Aircraft Performance Logger

Part IIB Project

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Technical Abstract

Aircraft have a number of performance parameters that characterize their behaviour. One of these is ground roll, defined as horizontal distance between the start point and point of lift off. Another is take-off distance required (TODR), defined as the horizontal distance from standstill to 15 m above the ground. Both of these are important to know in order for a pilot to understand how much space they need to take-off, and so they know if they can use certain runways or airstrips. These values gathered in testing and , alongside the conditions of the day, are used to construct performance charts, tables, or quoted figures that are required in aircraft manuals and pilot handbooks. The accuracy of this data is therefore important for the accurate creation of this official TODR and ground roll data.

The measurement of these performance parameters uses expensive, bespoke solutions for commercial aircraft, and these are not viable for smaller aircraft whose pilots cannot afford such solutions. They therefore resort to a 'by eye' approach, estimating distances using runway markers and aircraft instruments, all whilst piloting the aircraft. This leads to very inaccurate measures of ground roll and TODR, something which is not acceptable as the safety of the pilot and any passengers depends on these values being accurate. There is therefore a need for a cheap solution for measuring theses performance parameters accurately.

Differential Global Positioning Systems (DGPS) can give the accuracy required but is an expensive solution, and a cheaper but as effective alternative may be available. High data acquisition rate is also needed for the data to have great enough resolution to precisely find the points of take-off and 15 m climb. The project starts with investigation into an alternative DGPS solution, as well as characterization of the use of a pressure sensor to measure altitude, as GPS alone will not give acceptable accuracy in altitude. This preliminary testing aids the design of a 3D data logging module that saves GPS and pressure data to an SD card where the data be processed and performance parameters extracted. Preliminary testing also revealed that the

proposed DGPS system does not improve location accuracy and this idea is then abandoned for the module design, and the GPS built in Satellite Based Augmentation System is used instead. This system however requires a lower than desired data acquisition rate, trading resolution for accuracy.

The design of the final module ensured that the data was acquired at a high enough data rate, was small, easy to use and that the post processing gave accurate results. This involved the design of a PCB, module, firmware and software to create an all encompassing solution.

Testing of the module revealed that the accuracy in GPS was good, giving distance to within 1.4 m, but the pressure sensor had several sources of error, including its own self heating, the effect of propeller wash and the effect of wind-speed, as well as its oversampling rate causing its static accuracy to be less than the quoted value. All this meant an error in height measurement of around 2 m, very different from the desired accuracy. Despite this the module and post processing produces accurate results for ground roll and TODR, agreeing well with the test aircraft's quoted values despite sometimes overestimating the take-off point.

The module created in this project is an improvement on the by eye approach it set out to replace, and is an simple solution for measuring TODR and ground roll. With further improvements and development, it can become a more fully fledged aircraft performance measuring solution, measuring also landing distance required, climb rates and aircraft ground speed. All this is achieved without needing to be attached to the aircraft's systems, something that would require official licensing and testing.

Contents

Chapter 1

Introduction

1.1 Description of the problem

In order for a pilot to safely take off or land an aircraft, they must know the aircrafts take off distance and distance to clear 15 m. Conditions such as ambient temperature, pressure, wind speed, runway surface and gradient as well as aircraft weight all affect this distance. So pilots can determine this distance, aircraft performance charts are used. Given the weather conditions, runway conditions and aircraft weight, the pilot can read off take off distance from the chart. Constructing these performance charts so there take off distances are accurate is therefore of great importance for the safety of the pilot and others on board an aircraft.

There are well know equations or software that will take test data of take off distance and distance to clear 15 m as well as the weather and runway conditions and produce a performance chart by extrapolating from the data [4]. So for the performance chart to be accurate, the test data must be accurate. This however, for light aircraft, is not the case. Test pilots acquire this data 'by eye', using markers on the runway and the aircraft's altitude meters to try and determine these distances. This method is prone to human errors due to the test pilot also trying to operate the aircraft at the same time. Other factors, such as runway distance markers being laid out incorrectly, can also introduce error.

Accuracy is obtained in commercial aircraft testing by several methods, including using a Differential Global Position System (DGPS) solution, which has centimeter accuracy in surveying use. These however are expensive, with an 'off the shelf' DGPS solution staring at around £500, meaning test pilots either cannot afford them for testing light aircraft, or think that the gain in accuracy is not worth the cost. Furthermore, the altitude given by GPS is far less accurate than altitude given by an altimeter. There is therefore a need for a cheap but accurate method of collecting test data to construct aircraft performance charts. This is the goal of the project which, stated in one sentence is:

'To create a cheap module that can measure accurately take off distance and distance to clear 15 meters.'

1.2 Structure of this report

Firstly, some background will be given to current aircraft performance measuring techniques, Global Positioning Systems (GPS) and its accuracy improving systems, including Differential GPS (DGPS) and Satellite Based Augmentation Systems (SBAS). Then the project plan will be laid out, including the requirements of the aircraft performance logger module. Preliminary testing, which aided the design of the module, is described and the results and conclusions from these tests discussed. The design of both the electronics, firmware and post processing software is then discussed and design choices explained in light of preliminary testing and experience. Next, the testing of the module including static, 'terrain dynamic' and flight testing is laid out before the results and conclusion from that testing discussed. Finally, conclusions from the project are drawn which include conclusions on the testing, success of the project and suggestions for further work.

Chapter 2

Background

2.1 Aircraft Performance

To decide if an aircraft can use an airports runway, its take-off and landing distance must be known. Definitions and terms vary across aviation authorities, and there is no one definition of take-off distance. A definition of take-off distance required is needed for the project, and we shall state that a take-off consists of two stages:

1. Ground Roll: The horizontal distance from stand still to the aircraft leaving the surface of the runway.
2. Distance to clear the screen height: This is the horizontal distance it takes the aircraft to climb after lift off a certain altitude. While some use a screen height of 35 ft (10.6 m), in this project the screen height will be 50 ft (15 m)

The take-off distance required is then the sum of these two horizontal distances. This is the definition used throughout the project.

Runways also have a set of defined distances that pilots used to determine if an aircraft can take-off our land there, with the key one being take-off distance available, defined as the length of usable runway. Therefore, for a aircraft to be able to use a runway, the take-off distance required (TODR) must be less than the take-off distance available (TODA).

Take-off distance can be calculated though the appropriate equations of motion, with things such as aircraft weight, wind speed, air pressure and runway slope all accounted for. Other conditions, however, such as runway surface, are not accounted for. As it would be unpractical to calculate the TODR for each take off, TODRs for a standard set of conditions are recorded in flight manuals and pilot handbooks. There is again no standard way of displaying this result. For larger, commercial aircraft, aircraft performance charts can be used. Knowing the conditions of the day, a pilot can read off the TODR from the chart for that aircraft. For lighter aircraft, the TODR may be a single number, which can be multiplied by certain safety factors for different conditions (for example, multiply TODR by 1.3 for dry, short grass as in Appendix C). Figure 2.1 shows an example of a performance chart.

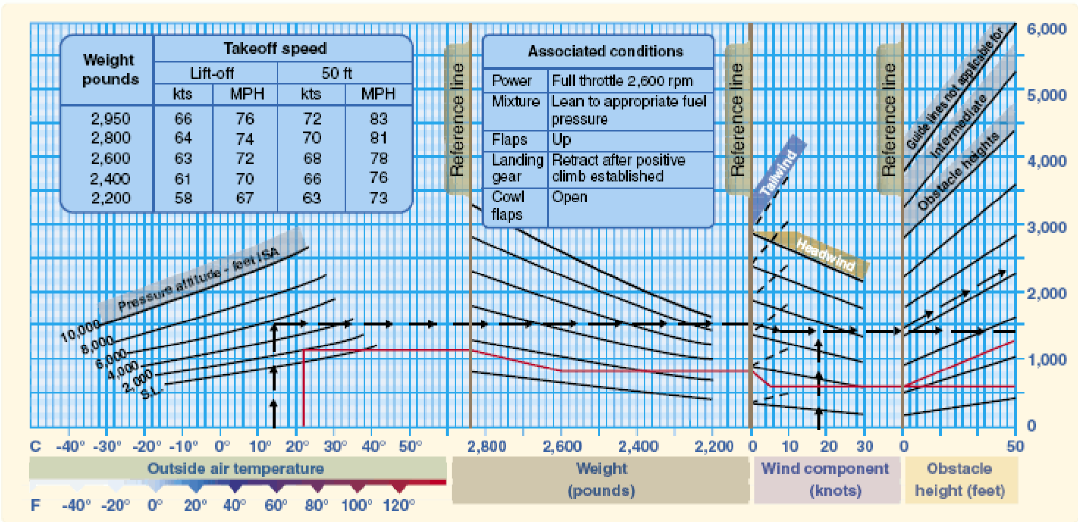


Figure 2.1: Example aircraft performance chart

2.2 Measuring Aircraft Performance

Given the importance of the value of TODR, one would assume that the measuring and recording of the value is done carefully and with great precision and accuracy. For commercial aircraft, this is true, with solutions such as differential global positioning systems and image processing or laser altimeters being used. For light aircraft however, there are no accepted methods for measuring TODR. Two methods for determining TODR and ground roll are descried below.

2.2.1 By eye approach

One of the prominent methods is a 'by eye' approach. A test pilot will use markings on the runway at known distances apart to determine the points of lift off and distance to clear 15 m. They will usually note this down on a pad rested on their leg whilst also trying to pilot the aircraft. The pitfalls with this method are clear: runway markers may not be correctly spaced, the human error involved in a pilot noting things down or using a stop watch whilst also piloting an aircraft, and not taking the conditions of the day or runway into account.

2.2.2 Trigonometry

A simple approach described by Maj Russell E. Erb [10], is to place a surveyor's transit a known distance from the runways center line. Then by measuring 2 angles, the angle of break release (θ_1) and the angle of take-off (θ_2), the ground roll distance can be calculated from:

$$s_g = d(\tan\theta_1 + \tan\theta_2)$$

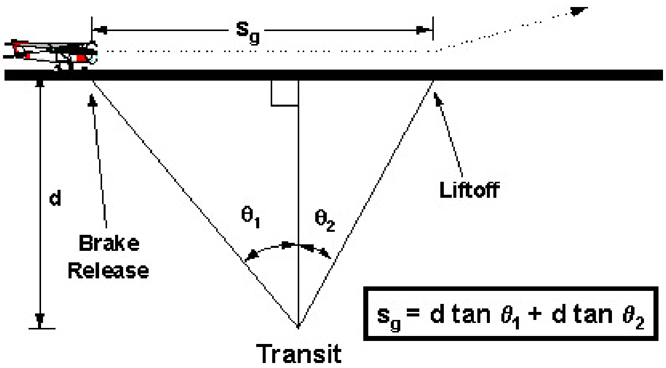


Figure 2.2: Diagram of the simple trigonometry method for measuring an aircraft's ground roll

This method, shown in Figure 2.2, is extremely simple and gives a more accurate measurement of ground roll than the by eye approach. It isn't however free from faults, one of which is how the error in distance measurement is proportional to the size of the angle measured. The derivative of the above equation shows that the error in distance measurement resulting from an error in angular measurement is:

$$\frac{ds_g}{d\theta} = d\sec^2\theta$$

So larger angles give a smaller error, suggesting that the surveyor's transit should be placed at the expected point of take off for minimum error, a place which is unknown. The method also assumes that the aircraft stays on the center line of the runway. Furthermore, the point of take-off is hard to define, and is prone to human error in seeing when the wheel leaves the tarmac. The method also requires somebody to operate the surveyor's transit, so acquiring the data needs both a pilot and a data collector.

Even if these errors are deemed acceptable, this method only measures ground roll, with a different method required to measure distance to clear the screen height. So a method that not only removes the above sources of error, but also calculates distance to clear screen height, is desirable.

There is therefore a need for a cheap, simple module that can measure the take off distance more accurately than the by eye approach, and is easier to use than the method described above.

2.3 Global Positioning System

The need for accurate measurements of location and distance lends itself to the use of a GPS solution. The Global Positioning System, developed by the United States, is a network of around 30 satellites that orbit the earth at an altitude of 20 000 km. Each satellite has atomic clocks on board and transmit information about there position at the current time. A GPS receiver can pick up these signals. If a receiver sees three satellites, it can then use trilateration to calculate its position on earth. With 4 satellites it can also calculate its altitude, and the more satellites it sees, the more accurate its prediction in location is. [18]

This calculation uses the distance between receiver and satellite and the time taken for the signal to reach the receiver. So for accurate location, the timing and distance signals must be accurate, and any errors in these signals cause errors and inaccuracy in the receivers calculated location.

The main source of error is propagation errors, which are introduced as the signal slows as it passes through the ionosphere (caused by ionized particles slowing the signal down) and troposphere (caused by changing refractive index). Deviations in satellite behaviour, including incorrect potion and number of satellites visible, also affect the accuracy of the position estimate.

2.3.1 Differential Global Positioning System (DGPS)

To overcome the error in position due to signal delay, DGPS can be used. This involves two receivers: a base receiver at a fixed, known position, and a roaming receiver.

Over time propagation errors average out to zero as they are random. So if a receiver does not move, its average location will be correct. So when a delayed signal is received from a satellite, it knows what the signal should be instead so

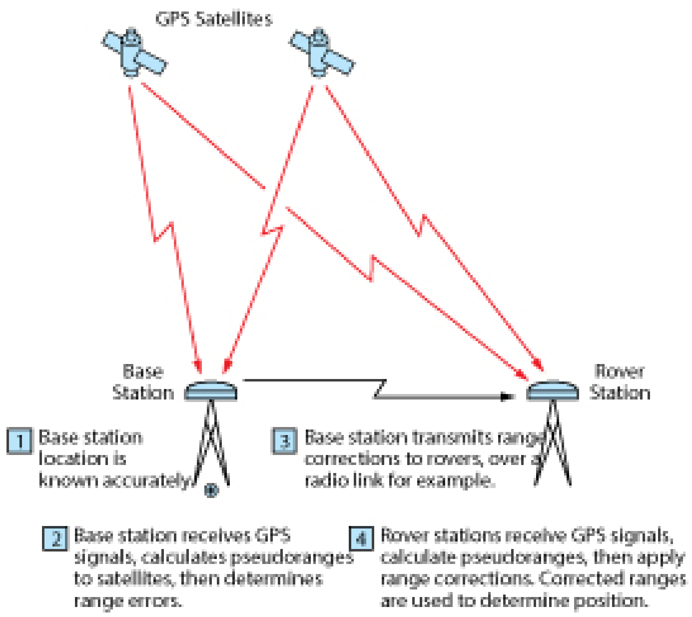


Figure 2.3: Diagram describing how DGPS works. Source: Hexagon Positioning Intelligence [12]

calculates the difference between the delayed signal and the signal it should have received from this satellite. This error for this satellite is then transmitted to a roamer station which can then correct the signal it gets from this satellite. By doing this for all the satellites both receivers see and then using these corrected signals for the position calculation, error from propagation delay can be removed. Figure 2.3 shows a diagram of how DGPS works.

DGPS greatly increases the accuracy of normal GPS from 3 m to a few centimeters for surveying grade DGPS [14]. This however comes at a high cost, with 'off the shelf' DGPS solutions for surveying costing £100s.

2.3.2 Satellite Based Augmentation Systems (SBAS)

Many GPS receivers come with Satellite-Based Augmentation System (SBAS) enabled. This delivers to the module corrections and integrity data as well as some ancillary information (timing, degradation parameters, etc.) through messages encoded in the signal [3]. The GPS module can use this information to correct errors in signals, such as those caused by propagation delays, and increase the accuracy in GPS location. This is included by default in most GPS receivers and improves the accuracy to within a meter, which is more than sufficient for most applications.

2.4 Goal of the project

The objective of this project then is to develop a 3D logger unit to be carried in the aircraft which measures distance and height very accurately.

Basic GPS alone cannot do this as its altitude measurement isn't accurate, with altitude accuracy between 1.5$\times$ [16] to 10$\times$ [7] less accurate than its 2D location. Therefore, a pressure sensor will be need for altitude measurement. Furthermore, the use of DGPS would greatly improve the accuracy of the distance measurement, but a full DGPS is far too expensive for use of light aircraft. The goal then is to create a alternative form of DGPS that is cheaper but produces some accuracy enhancement.

The project therefore involves the investigation of DGPS alternatives, before the design and manufacture of the 3D data logger. The resulting module should be cheap, small and be able to calculate TODR.

Chapter 3

Project Plan

3.1 Project Requirements

In order to aid the design of the module, the setting requirements focuses the design, and allows for a meaningful evaluation of the final design against these requirements. For this project, the module must meet the following requirements:

10 Hz Data acquisition rate

To allow a high enough resolution to determine take off and 15 m so distances can be calculated.

Measure height accurately to within 0.3m

At 15 m, this is an error of 2% which is has been deemed acceptable as it is relatively small.

Measure distance accurately to within 2m

Take-off distance required (TODR) for the aircraft the module will be tested on is 254 m, meaning an error of less than 1%, which is less than the 'by eye' approach and is a small enough error to be acceptable.

Standalone module

Can be taken from aircraft to aircraft, and have an external antenna plugged in so it has a clear line of sight with the sky. If it had to be connected to the aircraft, official testing and licensing would be required.

Removable memory

This allows for the data to be post processed, as on-board processing power will be limited.

Easy to use

A pilot has many things to do during taxi and take-off, so a module that is very simple to use is key.

3.2 Project Timeline

The project was split into 3 broad sections, corresponding to the three academic terms:

- Research phase: During Michaelmas term, investigating hardware to be used and assessing their suitability was key. DGPS alternatives where investigated. Decision where then made on if DGPS is needed as well as the architecture of the data logger.
- Design and make phase: This is where the PCB for the module is designed and fabricated, the casing designed, firmware written and post processing code written. This is to be done during Lent Term.
- Test and reporting phase. A testing plan is drawn up and a light aircraft owned by the supervisor is use for testing. The entire project will then be written up. This takes place at the end of Lent as well as during Easter term.

I elected not to plan the project in the form of a Gantt chart as with some aspects of the project being new to me, such as ECAD design, I don't know how long they take. Also, testing will be ongoing as features are added to the module and changes made to the design or software, allowing a more flexible approach to design. Instead, the project was planned by setting series of milestones to reach:

- Milestone 1: Using results from the research phase, come up with a list of design choices for module, firmware and software design.
- Milestone 2: Decide on PCB architecture.
- Milestone 3: Send PCB off to be fabricated. This means it must be designed as well.
- Milestone 4: Write completed firmware for the module, so it reads GPS and pressure sensor data and save the data to the SD card
- Milestone 5: Get take-off distance and distance to clear 15m from via post processing the data.
- Milestone 6: Successful testing of the module.

Chapter 4

Preliminary testing

4.1 Introduction

In the project brief, the idea of using a cheap version of DGPS was suggested, and so a logical starting point is the investigate cheap DGPS methods. Furthermore, to measure altitude, a pressure sensor with enough precision to meet the requirements is need. The first stage of this project then is Preliminary Testing: buying components, characterizing their behaviour and coming up with a prototype. This section of the report covers the experimentation and prototyping stage, first looking at a DGPS alternative before assessing the behaviour of the pressure sensor.

4.2 GPS

A wide range of GPS modules are available, all with different performance, output types and levels of customization. To get the experimentation started quickly, a break out board package is ideal as it would allow it to be quickly connected to a computer. Furthermore, good documentation is helpful for quick set up. While ease of use is important, the GPS module also had to have a high enough data acquisition rate and accuracy in order to meet the system requirements.

Taking all this into account, the Adafruit Ultimate GPS [2] was selected. This is a breakout board based on the MTK3339 chipset, which has the desired performance but also a large array of documentation and tools to allow for quick set up, experimentation and prototyping. Costing £30 per module, it also meet the low cost requirement.

4.2.1 Investigating DGPS alternatives

DGPS Method

As discussed in Section 2.3.1, DGPS corrects for sources of error such as propagation delay through the ionsphere, multipath, and viewing different satellites. However, if two GPS modules are not far apart and are on a flat, level surface with few obstacles such as an air field, they should see similar sections of sky so signals reaching them should have the same propagation delay, and the GPS receivers should see the same satellites. This means that their error in latitude and longitude should be the same, so the error correction could be done on the values of position, rather than on the signals themselves. This is the idea of our 'cheap' DGPS.

Consider two GPS modules, one stationary base module $\mathbf{b}$ and one roaming module $\mathbf{r}$. Over time, the readings from the base module $\mathbf{b_i}$ will drift around due to errors. The average of these readings $\bar{\mathbf{b}}$ should be the true location of the base module. Error vectors for reading at time t can then be calculated by subtracting the base reading at time t with the average location of the base module:

$$\mathbf{e_t} = \mathbf{b_t} - \bar{\mathbf{b}}$$

This error vector can be subtracted from a reading taken from a roaming GPS module $\mathbf{r}$ at the same time to get a corrected reading $\mathbf{r_{c,t}}$:

$$\mathbf{r_{c,t}} = \mathbf{r_t} - \mathbf{e_t}$$

This should then remove the error in latitude and longitude, giving 'corrected' GPS readings and is the form of DGPS that was tested.

DGPS Testing

To test this method of correcting GPS readings, 2 modules where placed at a fixed distance apart for a length of time. One module was used as the base module, and each roaming station reading ($\mathbf{r_i}$) was matched to the base location reading taken at the same time ($\mathbf{b_i}$). The correction method described above was applied to give 4 possible data sets:

1. Raw, uncorrected data.
2. Corrected roaming and unaveraged base.
3. Uncorrected roaming and average base.

4. Corrected roaming and average base.

The great circle distance between any two readings can then be calculated and Figure 4.1 shows a plot of the great circle distance between two points minus the true distance apart (91.44m due to the length of the rugby pitch) plotted over time.

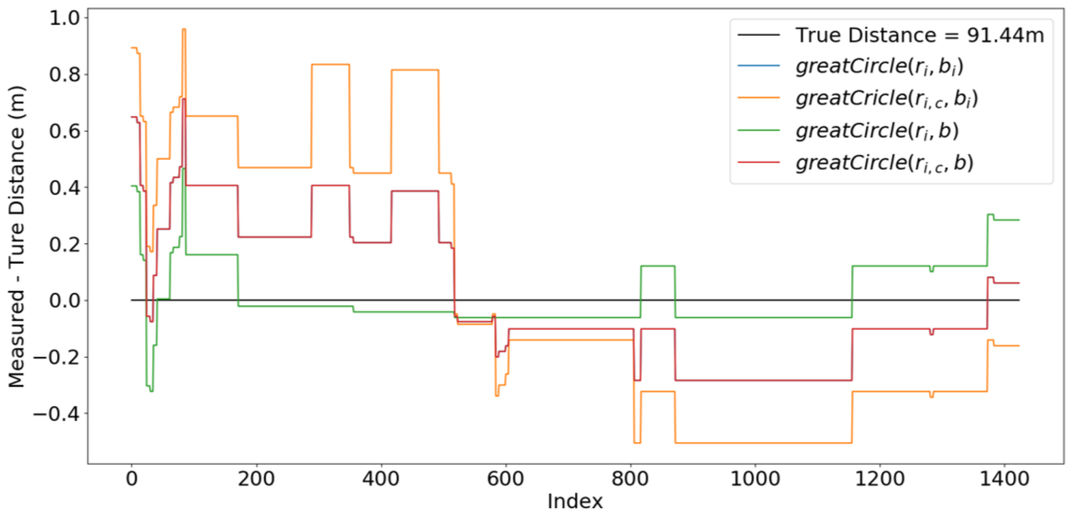


Figure 4.1: Plot of the error in distance between two points over time. b_i represents a base module reading and b the average base location reading.r_i represents a raw, uncorrected roaming station reading while $r_{i,c}$ a corrected roaming reading

Interestingly, the distance between uncorrected base $(\mathbf{b_t})$ and roaming $(\mathbf{r_i})$ readings (blue line, not visible) is the same as the distance between the average base location $(\overline{\mathbf{b}})$ and corrected roaming $(\overline{\mathbf{r_{t,c}}})$ readings (red line, on top of blue line). This makes sense as by subtracting the error vector $\mathbf{e_i}$ from both $(\mathbf{b_t})$ and $(\mathbf{r_t})$, the distance between the two points has not changed as $\mathbf{e_t}$ is parallel to itself.

One thing that does improve the accuracy and removes large jumps in readings is by using the average base location $(\overline{\mathbf{b}})$ and the uncorrected roaming readings $(\mathbf{r_t})$, as this removes the variation in the base location. Of course this could be further improved by averaging the roaming receiver location but this would be counterproductive when the roaming receiver starts to move, such as when taking off. However if we average the location of the module when sat still before taking off we can use that average location the measure distances from, which should improve the distance accuracy.

4.2.2 GPS Data Acquisition Rate

The GPS receiver has a variable data acquisition rate can can be set to 1,5 or 10 Hz. In the requirements of the project, a 10 Hz data acquisition was suggested in order to have a high enough data resolution to measure distances and precisely find the point of take off. However, the MTK3339 chipset supports SBAS (discussed in Section 2.3.2) up to data acquisition rates up 5 Hz, suggesting the accuracy of readings at 10 Hz is less than that of 1 Hz and 5 Hz.

To test this, the GPS module was placed stationary in a field, allowed to obtain a location fix and then logged data for 10 minutes. Table 4.1 shows the mean and standard deviation in latitude and longitude as well as the maximum variation in distance at each frequency.

Statistic	1 Hz	5 Hz	10 Hz
μ_{lat}(decimal degrees)	52.201457	52.201462	52.201493
μ_{lon}(decimal degrees)	0.0993762	0.0993744	0.0993608
$\sigma_{lat}(\times 10^{-6})$	2.610	3.985	7.020
$\sigma_{lon}(\times 10^{-6})$	3.363	3.834	0.9329
$\delta d(m)$	1.44	1.68	2.60

Table 4.1: Results of the data acquisition rate test, showing standard deviation in latitude, longitude and greatest distance between two points

As the table shows, the 1 Hz and 5 Hz agree well, having similar variation and position. At 10 Hz however, there is a larger variation and the location doesn't agree. This is because the SBAS (described above) is disabled above 5 Hz, even if the NMEA sentence says it is active. Without SBAS, the datasheet claims the position accuracy drop from 2.5 m to 3 m. This explains the greater variation in position and the shift in position, as the GPS module isn't making the signal corrects as it hasn't received the data to do so. This means there is a trade off of having a high data acquisition rate for greater resolution when moving at take off speed, or a lower acquisition rate to ensure better accuracy in position.

4.3 Pressure Sensor

As with the GPS module, quick and easy prototyping was desirable when choosing a pressure sensor. This meant a break out board that could be hooked up quickly to an Ardunio was necessary. Furthermore, a module with support and expansive

Arduino library would be useful. The pressure sensor also had to have a high enough data acquisition rate and accurate readings to within a meter for use as an accurate altimeter. Considering all these criteria, the Altitude/Pressure Sensor - MPL3115A2 Breakout board from SparkFun electronics [5] was selected. At a price of £12.82, it was also low cost.

Pressure readings are sensitive to a multitude of external factors, including temperature and dynamic effects. In order to characterize the sensor and see if it was a viable choice or corrections in readings where needed in was important to test how temperature affected readings.

4.3.1 Drift in readings

The pressure sensor also comes with a built in temperature sensor, meaning the effect of temperature on pressure can be seen.

To test this, the pressure sensor logged pressure and temperature at 5 Hz (the data acquisition rate chosen due to the SBAS system of the GPS) for 30 minutes. The readings are then plotted over time, as shown in Figure 4.2

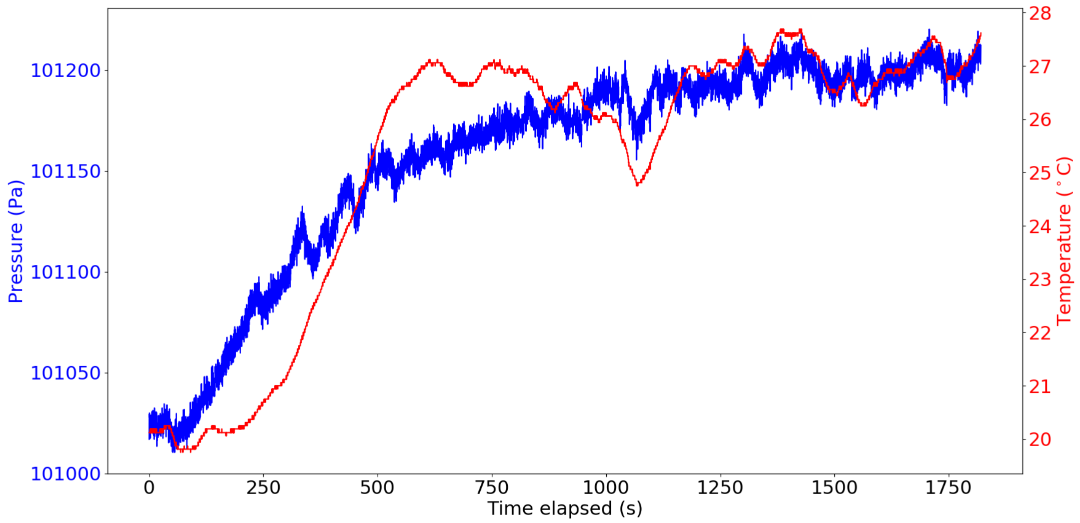


Figure 4.2: Plot of pressure and temperature over time

The weather conditions when this test was carried out where 11.8 °C and 100 900 Pa according to the Digital Electronic Group readings [9]. The pressure from the sensor initially agrees with the reading from [9], but as the module sits in the sun and the temperature rises, so does the pressure. Also, variations in temperature cause variation in pressure. This is to be expected as the ideal gas law states $p \propto T$.

The large discrepancy in temperature readings from [9] and the module can be down to a number of factors, including the black enclosure absorbing more heat, the module being sat in the sun for a while, the surrounding building of the college court, and its own self heating. The large heating up effect however can be mitigated by allowing the module to warm up before use. Furthermore, these readings where taken over 30 minutes, while a take-off last for a minute or so, meaning a large change in temperature is unlikely, meaning drift in pressure readings shouldn't be a problem.

If the module was to be used to measure climbs at greater altitudes, the change in temperature is an issue. The pressure sensor works using a piezoresistive MEMS sensor in a Wheatstone bridge arrangement [see page 2 of datasheet 5], meaning that it is sensitive to temperature changes and its own self heating. The pressure sensors datasheet claims that it has some self calibration to mitigate this, but it can be seen from both Figure 4.3.1 and in 4.3 that it has not completely removed this heating effect. The equation of the line of best fit gives a temperature coefficient for the pressure sensor of $19.81\,\mathrm{Pa}\,{}^{\circ}\mathrm{C}^{-1}$ so this could be used to compensated for temperature changes. However, for use in measuring take-off, allowing the pressure sensor to warm up should be enough to overcome the problem as there are no large changes in temperature at low altitude. For measuring other parameters, such as rate of climb between 1000 and 2000 feet, this compensation may be required.

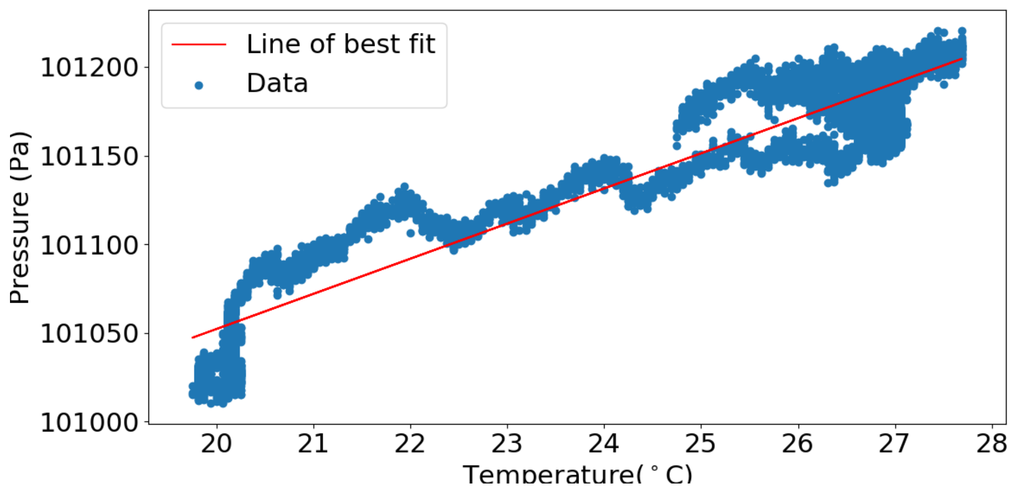


Figure 4.3: Plot of pressure vs temperature for the test above. Line of best fit has equation $P = 19.81T + 100656$ with an r-value of 0.9447

4.3.2 Comparing altimeter and GPS readings

The reason for including a pressure sensor to measure altitude is that the altitude readings from GPS are not as accurate as using pressure. This can be seen from comparing the altitude readings from the pressure sensor from the test above with those from the GPS module, as shown in Figure 4.4. While the altimeter readings do vary and there is a considerable amount of noise, their readings of altitude are much more accurate than the GPS module and agree much better with each other, justifying the need for an altimeter in the final module.

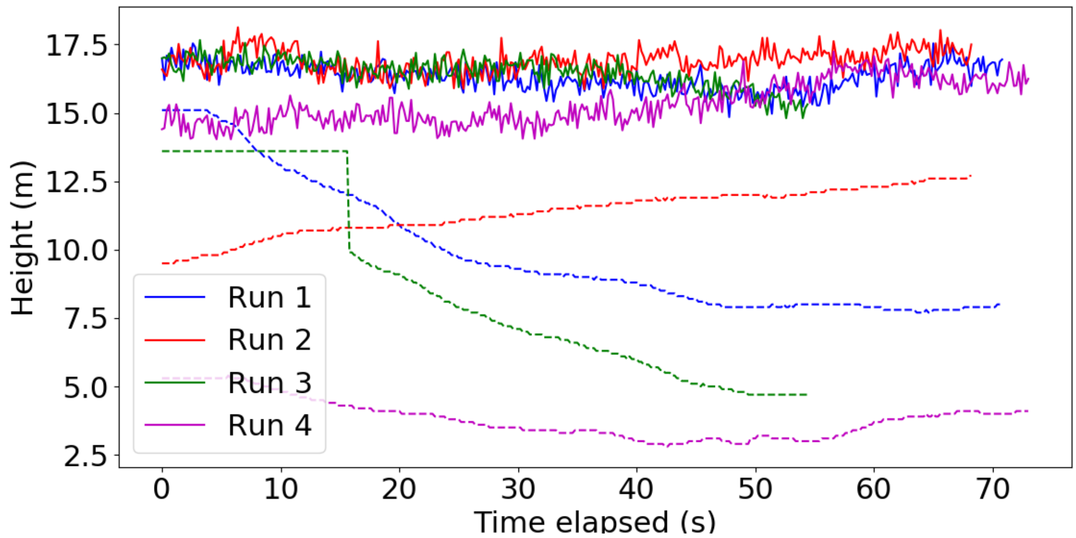


Figure 4.4: Plot comparing the height read by the pressure sensors and the GPS module. True height of test location is 16 m above sea level

4.4 Conclusions from experimentation

From this preliminary testing it was found that:

- The 'cheap' DGPS does not increase the accuracy of positioning as subtracting the calculated error vector either adds error (in the $greatCircle(r_{i,c}, b_i)$ case) or makes no difference (in the $greatCircle(r_{i,c}, b)$ case). Furthermore, any increase in accuracy isn't sufficient enough to warrant the design of another module, so 'cheap' DGPS will not be used.
- While the GPS module can operate at 10 Hz, the SBAS correction that it can do to improve accuracy can only operate up to 5 Hz. Therefore operating at 10 Hz decreases the accuracy of the module but does increase the resolution of

the data. Considering this trade off, it was decided to lower the data acquisition rate to 5 Hz as the increase in accuracy outweighs the loss in resolution.

- Taking the average base location of a module improves distance accuracy. This can be applied to the aircraft by requiring it to remain stationary before take-off and then averaging its start location. This will be applied in the final design.
- As the pressure sensor warms up or the ambient air changes temperature, the changes the pressure reading. Also other conditions such as wind affect pressure readings. So the pressure sensor on the device will need to be isolated to try and keep it at a constant temperature and shield it from wind in order to measure the true ambient pressure.
- The testing of the accuracy of a pressure sensor versus a GPS module for altimeter measurement confirmed the need for an altimeter sensor in the final module.

The results from this testing allowed for design choices to be made or modified, and this is discussed in the next chapter.

Chapter 5

Design

5.1 Introduction

Taking forward the conclusions from preliminary testing, the design of the module itself was the next step of the project. In this design, several factors were considered. Not only did the preliminary testing results affect several design choices, how the user interacts with the module must also be considered. Furthermore, the way in which the data is post processed is a large part of the project and care must also be taken in its design. In this section, both the design of the hardware, firmware and software are discussed, describing any choices made and why they where made. The final module is shown and described and then a description of how the module is used is given.

5.2 Circuit Components

5.2.1 Micro-controller

The choice of Micro-controller unit (MCU) was driven by several factors:

- The GPS module communicated via UART, meaning the MCU had to have serial pins or pins that could be programmed to act as serial pins.
- The pressure sensor is an I2C deice, meaning the MCU must also have I2C pins
- The SD card reader communicated via SPI, so the MCU must also have SPI pins.

- Sufficient programmable space and memory was required in order to interface with these 3 sensors.

At the start of the project, it was planned to program a MCU in PICBASIC pro. However, considering the time spent on getting the sensors to work with the Arduino Uno, it was decided that writing the drivers and code for these modules in PICBASIC would be too time consuming. Furthermore, all the modules came with extensive Arduino support and documentation, meaning that if the firmware could be written in the Arduino language, time could be saved in this part of the project.

It was therefore decided to use the ATmega328/P MCU [6] as this come with 1 UART, 1 I2C and 2 SPI interfaces, as well as 32KBytes of flash, plenty of room for the Audion firmware (see section 5.4). Choosing it in the 32-pin TQFP package also meant it could be soldered on by technicians within the department.

5.2.2 Enclosure

Before PCB design was started, it was important to specify the dimensions of the PCB and the module. It was briefly considered if 3D printing a case for the electronics was the way forward, but the additional time and effort required to design and make such a case was an issue. Instead, a standard enclosure was purchased and alternations made for things such as switches and lights. A 2910 Series Mobile Case [1] was selected as it looked small enough for the module to be portable but large enough to fit the required electronics. It also came with mounting holes for the PCB and a battery compartment with removable cover.

This enclosure allowed for a 64x56 mm PCB to fit inside the enclosure, with mounting holes 44 mm apart length ways and 52 mm apart width ways.

5.2.3 Sensors

It was briefly considered whether buying the none breakout board versions of the pressure sensor an GPS module used in preliminary testing would be beneficial. However, given the size of the chosen enclosure and the extra cost involved in buying more sensor, it was decided that the breakout versions of these sensors would be used in the final module. Also, the GPS module came with an antenna attachment, meaning one need not be designed and made.

5.2.4 SD Card

In order to save data form the module to be processed later, some form of readable storage was required. The MCUs EEPROM could not be used as is too small to hold enough data for several runs. It was decided to store the data on an SD card which could be read by a computer later on. Also an microSD card comes in a number of sizes to allow as much test data to be stored on it as required. The Adafruit MicroSD card breakout board+ [17] was chosen because it is compatible with the Arduino language, which comes with a standard SD card library.

5.2.5 Power

The MCU an sensors can be driven at a wide range of voltages between 3 and 5 volts, and 3.3V was selected as it is a standard. For the module to be portable, it must have on board power, such as a 9V battery. It therefore decided to use a 9V battery and a voltage regulator provide power to the board. The Analouge Devices ADP7118AUJZ-R2, LDO Regulator [13] was chosen in an adjustable package and then design rules followed in the data sheet to give an output voltage of 3.3 V [see page 13 of 13].

A 9V battery has a capacity of 500 mAh, and the final design draws 90 mA when collecting data. This means that the module should be able to run for 5 hours and 30 minutes before needing to replace the battery.

5.2.6 Additional features

Status LEDs

3 LEDs are used to give the status of the module. One is connected to the GPS modules 'FIX' pin, and flashes if the GPS has not got a location fix. The other two are connected to digital pins of the MCU and are used to indicate to the user the state of the module. These states, and the corresponding state of the switch, are described in Figure 5.1.

Switch

A switch, connected to an analogue pin on the MCU and the 3.3V supply, is used to switch the recording of data on and off.

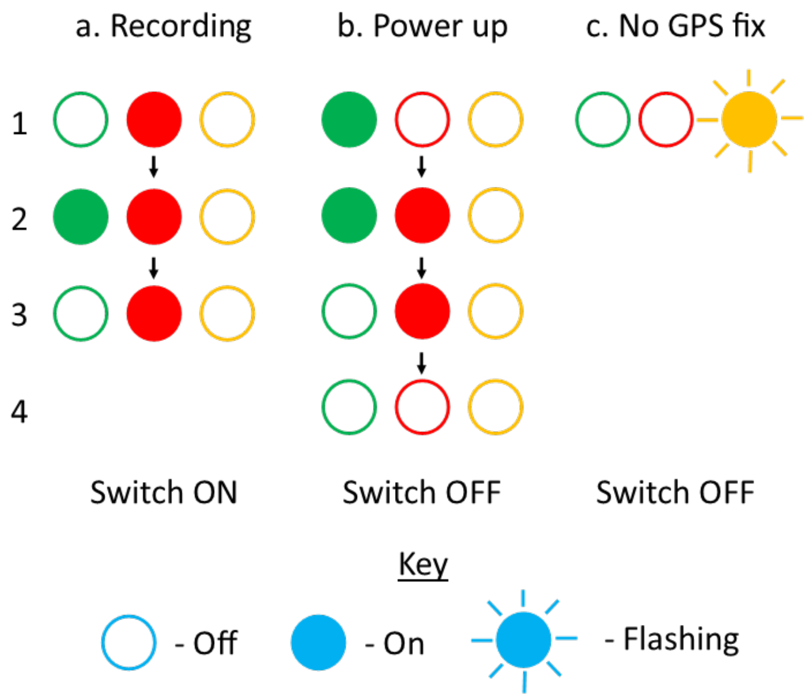


Figure 5.1: LED status of the module an what they describe: a) recording including the 3 stages 1. 5 second pause to let the GPS readings steady, 2. begin recording data but remain stationary for 5 seconds and 3. Module is recording and pilot can start a test run, b) Power up, cycling through the LEDs to show module has been turned off, and c) Flashing yellow LED to indicate GPS has no location fix

Antenna

The GPS module is contained within the enclosure, so does not have a line of sight to the sky. The module therefore requires antenna connected that can see the sky. The GPS module comes with a uFL connector which can be connected to a GPS antenna via a uFL to SMA adapter. The GPS module will automatically detect if an antenna is connected itself. The RF Solutions GPS Antenna ANT-GPSC-SMA SMA [11] the antenna was chosen.

5.2.7 Material Cost

One of the criteria of the module is that it be cheap. Table 5.1 shows the overall cost of all the components. Ignoring manufacture costs, the overall module comes to less than £60, fulfilling the low cost criteria. Furthermore the cost of this prototype will be more than if the module is manufactured in bulk because of the additional cost of extra components, such as GPS or SD card mounts, during development. Therefore, if the module was to be put into production as a TODR measuring system, it would

Item	Cost
GPS Module	£30.48
Pressure Sensor	£12.82
SD Card	£6.86
Voltage Regulator	£2.89
ATMega328/P	£1.42
Enclosure	£4.43
Total	£58.90

Table 5.1: Breakdown of the cost of the module components

fulfill the low cost requirement.

5.3 Circuit Design

Circuit design and PCB layout was done in KiCAD, with PCB fabrication done in the departments Electronic Design Group. All design files can be found in the projects Github repository [8], and the circuit schematic can be found in Appendix B.

5.4 Firmware Design

The choice of the ATmega328/P was made to make writing the firmware for the module as easy as possible. This MCU is the same as that used on the Arduino Nano, and can have an Arduino boot loader burned onto it via its SPI pins. This meant that the firmware could be written using the Arduino software and loaded onto it via the MCUs serial pins, meaning the libraries used to read the GPS, pressure sensor and SD card in preliminary testing could be used in writing the firmware. This meant time was not spent becoming familiar in another language, such as PICBASIC, or searching for/writing C drivers for the modules.

The firmware written, when the record switch is flicked, waits for 5 seconds before then continuously reading data from both the pressure sensor and GPS module and saving it to the SD card. The firmware ensures each run saves data to a different files and numbers readings sequentially so that the post processing can match the pressure and GPS readings that were taken in the same iteration. This is because the pressure sensor has no inbuilt timer so reading cannot be time stamped unless they are paired with the GPS readings. Recording stops when the switch is turned off and the firmware operates on the status LEDs. Figure 5.2 shows a flowchart of the firmware design.

One issue with using the ATmega328/P with the Arduino boot loader on is the small amount of memory available for programming. 2048 bytes can be used for both global and local variables, and if more than 75% of this is used for global variables, stability issues can occur. This lead to the data not being written to the SD card or the data being unreadable on the SD card. Care had to be taken in writing the firmware to ensure that it did not use too much memory and that it worked properly. This also means that the data processing couldn't be done in real time, and post processing was required.

5.5 Post processing Design

The addition of removable storage means that the data gathered from the module can be processed after testing. Therefore the post processing software needed to be written.

As with the data processing in Preliminary testing, this code was written in python due to availability of the NMEA sentence parser micropyGPS [15], as well as it lending itself to numerical data processing. The code had to parse the data from the SD card, calculate the start location, distance traveled and change in height. Form this it could then compute TODR and distance to clear 15m, as well as plot the results. Figure 5.3 shows a flowchart of the cod design and the code itself can be found in the project GitHub page [8] or the attached memory stick.

5.6 Final module

Figure 5.4 shows a selection of images of the module, as well as captions detailing what they show.

5.7 Module use

5.7.1 Module

The SD card slot is found by the battery compartment. Insert the microSD card into this slot before powering on, and only remove the SD card when the module is not recording and the battery is disconnected.

To power on the module, connect the battery. Cover the battery compartment and SD card slot with the compartment lid.

Attach an antenna to the module via the SMA connector at the top of the module.

The status LEDs give information on the state of the module (see Figure 5.1. Before pressing the record switch, wait for the yellow FIX LED to stop flashing.

Flick the switch into the record state, the red REC LED should turn on for 5 seconds, for which the aircraft should remain still. The green STABLE LED will then turn on for 5 seconds, where the aircraft should also remain stationary. One the green LED switches off and only the red LED is lit, a take-off run can began.

When a test is complete, flick the record switch to the off position.

Each test runs data is numbered sequentially starting from 1, with GPS files saved as 'GPSX' and pressure and temperature readings saved as 'PREX' where X denotes a number. In order to keep the numbers of the files related to the test number (ie 'GPS2' is the GPS file that related to the second take-off run), ensure that no other GPS or PRE files are in the home space in the SD card, either by moving other data to a different file (such as the date of the day those files where collected), deleting them, or saving them elsewhere. This is extremely important as the GPS and PRE files are paired by the use of their number so if any old files are left, the post processing software may pair the wrong pressure data to GPS data, giving incorrect results.

5.7.2 Post processing

With reference to Figure 5.5, the method of determining ground roll and TODR is:

1. The run data of distance vs height is plotted.
2. Assuming a linear rate of climb, the line of best fit for the climbing phase is calculated.
3. This line is extended for the entire run (orange line).
4. The average height for the runway is plotted and extended for the length of the whole run (green line).

5. The point where these two lines intersect is the take-off point, and the distance from the start to this point is the ground roll.
6. The point where the orange line of climb is 15 m above the runway height is the point where the aircraft has climbed 15 m. The distance from the start to this point is the TODR.

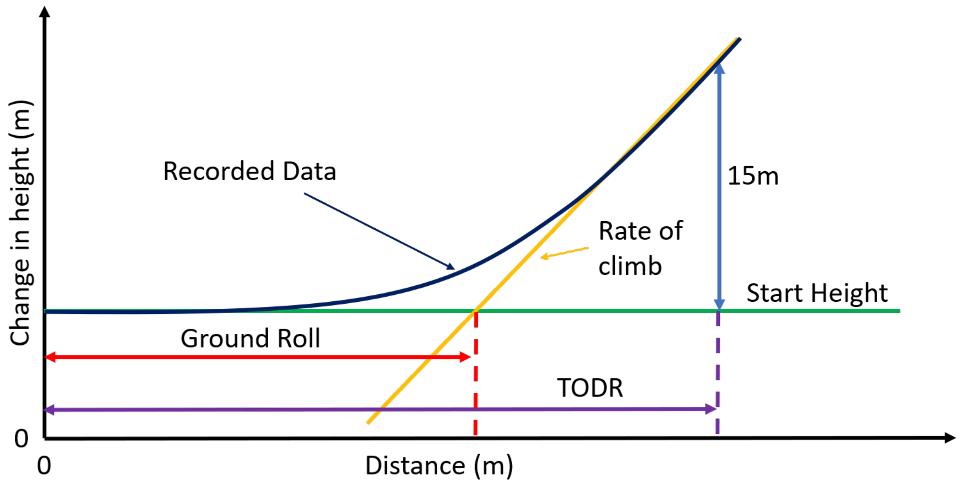


Figure 5.5: Diagram of how the post processing software calculates ground roll and Take-off distance required (TODR)

The linear rate of climb line has an equation $y = mx + c_1$, where m is the rate of climb (no units) and c_1 the y intercept (meters). The start height has the line $y = c_0$,

The take of point is the intersection of these two lines, that is:

$$mx + c_1 = c_0$$
$$\therefore \text{Ground roll} = x = \frac{c_0 - c_1}{m}$$

While the TODR is when the line of best fit reaches a y value of 15 meters ($y = 15$), meaning the TODR is:

$$\text{TODR} = x = \frac{15 - c_1}{m}$$

This is the method that is planned to be used with the aircraft test data, but may change in light of data and results. This is discussed in the next chapter.

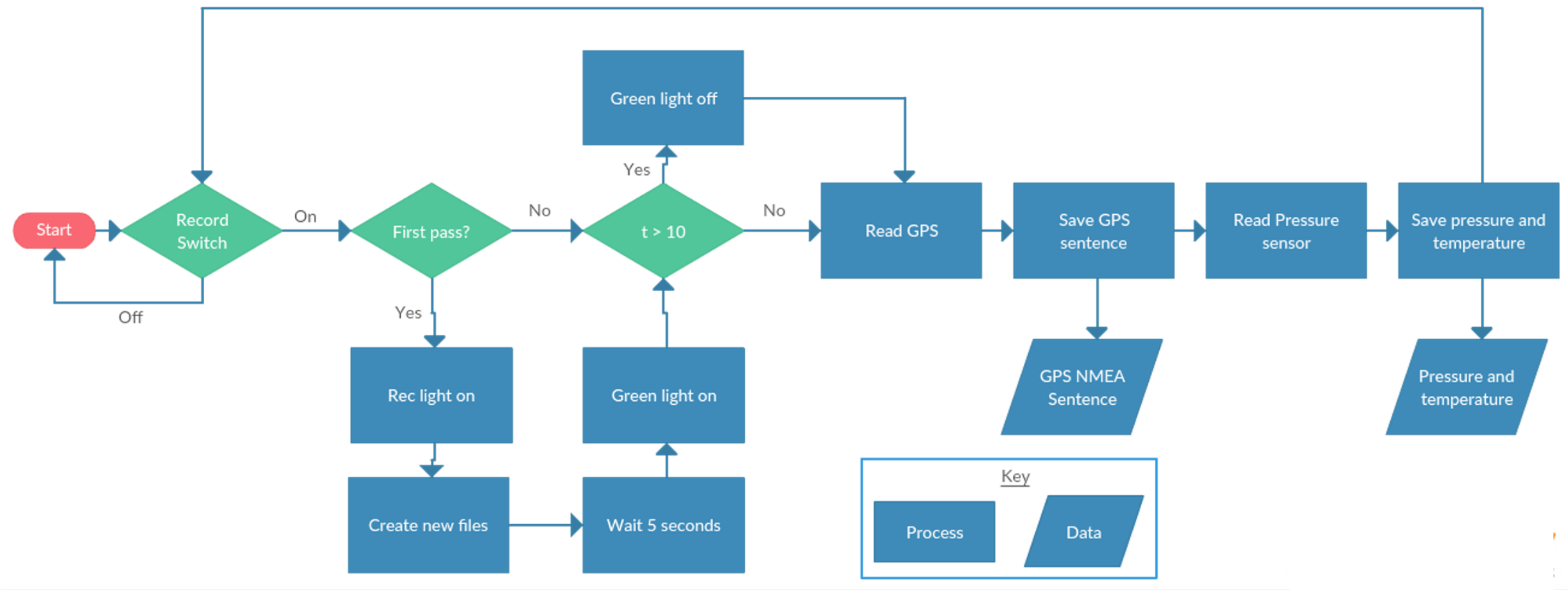


Figure 5.2: Flowchart of the modules firmware design

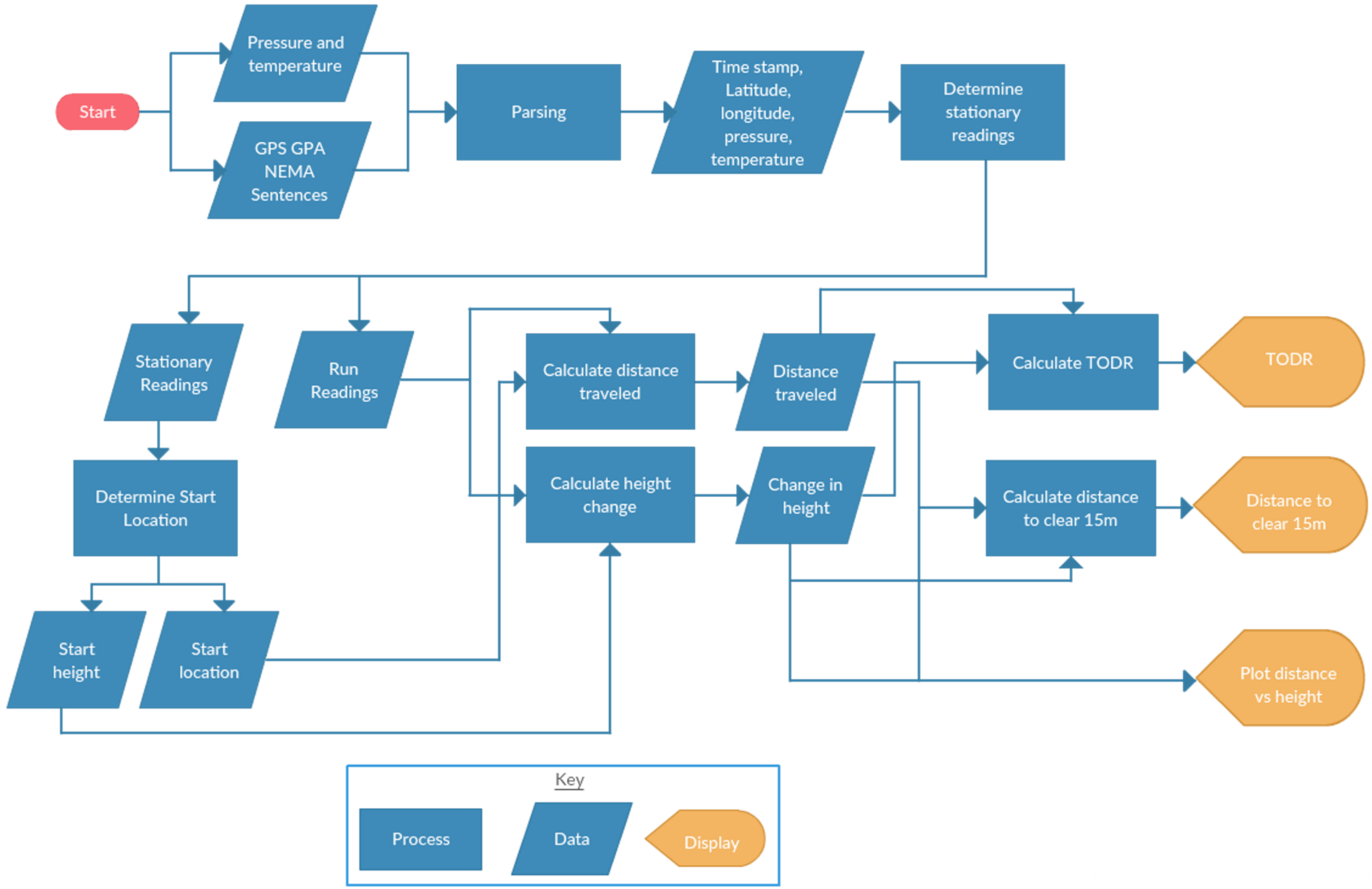


Figure 5.3: Flowchart of how the module data is processed to compute TODR and distance to clear 15m

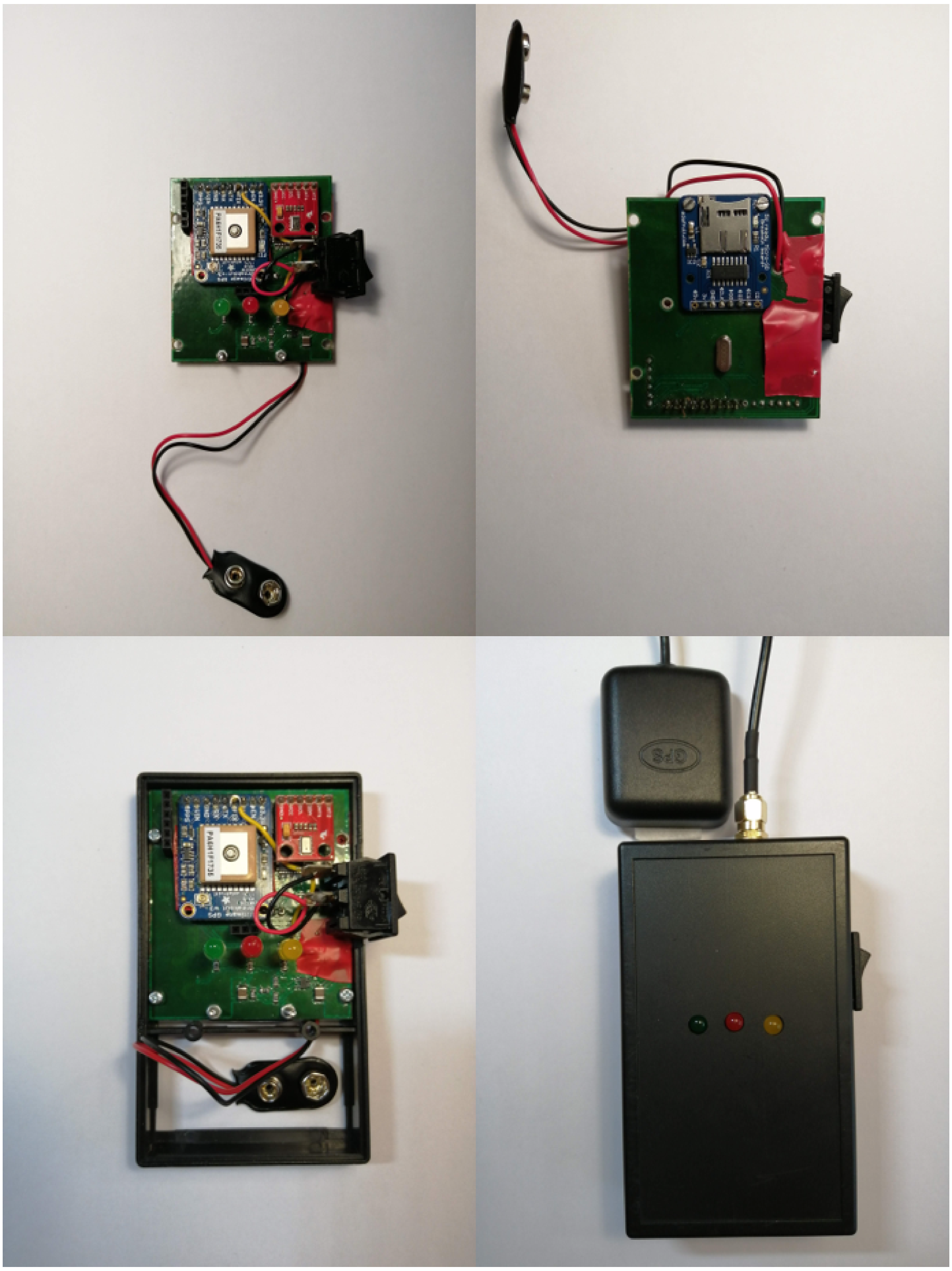


Figure 5.4: Top left: Top view of circuit board. Top right: Bottom view of circuit board. Bottom left: Circuit board installed in the enclosure. Bottom right: Complete module with status LEDs and antenna

Chapter 6

Testing and Results

6.1 Introduction

With the module now made, its performance must be assessed through testing. Data must also be collected to aid the development and troubleshooting of the post processing software and module firmware. In this section, the testing carried out is described and the result gathered from testing are discussed. These results are them summarized in the conclusion to this section.

6.2 Non-flight testing

Before taking the module flying to acquire a data set, some 'terrain testing' was carried out as a proof of concept, and to test the accuracy of the module.

6.2.1 Distance Test

The key measured parameter of the module is the distance travelled, be it take-off distance or the distance to clear 15 m. After it was decided the DGPS was not needed in light of the results from section 4.2.1, it is important to test the accuracy of the distance measurement returned by the module and the post processing method.

To test this, 100 m was measured out using a surveyors tape measure, and the module was walked this 100 m 10 times, 5 times in each direction. In order to keep the module at a constant height it was fixed to a bike, with the start and end of each test run being the point where the front fork passed the marked out 100 m

Run	Distance (m)
1	101.4962409
2	98.33538936
3	97.3355641
4	98.1994995
5	99.33234359
6	99.32957048
7	99.94672569
8	99.08727754
9	99.65247642
10	99.03089823

Statistic	Value
μ	99.17459858
σ	1.064372273
MSE	1.814175833
RMSE	1.346913447

Table 6.1: Results from the 100 m walk test (left) and statics from the results (right)

point. The distance is then calculated the same way it would be for take off: taking the average of a 5 second stationary reading period (averaging 25 readings) to get a starting point, then calculating the great circle distance between each reading and this average start point. The module was turned off as it passes the 1100 m mark so the distance measured by the module was taken to be the maximum calculated distance. These results are shown in Table 6.1

The first thing to note is how the majority of readings fall slightly short of the 100 m. This could be because when laying out the tape measure, if it isn't perfectly straight due to laying it out in wind, then the true distance may be slightly shorter. Secondly, the stopping of the GPS may have been done just before the 100 m mark. Also, with the data acquisition rate being 5 Hz, the module could have stopped recording just before the next measurement was taken. In this time (0.2 s), and taking the average walking speed to be 1.4 m s^{-1}, this means the reading could be out by 0.29 m due to resolution. This could become an issue at take off speeds. The TODR data for the test aircraft (Appendix C) lists its manoeuvring speed (V_a) as 72 Knots (37 m s^{-1}), which means the resolution at that speed is 7.4 m. The results above show that the distance is accurate to within 1 to 1.4 m, which meets requirement to measure distance to within 1.4 m. Some interpolation of results may be required when it comes to measuring TODR in an effort to overcome the decreased resolution due to aircraft speed.

6.2.2 Climb testing

To test the height measuring capabilities of the module, it was ridden on a bike up a hill 5 times. The change in height vs distance for each of these 5 runs is shown in Figure 6.1.

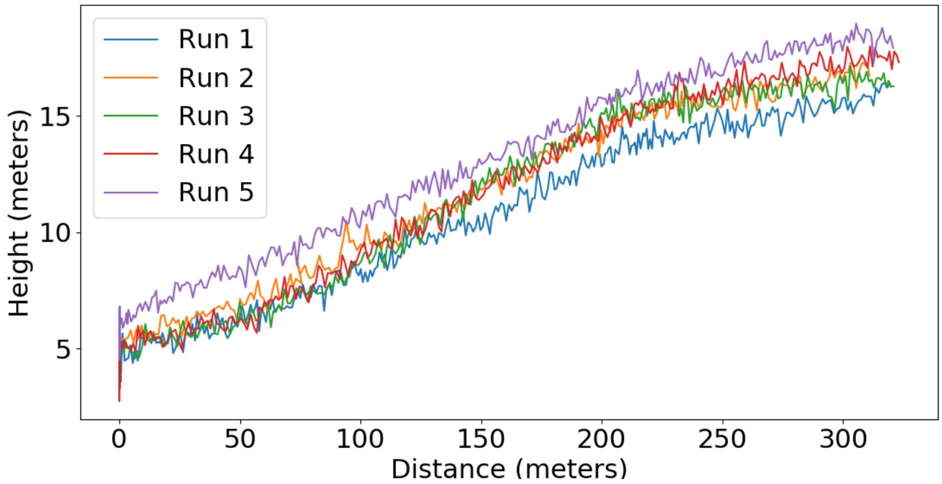


Figure 6.1: Plot of change in height over distance for 5 runs up the same hill

All the results show the same climbing profile, but are quite noisy readings. In order to obtain pressure readings at 5 Hz, the pressure sensor readings become more noisy [see page 5 of data sheet of 5], as less samples are taken an averaged to produce a reading (called oversampling). At 5 Hz, the over sample ratio is 64 which means the minimum space between readings in 138 ms [5].

In an effort to reduce the noise, some moving averaging filtering could be introduced. In order to not introduce a time delay, the averaging window must be centralized. Care must be taken in choosing both the size of the window and the window function. To larger window size will hide small and sudden changes in height, such as those caused by turbulence but a too small window will be ineffective in removing the noise in the readings.

6.2.3 Flat test

In the same runs that where used to collect data for the distance test in Section 6.2.1, pressure data was also collected. Figure 6.2 shows these results as a plot of change in height over distance. This data allows us to characterize the noise of the pressure sensor fully, and in a much more quantifiable way than in Section 4.3.1. Taking the average change in height as 0 m, the Root Mean Squared Error (RMSE), as well as Standard Deviation, can be calculated for each run. These results are shown in Table 6.2.

The results from this show that the pressure sensor has an error of around 0.8 m when reading static pressure.

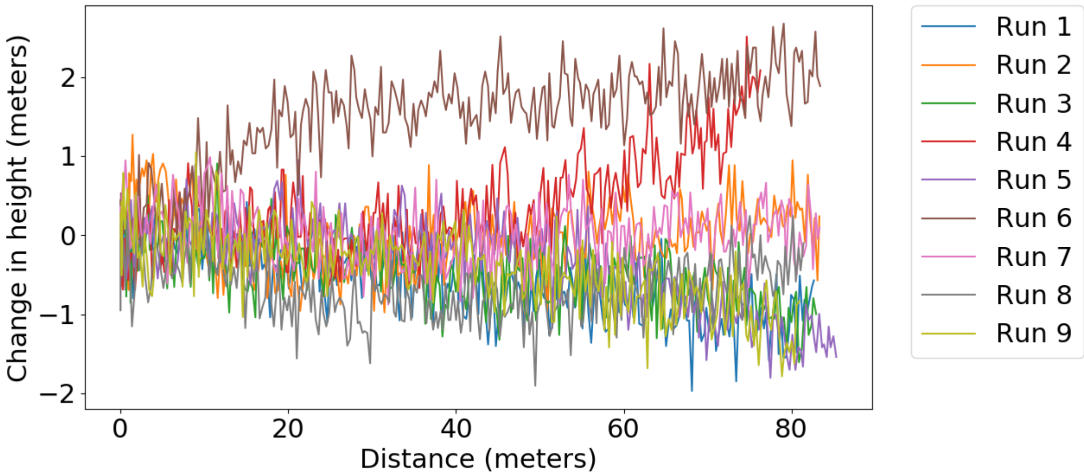


Figure 6.2: Plot of distance vs change in height for the distance test

Statistic	Value
MSE	$0.638\,\mathrm{m}^2$
RSME	$0.799\,\mathrm{m}$
σ	$0.795\,\mathrm{m}^2$

Table 6.2: Statistics from the pressure sensor readings

6.3 Flight Testing

For flight testing, a small single engine aircraft was used, with the antenna and module mounted on the dashboard in the cockpit, as per Figure 6.3. 3 test flights were carried out, with data collected in slightly different ways:

- Flight 1: A standard take-off, circuit and landing was conducted with only the pilot in the aircraft. The module recorded data for the entire flight, including the 10 second stationary period for the module to get an average start location.
- Flight 2: A standard take-off, circuit and landing was conducted with only the pilot in the aircraft, the same as in Flight 1 The module recorded data for the entire flight, but without the 10 second stationary period.

- Flight 3: A standard take-off was conducted before a small ‘pleasure flight’ was conducted with the pilot and a passenger. The module recorded the take-off only, including the stationary 10 second period.

An example of a test circuit, as well as its altitude profile, is shown in Figure 6.4

Figure 6.3: The aircraft the module was tested on (left) and the module installed in the cockpit of the aircraft (right)

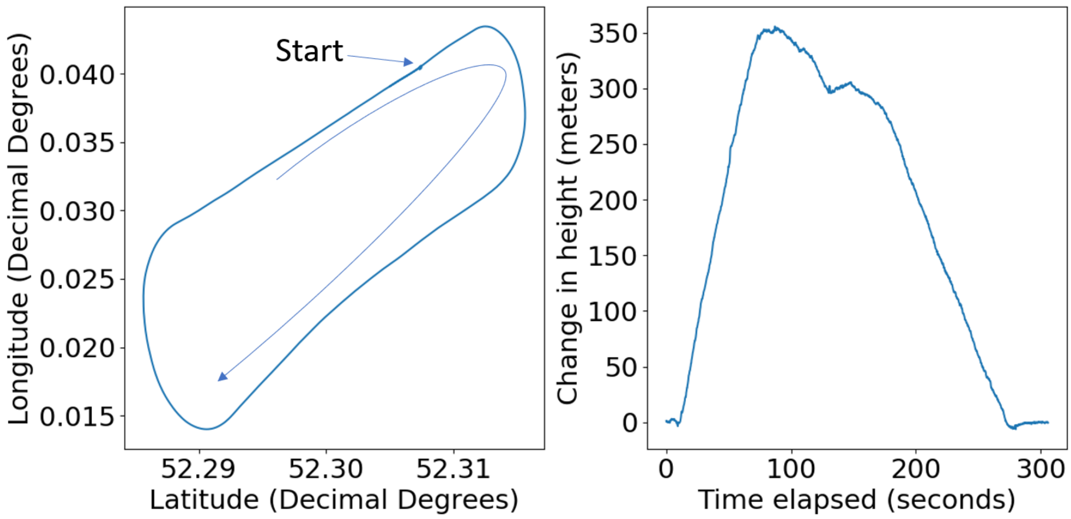


Figure 6.4: Plot of latitude and longitude for Flight Test 1 (left) and the change in height profile for Flight test 1

The TODR data for the aircraft can be found in Appendix C, and gives the TODR after applying the safety factor of 1.3 to be 254 m, which is 195 m without the safety factor. It is unknown how this value was measured or if the aircraft had a passenger or not, so direct comparisons between the values calculated here and the handbook value are hard, but this value can be used as a ballpark estimate of the TODR.

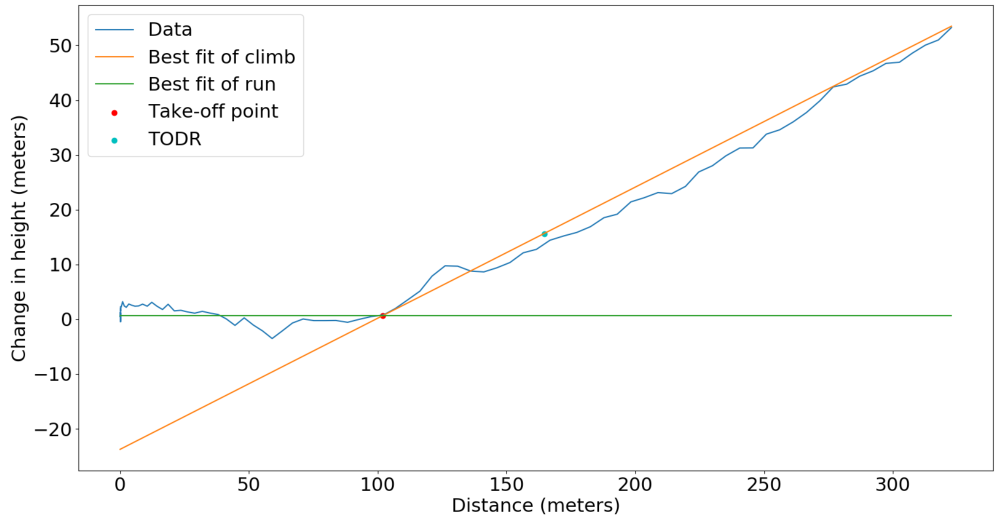


Figure 6.5: Change in height vs distance for take-off run 1

Statistic	Distance (m)
Ground Roll	101.91
TODR	164.58

Table 6.3: Results from take-off run 1

6.3.1 Flight 1

The results from this flight are plotted in Figure 6.5, with statistics being presented in Table 6.3.

Firstly, the calculated TODR value is here -15.9% different from the given value. As discussed in the introduction, the TODR varies hugely with conditions such as wind speed, air pressure, and runway slope and take-off weight, so an exact match was unlikely. However, the value is very close, and if the TODR was taken from the actual data and not from the line of best fit it would be even closer to the true value.

Secondly, the method that has been chosen to calculate ground roll and TODR may slightly over estimate the ground roll. This is most clearly seen in both Figure 5.5 from the Design section and in the next flight. This method is chosen however as it is hard to determine the exact point of take off. For example, a height threshold is hard to set as the runway may slope up or down, as is the case at the airstrip where this test was carried out. Also, with the error in the pressure sensor meaning readings in height can jump by as much as 0.8 m, an instantaneous rate of climb cannot be used as it may choose an erroneous pressure reading as the point of take off.

6.3.2 Flight 2

The results from this flight are plotted in Figure 6.6, with statistics being presented in Table 6.4.

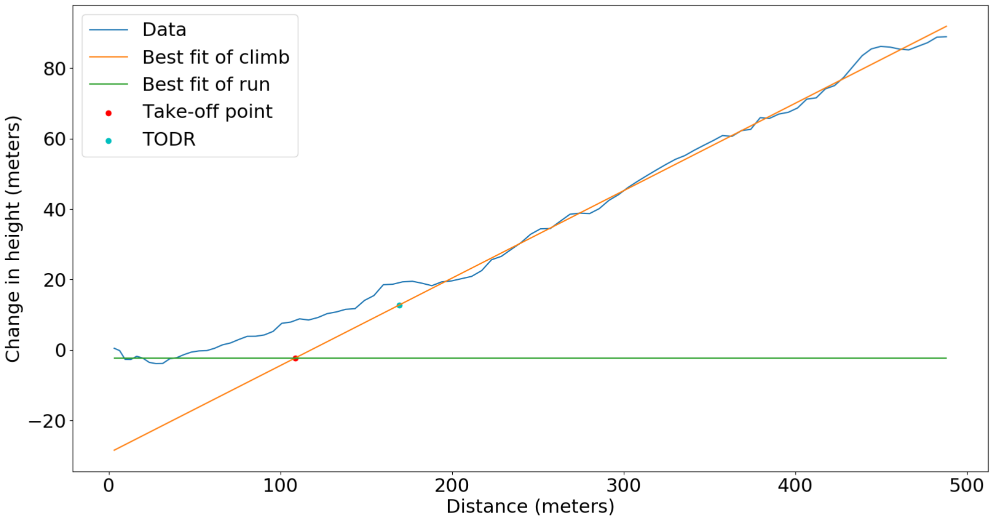


Figure 6.6: Change in height vs distance for take-off run 2

Statistic	Distance (m)
Ground Roll	108.57
TODR	169.09

Table 6.4: Results from take-off run 2

The values for ground roll and TODR between flight 1 and 2 agree well, with Ground roll being 6.54% different and TODR being only 2% different. In this run, the average base location was not taken as the run had started before the green light had switched off, so the very first reading is taken as the start location. This however could explain what appears to be the massive overestimation of the ground roll, as it appears the actual data is 10 m above this point. This could also mean that the TODR point as also been overestimated. Further test runs would be required to confirm this.

6.3.3 Flight 3

The results from this flight are plotted in Figure 6.7, with statistics being presented in Table 6.5.

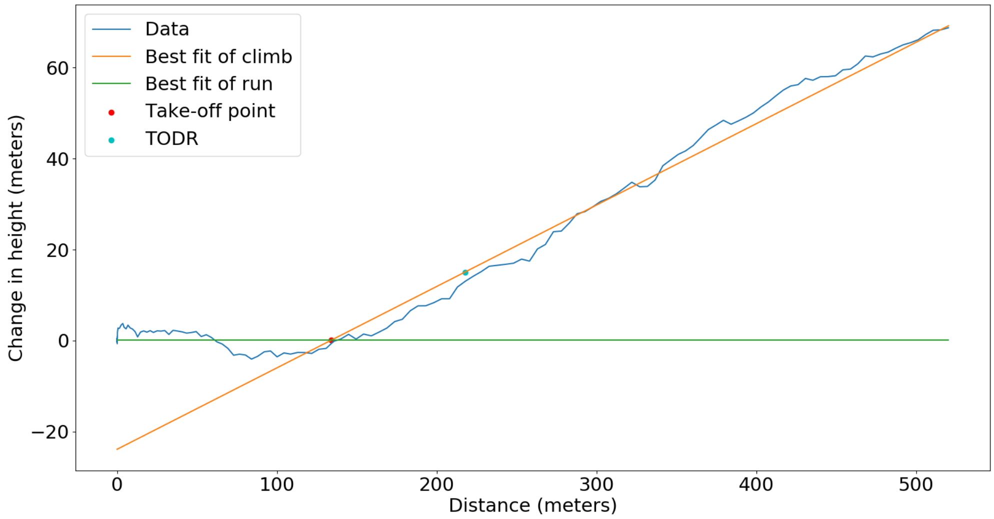


Figure 6.7: Change in height vs distance for take-off run 3

Statistic	Distance (m)
Ground Roll	133.82
TODR	217.64

Table 6.5: Results from take-off run 3

This run had a passenger on board, and with the aircraft being small this means a significant percentage increase in weight, which in turn increases the ground roll and TODR values. In this run, the ground roll and TODR don't appear to be as overestimated as in flight 2, suggesting that the lack of a confirmed start location in flight 2 causes the large overestimation.

The TODR value for flight 3 (see Table 6.5 is 11.6% greater than the quoted value with no safety factor applied due to the additional weight.

The results from flight 1 and 3 therefore suggest that the module and post processing are suitable for measuring TODR and ground roll, giving results close to the quoted value.

6.3.4 Landing

The module can also be used to measure landing distance required (LDR) with some modification. In this testing, a test landing (where the aircraft comes to a complete stop) was not carried out, so LDR could not be calculated. The calculation would be as simple as measuring the distance between the stop point and the point the aircraft was 15 m above the point the aircraft came to a stop. Figure 6.8 shows a landing profile, with distance defined as negative before the stop point.

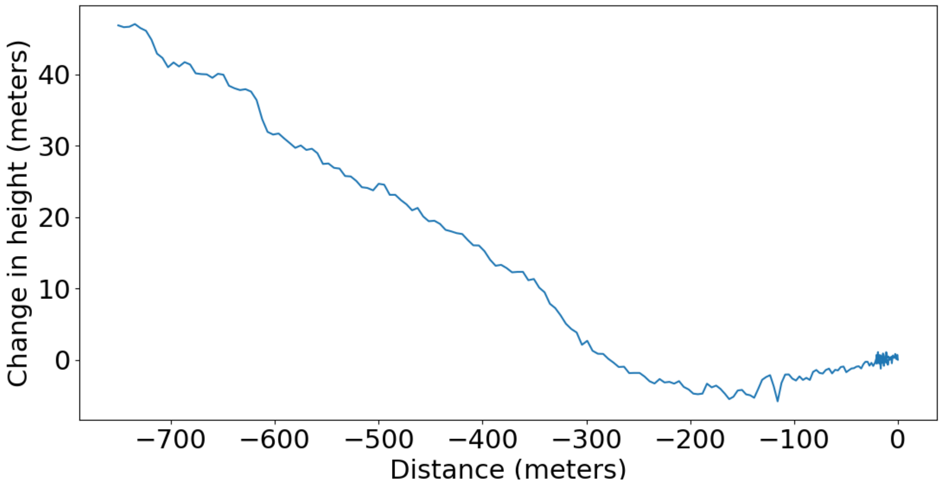


Figure 6.8: Plot of change in height vs distance for the flight 1 landing, taking the last recorded data point as the stop point.

6.3.5 Sources of error

The plots and values presented in the above sections are prone to numerous sources of errors and analysis of these errors, in absence of fully accurate test data to compare the performance of the module to, can aid in the evaluation of the module against its performance criteria as described in the project requirements chapter.

Airspeed

In Figure 6.5 and Figure 6.7, there is a large jump in the height measurement at a distance of 0 m, a jump which is more clearly seen by plotting the pressure over time for this initial period in flight 1 and 3. These jumps are shown in Figure 6.9 and 6.10 respectively.

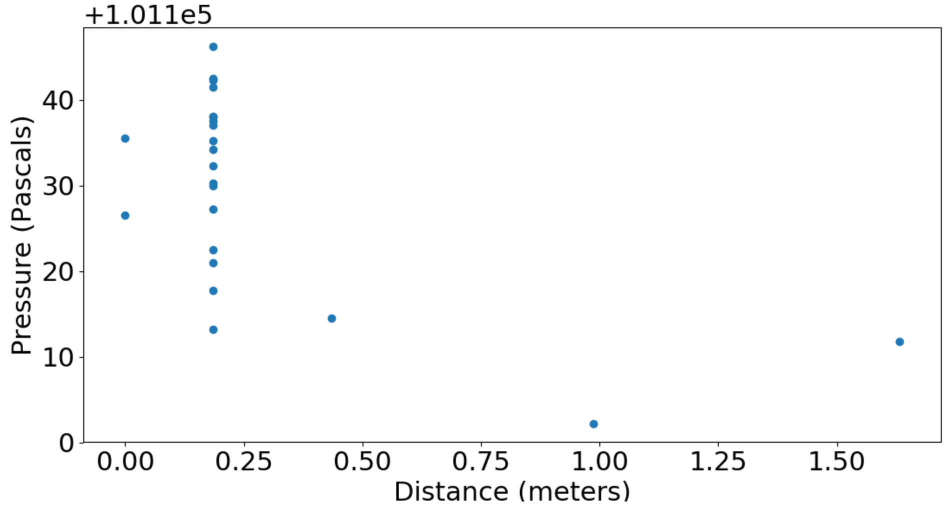


Figure 6.9: Plot of early pressure readings vs distance from Flight 1

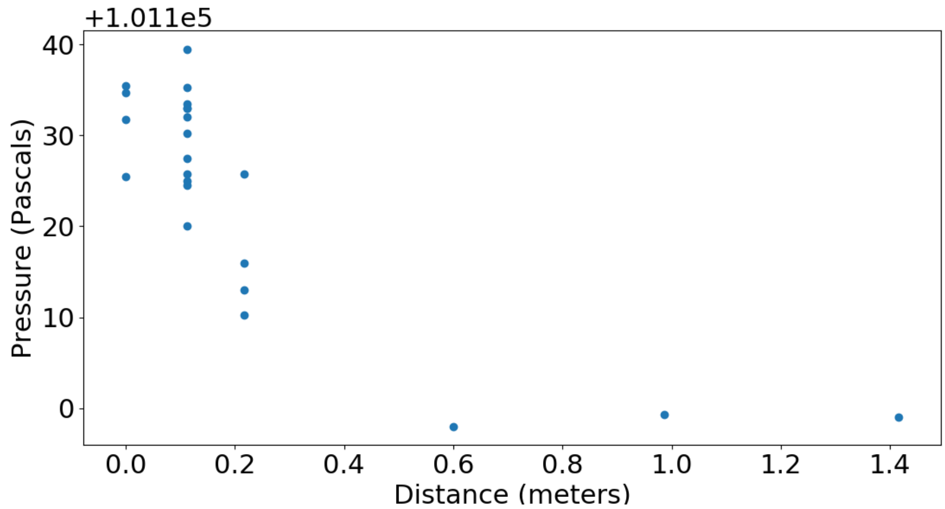


Figure 6.10: Plot of early pressure readings vs distance from Flight 3

One theory as to the source of the jump is that the propeller wash is decreasing the measured pressure. As the plane initiates take-off, the propeller increases its speed. This increases the air velocity through the propeller and in the cockpit. This increase in speed will cause a decrease in the measured pressure.

Consider Bernoulli's principle before and after take off is initiated. Before the propeller is turn up to full speed, the pressure and air speed are p_1 and v_1 respectively. After the propeller is turned up to full these change to p_2 and v_2. Bernoulli's principle states that:

$$p + \frac{1}{2}\rho v^2 = Constant$$

Assuming this is time-invariant, for the two cases:

$$p_1 + \frac{1}{2}\rho v_1^2 = p_2 + \frac{1}{2}\rho v_2^2$$
$$p_2 - p_1 = \frac{1}{2}\rho\big(v_1^2 - v_2^2\big)$$

Since $v_2 > v_1$, $\frac{1}{2}\rho\big(v_1^2 - v_2^2\big) < 0$. Meaning that $p_2 < p_1$. So as propeller speed increases, pressure reading decreases.

To see if this theory is correct, we can look at the pressure readings just before the aircraft starts moving in flight 3, shown in Figure 6.10 Reading from Figure 6.7, the worst case jump in height is 3.44 m. The temperature of the day of the test was 30 °C as measured by the pressure sensor, meaning the air density (assuming international standard atmosphere) was $1.1644\,\mathrm{kg\,m^{-3}}$. The rate of change of pressure with respect to height is given by:

$$\frac{dp}{dh} = -\rho g = -1.1644 \times 9.81 = -11.423\,\mathrm{Pa\,m^{-1}}$$
$$\therefore \frac{dh}{dp} = -0.0875\,\mathrm{m\,Pa^{-1}}$$

From Figure 6.10, the two points with the largest difference in pressure are $p_1 = 101\,140\,\mathrm{Pa}$ and $p_2 = 101\,098\,\mathrm{Pa}$, which is is a difference in pressure of 42 Pa. Multiplying this by the rate of change of height with respect to pressure:

$$\Delta h = 42 \times 0.0875 = 3.675\,\mathrm{m}$$

Results from the flat test suggests that the errors in pressure reading give an error in height of ± 0.8 m. Meaning that the jump in height due to propeller speed is between 2.875 m and 3.475 m, which includes the measured jump in height, suggesting that the jump in height is caused by the change in propeller speed speeding up the flow of air over the pressure sensor.

The same analysis can be carried out for flight 1. Figure 6.9 shows the early pressure readings for the flight, to see if this is also the cause of its sudden jump of 3.2 m in height as shown in Figure 6.5:

$$p_1 = 101\,146.25\,\mathrm{Pa}, \quad p_2 = 101\,113.25\,\mathrm{Pa} \implies \Delta p = 33\,\mathrm{Pa}$$
$$\therefore \Delta h = 33 \times 0.0875 = 2.888 \pm 0.8\,\mathrm{m}$$

So the true change in height is between 2.088 m and 3.688 m, which again includes the measured jump in height, and further supporting the theory that the wash from the propeller is the cause in the jump in height.

Aircraft speed on GPS

With a data acquisition rate of 5 Hz and a measured take off speed of $20\,\mathrm{m\,s^{-1}}$, it means that the distance between two readings is around 4 m. So, if the method of calculating TODR picks the point either side of the true 15 m height, the result can be anywhere in an 8 m range, which is 4 time greater than the proposed 2 m accuracy in distance. The use of the line of best fit and interpolation may be able to solve the problem, but without accurate data to compare the measured TODR to, it is hard to evaluate this method.

Aircraft speed on pressure

The effect of the speed of the air due to the propeller has already been discussed, but the dynamic pressure caused by the aircraft speed during take off must also bee considered. Considering Bernoulli's principle again, the total pressure p_t is the sum of the static p_0 and the dynamic pressure $\frac{1}{2}\rho v^2$:

$$p_t = p_o + \frac{1}{2}\rho v^2$$

As the pressure sensor measures the total pressure, it is important to consider the effect of dynamic pressure.

The velocity term will have two components, the part from the aircraft's velocity and the part from the propeller wash. The initial jump in pressure as discussed is caused by the sudden increase in propeller speed and therefore the increase in propeller wash. During take-off we can assume that this wash is constant and that, for a flat runway, the change in dynamic pressure is caused by the change in aircraft speed.

We can look at this by plotting the aircraft speed (as measured by the GPS) versus pressure, and this is shown in Figure 6.11. $R^2 = 0.8455$, suggesting that the pressure measured follows the model suggested by Bernoulli. That is, $p_t \propto v^2$, suggesting that the dynamic pressure from aircraft will effect total pressure and therefore the calculated change in height. However, theses in height are also prone to error in the pressure sensor itself, as well as the runway not being flat, possible wind gusts and using aircraft speed and not true wind speed, so more data would need to be collected in a more controlled environment to fully quantify this error.

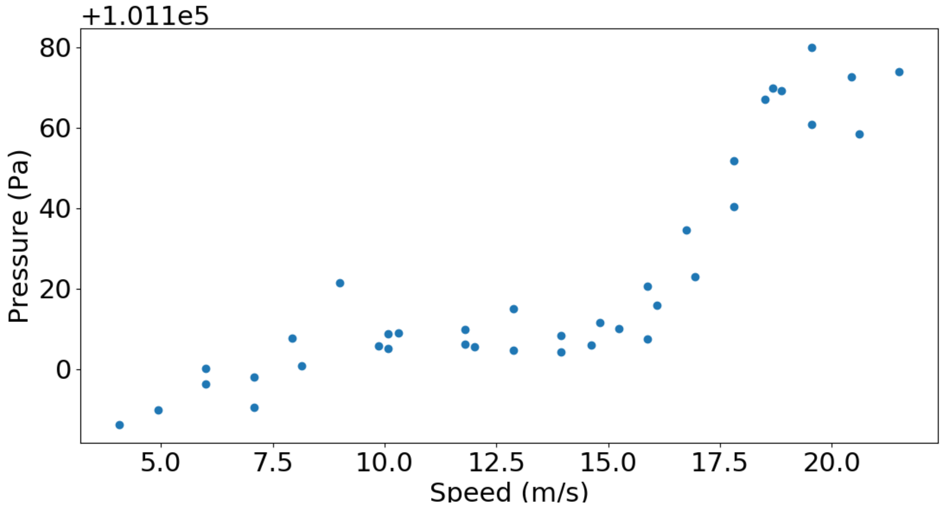


Figure 6.11: Plot of speed vs pressure for the runway portion of take-off of flight 3. $R^2 = 0.8455$ assuming a quadratic model

6.4 Conclusions from Testing

From this testing it was found that:

- The GPS with a 5 Hz data acquisition rate and the averaging of the start location gives distance accurate to within 1.4 m, which meets the accuracy requirement in the project plan without the need for DGPS.
- The pressure sensor can repeatedly measure the same increase in height, making it suitable for the use in measuring take-off.
- The variation of the pressure reading at the higher data acquisition rate of 5 Hz (quicker than the default pressure sensor setting) means a height variation of 0.8 m, which is already bigger than the required 0.3 m before dynamic effects are considered.
- The method discussed in the design section for determining ground roll and TODR works well, but may slightly overestimate ground roll. This is more of an issue when the module isn't used correctly and there is no average start location, as is seen in flight 2.
- The error in GPS is mainly due to effect the lower data acquisition rate has on the data resolution, and wouldn't have been improved with the addition of DGPS.
- Errors in pressure readings during flight come from 2 sources:
  - The effect of the propeller wash causes a large apparent jump in height at

the start of around 3 m, due to the sudden jump in air speed and hence dynamic pressure. If this wash is assumed to be constant during take-off, this can be taken into account during the calculation of TODR.

- The effect of the aircraft speed also increases the dynamic pressure and therefore the measured total pressure, but this effect is much smaller than the effect of propeller wash.

Chapter 7

Conclusions

7.1 Conclusions from Results

At the start of the project, the idea was to use DGPS alongside an accurate pressure sensor to create a 3D datalogger for an aircraft. In the end a 3D data logger was produced, but the DGPS idea was abandoned. This was because in preliminary testing the proposed method of 'cheap' a DGPS produced no accuracy improvements, and sometimes made the accuracy worse. Furthermore, for the majority of needs, an uncertainty of 2 m only meant a 1% uncertainty or less in distance measures, which is both good enough for the majority if cases, and much better than the 'by eye' approach that this method aimed to replace.

The project brief also suggested a 10 Hz data acquisition rate. It was found however that above 5 Hz the modules SBAS system, which helps with improving the accuracy of the GPS, is disabled and results in a large drop in accuracy. The trade off between more accurate location data at a lower resolution was considered but in the end the added accuracy of SBAS was decided to be more important, meaning a 5 Hz data acquisition rate.

The final module then only used GPS and gives accurate enough distance. The use of a pressure sensor for altitude was found to also be needed due to the inaccuracy in using GPS to measure altitude. While the pressure senor chosen quoted an accuracy of 0.3 m, this was in static testing with its oversampling at maximum. In 5 Hz data acquisition mode, this oversampling had to be turned down, decreasing the accuracy in static testing to 0.8 m. In flight testing the effect of aircraft speed and propeller wash further complicated measuring height using the pressure sensor. But if during take-off the propeller wash is constant then this can be accounted for.

In testing the module did produce values for ground roll and TODR that agreed well with the quoted value. It was hard to fully quantify the accuracy of the results due to lack of flight testing, standardized take-off producers, and not knowing how the quoted TODR value in Appendix C was acquired, both in how the take-off was carried out and how it was measured.

7.2 Design Evaluation

A successful design should meet most, if not all, the criteria. These criteria may have changed in light of test results, and some may have not been feasible. This is discussed below.

10 Hz Data acquisition rate

The results from the preliminary testing fond that the SBAS was disabled on the GPS module at data acquisition rates above 5 Hz. This led to a an increase in variation of distance by almost a meter (54% increase). This loss in accuracy was deemed to be more of an issue than the loss of resolution at 5 Hz, and with the decision not to use DGPS, increased accuracy at a lower data acquisition rate was deemed to be more important. This requirement was therefore changed to be a data acquisition rate of 5 Hz, which was met.

Measure height with accuracy to within 0.3m

While this is possible at lower data acquisition rates according the the pressure sensors datasheet, at the data acquisition rate required it is not. Furthermore, the affect of aircraft speed and propeller wash mean this requirement was not feasible.

The pressure sensor has an error of 0.8 m in static testing, with the adding uncertainty of around 1 m due to aircraft speed. Propeller wash can be ignored as it should be constant for the duration of take-off, meaning the error in height reading is 1.8 m overall, which is an error at 15 m of 12%. So while the requirement has not been met, this is still a relatively small error and is still an improvement on the 'by eye' approach, which was the aim of this project.

Measure distance with accuracy to within 2m

In static land testing, this requirement was achieved, with a RMSE of 1.4 m, under the 2 m required. In flight testing, this accuracy is limited by the data acquisition rate and the speed of the aircraft, as well as the difficulty in choosing the exact point of take-off. All of these issues would not have been solved by the use of DGPS, as that only solves the errors in the GPS readings themselves, not any errors caused by the choice of take-off point or the ambiguity in height caused by the error in the pressure readings.

Standalone module

The module was designed to be a small, hand held module within an enclosure. It is powered via a battery and can have antenna attached. This requirement has been met.

Removable memory

The addition of an SD card reader on the module allows the data to collected and processed, meaning this requirement has been met.

Easy to use

The module itself has status LEDs to inform the user of the its state, and only a single switch recording on and off. The post processing only needs the path to the required data file to be entered in order to get the ground roll and TODR data.

7.3 Suggestions for further work

The main goal of this project as been achieved, with a creation of a cheap module that can measure accurately take off distance and distance to clear 15 m. During the project though some ideas on how the project could be extended or improved where discovered.

The module can collect pressure and GPS data for all of a aircraft's flight. This data can be further processed to find out other performance characterize of an aircraft, such as the rate of climb between 1000 feet and 2000 feet (304.8 m to 609.6 m), a common performance parameter. Therefore some additional post processing can be done to extract even more performance data from an aircraft.

The module was designed to be stand alone, allowing it to be carried in an aircraft, meaning it can only measure the ground speed using the GPS module. To measure airspeed, and therefore adjust altitude readings, the module would need to be connected to an aircraft's pitot-static system, which would require official testing and licensing. The development therefore of a second module that could be used in official aircraft testing that can be connected to the aircraft's pitot-static system is of interest to see if pressure and altitude readings can be improved via compensating for airspeed.

Additionally, in the non-flight testing it was suggested that a smoothing filter could remove some of the noise present in the pressure readings. Some investigation into the best type of filter could be carried out. For example, if a moving average filter was chosen, the choice of window type and size could reduce the noise, but at a risk of obscuring actual sudden changes in height or pressure.

Finally, creation of performance charts involves the collection of take-off data and the conditions of the day, including wind speed, pressure, temperature and runway gradient. These take-off distances can then be standardized to some predetermined standard conditions through the use of Herrington's method [4] [10]. Then, by reversing this method, the take-off distance for any set of conditions can be determined, and a performance chart plotted. The data from this module then, with additional post processing, can be used to create performance charts for aircraft, providing more information then a simple quoted number and safety factor, such as that found for the test aircraft in Appendix C.

7.4 Success of the project

At the start of project, the goal of creating a cheap module that can measure accurately take off distance and distance to clear 15 m was set. The final result is a module and post processing package that can easily calculate the ground roll and TODR values. While the accuracy is less than originally intended, and the idea of a cheap DGPS abandoned early on, the final result still meets the requirements set in the project brief and those set out in this report. If the suggestions for future work are followed, not only can the accuracy be improved, but a fully fledged aircraft performance module can be developed that would be invaluable in obtaining key aircraft performance parameters.

Appendix A

Risk Assessment Reflection

In the risk assessment filled out in at the start of the project, the main hazards identified where:

- Soldering: The use of solder leads to fumes and a hot soldering iron is a hazard. Soldering as to be carried out in the EIETL in a well ventilated area, and lead-based solder was not to be used.
- Hand held tools: In the modification of an enclosure, saws, drills and files where used. Care was to be taken and appropriate PPE wore when using hand tools.

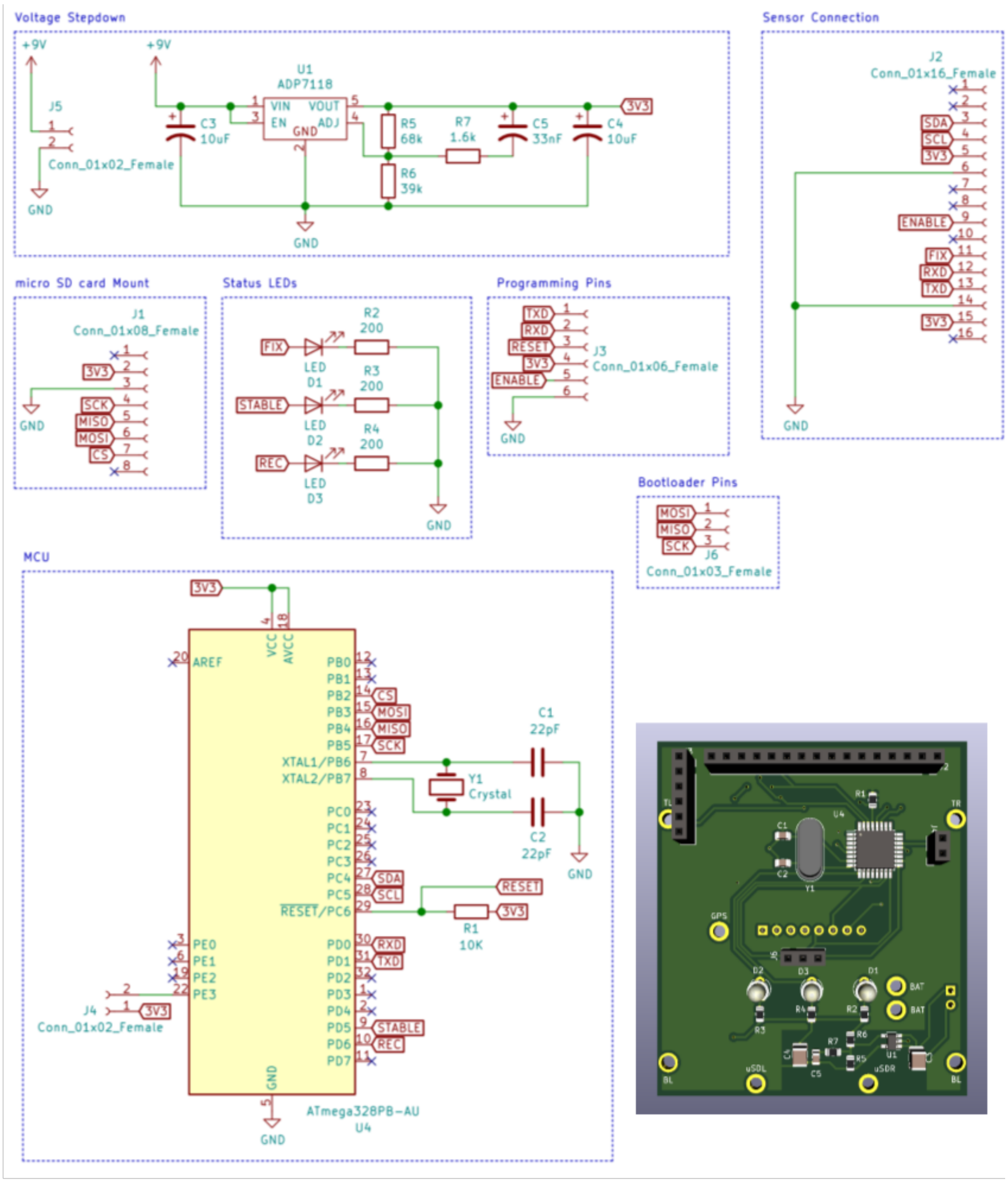
These where the only hazards that where present during the design and make of the module, and the risk assessment covered them fully.

For testing, some additional risk assessment should have been carried out. For example, riding a bike whilst also operating the module for the climbing test, or a risk assessment for the flight testing, should have been conducted before testing in order to identify and protect against hazards.

In future, before conducting any project work in the lab or before testing, it should be considered first if any hazards are present and if these hazards warrant the need of a risk assessment (for example, the case of flight testing). If so, the risk assessment can be conducting to help protect against potential hazards.

Appendix B

Circuit Schematic



Appendix C

Test Aircraft Data

Safety Data Page

e) Weight limitations:			
Max Test AUW:	450	kg	
Min Test AUW:	320	kg	
Empty weight:	265	kg	
Empty CG (3 axis only)	0.342m fwd		
CG Range (3 axis only):	0.36m fwd fwd	0.21m fwd aft	
CG datum (3 axis only):	0.04m fwd mainwheel axle ℄		

f) Trial only airspeed limitations:		
Max speed (Test flying):	120	
V_{NE}: (Other flying)	108	
Va:	72	
Expected Vs1	35	
Expected Vso	33	
Flap limiting speed(s) (if applicable)	tting	
	ANY NON-ZERO	66

Other Airspeed limits:	tion	

Airspeed Units:	KNOTS
IAS or CAS	CAS

Predicted Performance

(MTOW / ISA / Sea-level / short dry grass / 1.3 factor in TODR, no other safety factors)
Field perf calcs mandatory below 1.3x standard field length, retain calcs with this form.

TODR:	254 m	LDR:	250 m
Climb rate:	1100 fpm	Glide Performance:	9:1

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