - The payload will be appropriately labelled to inform the general public of the ownership, purpose and how to handle the payload

In addition to the operational details outlined in the above extract, there are a number of important engineering related procedures that will have to be carefully followed. These include preparing detailed pre-flight checklists and the guaranteed availability of portable test and launch equipment. The Iridium satellite network avoids the need for a centralised ground station, because the LAP is able to communicate with a number of mobile devices via email. However, this also has the potential to create ‘confusion under pressure’ and the ability to send command emails to the LAP will have to be strictly limited. One solution would be to appoint a Flight Controller who is assigned a unique email address. Therefore, experiment operators will have to request the Flight Controller to issue commands to the LAP. The nature of balloon flight means that the resulting latency should not prove a problem.

## 8. FINAL DISCUSSIONS AND CONCLUSIONS

### 8.1 Avionics

The major aims of the project have been achieved with the development and environmental testing of the LAP board shown in Figure 35 and schematically in Figure 36.

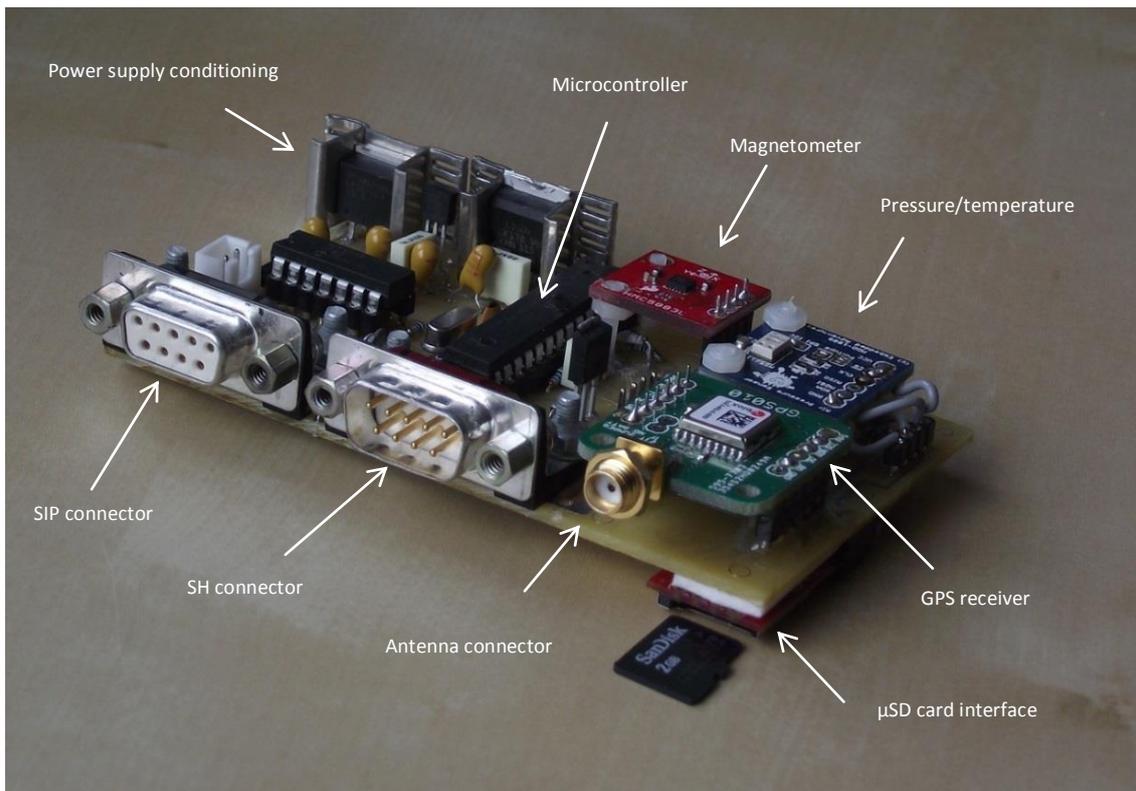


Figure 35: Photo of Lightweight Avionics Platform (LAP) board.

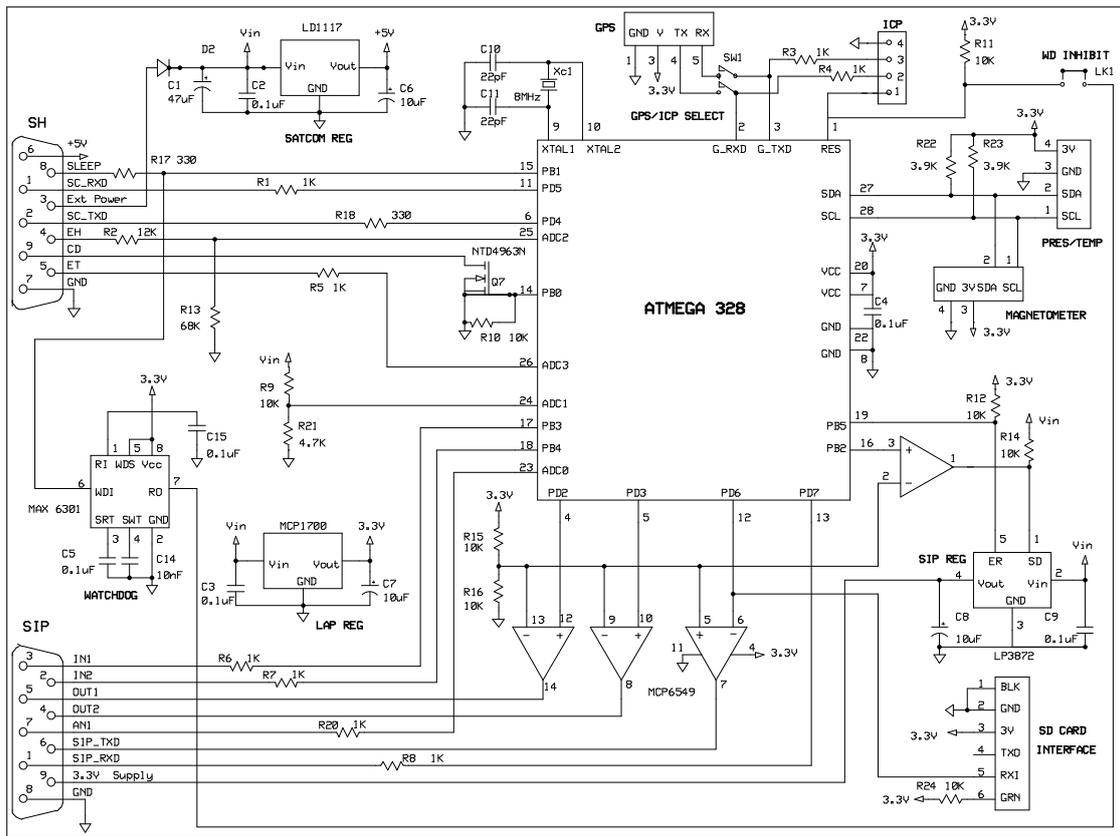


Figure 36: Schematic of Lightweight Avionics Platform (LAP) showing sockets for plug-in modules

The board weighs 78 grams and even with the additional weight of the screened enclosure and satellite transceiver, the total of 178 grams is less than 10% of a typical latex balloon payload. The LAP board's current consumption of < 10 mA places modest demands on the payload 6 volt battery supply. A single connector is used to provide a robust and flexible interface and researchers only need to know the SIP standard serial communications protocol to interface their experiments. The existing LAP operating software was written specifically to assist development and testing, but much of the proven sensor interfacing and serial communications code will be available to use in the flight version of the software. As a consequence of the LAP performing reliably during all ground tests, only two minor design revisions are proposed and described later in this section.

## 8.2 Proposed Revision to External Temperature Sensor Circuitry

It was only after the thermistor had been used during the environmental tests that the potentially adverse effect of condensation on the relatively high impedance (e.g. thermistor resistance of 1.4 Mohm at  $-60^{\circ}\text{C}$ ) interface circuitry was considered. Therefore, it is proposed to replace the thermistor with a low output impedance active semiconductor sensor that should provide more reliable operation but this will be at the expense of reduce measurement range. The Texas Instrument's LM19 was selected because it is specified to measure down to  $-55^{\circ}\text{C}$  with a maximum output impedance of 160 Ohms [74]. This sensor has the additional advantage of having a near linear temperature response that avoids the need for post-processing. Figure 37 shows how the LM19 could be mounted on the same board as the Relative Humidity (RH) sensor mentioned previously. The value of the interference suppression feed-through capacitor exceeds the LM19's maximum specified load of 300 pF. Resistor R19 is therefore placed in series with the sensors voltage output. Resistor R5 has been retained to protect the ADC input from over/reverse voltages that may be inadvertently applied when the sensor board is unplugged from the SH connector.

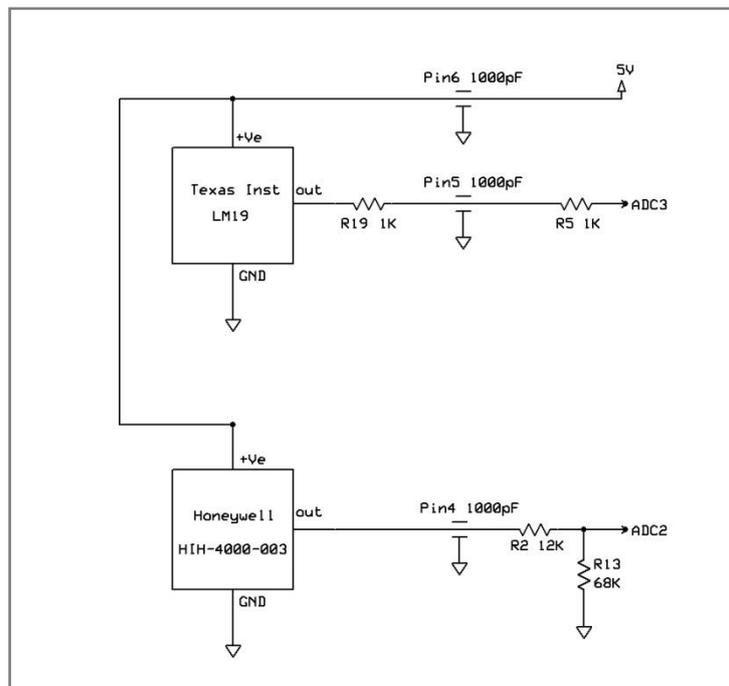


Figure 37: Proposed external humidity and temperature board

### 8.3. Proposed Revision to Iridium Transceiver Supply Circuitry

The fixed 5 volt low-drop linear regulator currently used to supply the Rockblock will be changed for an adjustable Texas Instruments REG104 regulator [75] (see Figure 38) configured to output 4.2 volts. This will improve the regulator's input/output overhead margin to extend the useful battery life, whilst remaining above the Rockblock boards specified minimum supply voltage of 4 volts. The output voltage is set by the potential divider that feeds the regulator's reference input, using the formula  $v_{\text{supply}} = (1 + 27 / 12) * 1.295$ .

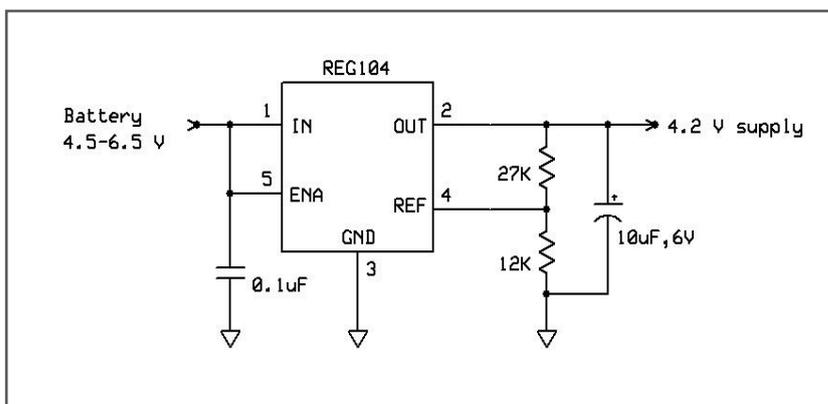


Figure 38: Revised regulator for Rockblock supply

### 8.4 Test Equipment and SIP Example

A significant part of the project involved the construction of environmental test chamber, which is transparent to satellite communications and GPS radio signals, and to the development of a supporting PC based monitoring and logging system. From the experience gained it should be possible to produce a more capable low cost environmental chamber for testing and, if necessary, calibrating balloon payloads.

The final stage of the project was dedicated to the design of a prototype LAP compatible experiment controller, which will be integrated with a dust sampling experiment. Much of the information included in the description below could be of use to researchers interested in developing LAP compatible experiments. At the time of writing the prototype controller has not yet reached the printed circuit

stage but has run in plug-board form. The description concludes with general comments relating to the payload gondola design and electromagnetic compatibility considerations.

### **8.5 Prototype Experiment Controller**

The proposed Dust Sampling Experiment (DSE) will employ the same type of diaphragm pump and valves that were used successfully to draw air thorough a filter on the CASS-E stratospheric dust sampling experiment [76, 77]. The basic configuration will however differ in that it will be possible to select which filter will be routed to the pump via four valves. This will be achieved by issuing commands from the ground to open and close one of four valves and to turn a common pump on and off. By restricting the number of filters it would have been possible to control two valves directly from discrete SIP outputs but it was decided to provide the proposed dust sampling experiment with a dedicated microcontroller that communicates serially via the SIP. This more scalable approach could also form the basis of a ‘reference design’ for use by students and research staff undertaking the development of other experiments.

The adoption of a standard asynchronous serial interface for SIP communications provided a wide choice of compatible microcontroller that could be used for the DSE (from the 8-pin PICAXE that can be programmed in BASIC, to an ARM running Unix). However, the design shown in Figure 39 is again based on an Atmel ATmega 328 as it uses the same Arduino development environment as the LAP microcontroller. The DSE microcontroller will also be conservatively run an 8 MHz clock rate to ensure reliable operation from the 3.3 volt SIP supply. A watchdog timer will also be included for the reasons outlined previously but will have a shorter time-out period to reflect the faster DSEs main loop.

The pump and valves are controlled by the DSE microcontroller’s digital outputs using Infineon BTS 462T smart power switches [78]. These devices are termed ‘smart’ by the manufacturer because of their integral short-circuit and over-voltage protection, plus thermal shutdown and current limiting (at 4.4 A). They

operate as high-side switches, where a logical '1' at the input terminal causes current to flow from the output terminal to ground and a logical '0' switches the current off. The pump and valves must therefore be connected between smart switch outputs and ground, as shown by Figure 40. This flexible configuration allows actuators with different supply voltage requirements to be accommodated.

The smart switches have open-drain diagnostic outputs that can be monitored by the DSE microcontroller's digital inputs, (provided their internal pull-up resistors are selected during set-up). A logical '1' at the diagnostics output indicates that the switch is operating normally, whilst a logical '0' indicates the switch has shut-down automatically. The temperature of the pump motor could be monitored by connecting a remote LM19 sensor to an analogue input of the DSE microcontroller, via a 3-pin socket (J2). The low-pass filter, formed by R6 and C6, will attenuate electrical magnetic interference that may appear on the temperature sensor cable. A second LM19 sensor is mounted on-board to allow the internal temperature of the DSE enclosure to be monitored by the LAP microcontroller via the SIP analogue input.

During environmental testing of the prototype DSE it is proposed to use a PC to simulate SIP communications. The PC will run the 'Test' version of the Firmata open source software [79] and the DSE microcontroller will be programmed with the 'StandardFirmata' library that is supplied as a standard part of the Arduino IDE. These two Firmata serial communications packages allow the PC to control and monitor the individual digital output and input lines. The user is able to exercise actuators and monitor diagnostics feedback, in real-time, with the aid of a virtual on-screen control panel. This panel is also able to display data from the two ADC channels that are used to measure temperature.

Although the above software tools are adequate for environmentally testing the prototype DSE, embedded software will need to be developed for the flight version. This will support a primary mode, that controls the experiment from the ground station, and a backup mode that responds to a satellite communications failure. The backup mode would enable samples to be automatically collected at predetermined altitudes using LAP supplied pressure, temperature and GPS data.



## 8.6 Payload Gondola Design

It is anticipated that the experiment will normally be significantly larger and heavier than the LAP and will therefore dictate the design of the gondola. In fact, conceptually the LAP enclosure should be considered a routine accessory to the experiment. Payload gondolas could be constructed from glued sheets of extruded polystyrene foam (XPS) to match individual experiment and battery configurations. This lightweight structure would provide mechanical support and thermal insulation for the internally mounted components and also offer a level of shock protection on landing. The task of developing a thermal model for each unique payload gondola is probably not justified, given that measurements from routine 2-3 hour latex balloon flights indicate that a wall thickness of 25 mm is able to maintain internally mounted electronic components within their specified operating range [80]. Battery power constraints normally mitigate internal heating issues, but due consideration should be given to the effects of reduced ventilation at low pressure.

Testing to determine if there is electromagnetic interference between subsystems (e.g. electromechanical actuators and microcontrollers) must be performed on the final payload gondola configuration. As any subsequent changes to the wiring layout and location of the LAP, experiment and battery pack/s would invalidate such tests. A major area of concern during development was the possible of the 1,616 -1626.5 MHz Iridium transmissions jamming the nearby GPS 1575.42 MHz signal. No evidence of radio frequency interference was observed during ground tests but due consideration should be given to the relative positioning of GPS and Iridium antennas on the payload gondola.

## **9. FUTURE WORK.**

The LAP and Rockblock combination shown previously by Figure 21 weighs a total of 173 grams and measures 12 x 6.5 x 5.5 cm in size. Having worked faultlessly throughout a programme of severe environmental tests, this hardware has been shown to be capable of performing reliably within the payload gondola of a latex balloon during a typical ascent -to- burst flight profile. Once flight proven, the weight and size of the existing design could be significantly reduced by producing a new printed circuit with the smart sensor and GPS chips mounted directly on the board (rather than via plug-in modules). The revised board could also use surface-mount versions of the other LAP components and directly mount the 30 gram Iridium satellite transceiver module. This module is the only component used on the Rockblock board, as the LAP bypasses most USB interface and power supply circuitry. However, given that the weight of the existing LAP and Rockblock combination would represent less than 10% of latex balloon payload capacity; such an additional manufacturing step may only be justified for super-pressure balloon applications.

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## APPENDICES

### Appendix A

<u>Direct Header Pin No.</u>	<u>Function</u>	<u>Direction</u>	<u>SH Connector Pin No.</u>
2	5 volt supply	<	6
3	serial data output	>	1
4	serial data input	<	2
7	sleep command	<	8
10	system ground	-	7

Wiring between the LAP and RockBlock connectors.

## Appendix B

<u>SIP pin No.</u>	<u>Function</u>	<u>Direction</u>
1	serial data input	<
2	discrete input 2	<
3	discrete input 1	<
4	discrete output 2	>
5	discrete output 1	>
6	serial data output	>
7	analogue input	<
8	system ground	-
9	3.3 volt, 1.5A supply	>

SIP Connector pin assignments

## Appendix C

### Cranfield University framework for the launching, flights and recoveries of lightweight tropospheric and stratospheric balloons

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#### Author:

Prof David Cullen, School of Engineering, Cranfield University with inputs from Michael Bessant  
9<sup>th</sup> April 2014, v2a\_09-04-14\_DCC&MFB

#### Document history:

Initiated in meeting between DC Cullen and MF Bessant on 10/01/2014 (and originally documented in email from Cullen to Bessant sent on 10/01/2104 titled *FW: Details of meeting of 16/10/13 - inc. Risk / Health / Safety consideration of a HAB flight*)

Updated during meeting on 09/04/2014 between DC Cullen & MF Bessant and then further by DC Cullen later on 09/04/2014

#### Background and context:

Cranfield University, in the form of research activities led by Prof David Cullen in the School of Engineering, would like to perform a series of flights of lightweight stratospheric balloons. The reason for the flights are various planned scientific, teaching and pre-commercial development activities. Scientifically there is interest in the collection of stratospheric particles, using stratospheric balloon flights, for post flight analysis especially in the context of detection of (i) particles associated with stratospheric microbial species and (ii) particles associated with volcanic eruptions. For teaching, the preceding scientific objectives form part of research degree and research project elements of taught degree teaching. Performing pre-commercial demonstrations associated with possible future commercial activities involving monitoring of volcanic dust plumes in relation to the management and operation of commercial airspace.

Cranfield University has had previous experience of such activities in that:

- D Cullen has flown particle collection experiments on two lightweight stratospheric balloon flights (in 2009 and 2010) organised by the Cambridge Spaceflight group (a student body associated with University of Cambridge)
- D Cullen has lead a Cranfield team that flew a particle collection experiment twice on a large stratospheric balloon flights (Oct and Nov 2010) organised by the European Space Agency

Cranfield University, in the form of research activities associate with Prof D Cullen, would like to perform lightweight stratospheric balloon flights from mid-2014 onwards. It is assumed that the frequency of flights would be a maximum of twelve flights per year and for a period from 1<sup>st</sup> June 2014 to 31<sup>st</sup> May 2019 – a five-year period and therefore ultimately a maximum total of sixty flights.

**To perform such flights, Cranfield University would expect that insurance cover is needed to minimise the liability associated with the flights. Therefore this document is intended to provide information about the planned stratospheric balloon flight activities to help insurance cover to be obtained.**

The following are the details of the planned flights and the various risks and risk mitigations that would be implemented as well as information on established activities that appear to be similar in terms of operations and risks.

## Definition of a lightweight stratospheric balloon

- Balloon to have a maximum lift capability – i.e. the amount of payload mass it can fly – of  $\leq 3\text{kg}$ 
  - This emerges from the upper limit of practical availability of latex weather balloons that are routinely used for such flight

## Details for launch, flight and recovery of lightweight stratospheric balloons:

- Existing activities that are similar to the proposed Cranfield University stratospheric balloon flights
  - A global High Altitude Ballooning (HAB) hobby community exists that regularly flies lightweight stratospheric balloons and broadly comply with local regulations concerning (i) radio transmission and (ii) airspace / air traffic control – the flights do not appear to routinely have insurance / liability cover
  - Meteorological weather sondes – i.e. lightweight weather balloons with simple instrument payloads – have been regularly flown for decades
  - A well-established activity similar to HAB is Meteorological weather sondes – balloon lofted payloads of typically 1kg in size that rise until balloon burst and then payload mass descends under parachute
- Details for typical flight
  - Avionics / payload features
    - Two way communication to balloon
    - Ability to real-time track
      - Via two-way communication (GPS)
      - Radar reflector as established by the HAB community (for warning of radar equipped aircraft and ground-based radar)
    - Ability to remote terminate flight if flight path is predicated to deviate to an unsafe area by use of a cut-down mechanism to cut tether between balloon and payload
    - Ability to have a watchdog capability such that if two-way communication is lost, system will cut-down
    - All radio communication is performed within the local (national) approved guidelines for licensing / frequency / broadcast power / duty cycle
    - Mass typically of payload  $\leq 3\text{kg}$
    - Altitude of flights up to
    - Size / volume of payload such that peak impact force per unit area on landing is minimised (i.e. no “sharp pointy bits”)
    - Parachute used (sized) to have descent velocity close to ground of  $\leq 7\text{ m/s}$  for payload mass
    - Chemical hazard minimised – e.g. for lithium-based batteries, choose format with appropriate case strengths – e.g. standard domestically common formats - AAA, AA, B, C, D
    - Only use non-flammable lifting gases (e.g. helium not hydrogen)

- Pre-flight planning
  - Use of community established predictive flight path planning software
  - Assessment of flight path – only fly when predicated flight path avoids large urban areas and airfields
  - Duration of flights – typically 2-3 hrs (balloon ascends until burst and then descent under parachute)
  - Flight distance typically 100 miles
- Pre-flight approval
  - Will use the established UK CAA NOTAM route to inform CAA of planned balloon flight (unusual activity - see <http://www.ukra.org.uk/notam>)
- Launch
  - For Cranfield University launches, launch locations will be one of (and with approval from location owner):
    - Cranfield sports-field (preferred option)
    - Cranfield airfield when non-operational
    - Launch site of the East Anglian Rocketry Society (Ellsworth, Cambridgeshire)
    - Other local launch sites
    - Launch sites to be assessed for risk of hitting power and other overhead line and other structures
  - Assess low level weather conditions – wind, rain, etc
  - Appropriate control of pressurised gas containers
  - A Cranfield employee will be nominated as the launch, flight and payload recovery manager and be responsible for health and safety aspects
  - The launch, flight and payload recovery crews will be briefed by the launch, flight and payload recovery manager
  - No balloon will be flown with a lifting capability of  $>1/5$  (a safety factor of 5) of the weight of a typical UK adult (all launch crew to be adults) – i.e. minimised risk of crew being lifted off the ground
- Flight
  - The flight will be monitored continuously to assess the current and updated predicted flight path to minimise the chance of landing in urban and other high risk areas via ability to remotely terminate flight using cut-down mechanism
  - To guide the recovery crew to the predicted landing location
- Recovery
  - Payload recovery crew will use appropriately insured vehicles to travel to and from the landing site and will have the necessary driving credentials
  - Payload size and mass and use of parachute (landing velocity) is designed to minimise impact damage to objects / property at the landing site
  - If the landing location is not publically accessible, the recovery crew will make contact with the owner and agree a means of accessing the landing site to allow payload recovery

- The payload will be appropriately labelled to inform the general public of the ownership, purpose and how to handle the payload

## Appendix D

```
/*
EMBEDDED ARDUINO SOFTWARE FOR LAP ENVIRONMENTAL TESTS:
Performs the following main tasks:

Execute commands received via Satellite Communications Port(SCP).
Accept and parse serial GPS data.
Read analogue and digital input channels.
Read data from magnetometer, pressure and temperature sensors via I2C bus.
Build StampPlot Pro compatible serial data packets.
Transmit packets to the Science Interface Port (SIP) and the SD card at 1 Hz.

Author, Mike Bessant, 12-4-2014.
*/
// Libraries for interfacing with following:
#include <SoftwareSerial.h> // Satellite and Science serial
communications.
#include <TinyGPS.h> // GPS receiver.
#include <Wire.h> // I2C bus.
#include <MS561101BA.h> // Pressure and temperature sensor.
#include <HMC5883L.h> // Magnetometer sensor.

// Define I/O pin constants:
const int sipout1Pin = 2; // Discrete SIP output 1.
const int sipout2Pin = 3; // Discrete SIP output 2.
const int scp_txPin = 4; // Satellite Com's Port (SCP) serial output.
const int scp_rxPin = 5; // SCP serial input.
const int SIP_rxPin = 7; // Science Interface Port (SIP) serial
input.
const int SIP_txPin = 6; // SIP serial output.
const int cutdownPin = 8; // Cut-down switch control.
const int sleepPin = 9; // Satellite transceiver (RockBlock) sleep
ctrl.
const int sippowerPin = 10; // SIP power supply control.
const int IN1pin = 11; // Discrete SIP input 1.
const int IN2pin = 12; // Discrete SIP input 2.
const int POWFLAGpin = 13; // SIP power supply status.

const int SipTempInPin = A0; // Analog input for remote SIP temp sensor.
const int BattVoltInPin = A1; // Analog input for battery voltage
monitoring.
const int humidityInPin = A2; // Analog input for humidity sensor.
const int temperatureInPin = A3; // Analog input for external temperature
sensor.

// Declare variables
int humidityValue = 0; // value read from the humidity sensor
int temperatureValue = 0; // value read from the thermistor
int siptempValue = 0; // Value read from the remote SIP temperature
sensor
int battVoltValue = 0; // Value read from battery input
int POWFLAGstate = 0; // state read from SIP power flag
int IN1state = 0; // state read from SIP input 1
int IN2state = 0; // state read from SIP input 1
unsigned long fix_age,time,date;
```

```

// Create objects
SoftwareSerial serial_sip (SIP_rxPin,SIP_txPin); // Inverted data to SD card.
SoftwareSerial serial_scp (scp_rxPin,scp_txPin,true); // True data to SCP.

HMC5883L compass;
MS561101BA baro = MS561101BA();

TinyGPS gps;

// Function to launch interfaces and configure StampPlot PC display software.

void setup()
{
  // Open asynchronous serial ports and set their Baud rates.
  Serial.begin(9600);          // Hardware GPS communications.
  serial_sip.begin(19200);     // Software SIP communications.
  serial_scp.begin(19200);     // Software SCP communications.

  Wire.begin();               // Open I2C interface bus.

  compass = HMC5883L();
  compass.SetScale(4);        // Set magnetometer sensitivity.
  baro.init(MS561101BA_ADDR_CSB_HIGH); // Set I2C address.

  // Set following pins as inputs and enable on-board resistors:
  pinMode (POWFLAGpin, INPUT_PULLUP);
  pinMode (IN1pin, INPUT_PULLUP);
  pinMode (IN2pin, INPUT_PULLUP);

  // Set following pins as outputs:
  pinMode(cutdownPin, OUTPUT);
  pinMode(sleepPin, OUTPUT);
  pinMode(sippowerPin, OUTPUT);
  pinMode(sipout1Pin, OUTPUT);
  pinMode(sipout2Pin, OUTPUT);

  digitalWrite(sippowerPin,HIGH); // Set state to ON.
  digitalWrite(cutdownPin,LOW); // Set state to OFF.
  digitalWrite(sleepPin,LOW); // Set State to OFF.

  serial_sip.println("Envitest_Version 3.1_12/4/2014"); // Output on start-
up.

  // Output set-up instructions to StampPlot Pro PC display software.
  serial_sip.println("!RSET");
  serial_sip.println("!RSET");
  serial_sip.println("!RSET");
  serial_sip.println("!TMAX 30");
  serial_sip.println("!SHFT ON");
  serial_sip.println("!SAMT 95");
  serial_sip.println("!FLSH OFF");
  serial_sip.println("!SPAN 100,1100");
  serial_sip.println("!PLOT ON");
  serial_sip.println("!STAT");

```

```

}

// Run main loop until power removed or system reset.

void loop()
{
  if (serial_scp.available())          // Check character is in SCP
  buffer.

  {
    char ch = serial_scp.read();      // Read SCP input buffer.

    switch (ch)                       // Define switch variable.
    {
      case '1':
        digitalWrite(sipout1Pin,HIGH); // Action if above char' is
received.
        break;
      case '2':
        digitalWrite(sipout1Pin,LOW);
        break;
      case '3':
        digitalWrite(sipout2Pin,HIGH);
        break;
      case '4':
        digitalWrite(sipout2Pin,LOW);
        break;
      case '5':
        digitalWrite(sippowerPin,HIGH);
        break;
      case '6':
        digitalWrite(sippowerPin,LOW);
        break;
      case '7':
        digitalWrite(sleepPin,HIGH);
        break;
      case '8':
        digitalWrite(sleepPin,LOW);
        break;
      case 'C':
        digitalWrite(cutdownPin,HIGH);
        break;
      case 'A':
        digitalWrite(cutdownPin,LOW);
        break;

      serial_scp.flush();
      delay (50);
    }
  }

  // Parse selected data from GPS sentences.
  while(Serial.available()){
    if(gps.encode(Serial.read())){
      gps.get_datetime(&fix_age,&time,&date);

      // Read following analogue input channels:

```

```

humidityValue = analogRead(humidityInPin);
temperatureValue = analogRead(temperatureInPin);
siptempValue = analogRead(SipTempInPin);
battVoltValue = analogRead (BattVoltInPin);

// Read following digital input channels:
POWFLAGstate = digitalRead(POWFLAGpin);
IN1state = digitalRead (IN1pin);
IN2state = digitalRead (IN2pin);
delay(100);

{
  float temperature = NULL, pression = NULL;      // Read internal
temperature.
  while(temperature == NULL)
  temperature = baro.getTemperature(MS561101BA_OSR_4096);
  {
    while(pression == NULL)
      pression = baro.getPressure(MS561101BA_OSR_4096); // Read pressure.
  }
  compass.SetMeasurementMode(Measurement_Continuous); // Read
magnetometer.
  MagnetometerRaw raw = compass.ReadRawAxis();

  // Display pressure, GPS and temp' in easily readable 'Status' window.
  serial_sip.print("!STAT ");
  serial_sip.print(temperature);
  serial_sip.print(" C");
  serial_sip.print(": ");
  serial_sip.print(pression,0);
  serial_sip.print(" mbar");
  serial_sip.print(": GPS ");
  serial_sip.println(time);

  // Also display pressure, GPS and temp' in loggable 'Message' window.
  serial_sip.print (" : DATA ");
  serial_sip.print(temperature);
  serial_sip.print(" C");
  serial_sip.print(": ");
  serial_sip.print(pression,0);
  serial_sip.print(" mbar");
  serial_sip.print(": GPS ");
  serial_sip.println(time);

  // Display analogue channels in main 'Plotting' window and on meters.
  serial_sip.print(pression,0);          // Drop decimal points
  serial_sip.print(",");
  serial_sip.print(temperature * 10+400,0); // Avoid negative trace
  serial_sip.print(",");
  serial_sip.print(humidityValue);
  serial_sip.print(",");
  serial_sip.print(1023 -temperatureValue); // Invert external temp'
value.
  serial_sip.print(",");
  serial_sip.print(battVoltValue);
  serial_sip.print(",");

```

```

        serial_sip.print(battVoltValue/10);           // Match StampPlot meter
scaling.
        serial_sip.print(",");
        serial_sip.print(humidityValue/10);         // Match StampPlot meter
scaling.
        serial_sip.print(",");
        serial_sip.print(raw.XAxis+512);           // Avoid negative trace.
        serial_sip.print(",");
        serial_sip.print(raw.YAxis+512);
        serial_sip.print(",");
        serial_sip.println(raw.ZAxis+512);

        // Also display status of the digital channels in main 'Plotting'
window.
        serial_sip.print("%");                     // Set binary indicator.
        serial_sip.print (POWFLAGstate);           // Send state '1' or '0'.
        serial_sip.print (IN1state);
        serial_sip.println (IN2state);

    }
}
}
}

```