TO THE EDGE OF SPACE

070172384

ABSTRACT. The aim of the project was to design, construct and launch a balloon-borne experiment to take a photograph or video showing the curvature of the Earth from the edge of space (~30 km), and measure the variation of temperature and pressure with altitude in the Earth's atmosphere. A balloon was successfully launched and recovered on 8 April 2011. A simulation was also written to predict the atmospheric readings obtained by the onboard instruments, as well as the flight path and landing location. The pressure readings inferred a maximum altitude of 45.3±9.1km, drag coefficients of 0.125±0.0025 and 0.655±0.0025 for the balloon and parachute respectively and fitted the predicted profile well. The primary temperature device had a partial failure but produced the expected trend. Excellent photographs were taken throughout the flight and good measurements of humidity, internal payload temperature and acceleration were also taken.

1. INTRODUCTION

The use of meteorological balloons in private ventures to the edge of space are becoming increasingly popular and regularly feature on local and national news bulletins. The upper regions of the atmosphere reached are beyond the capabilities of any aircraft but are still far below the path of orbiting spacecraft. The only way to access this region is either via meteorological balloons or sounding rockets. The former are cheaper and more reliable, making them an obvious choice for upper-atmosphere experiments. With modest budgets of around £500; individuals, friends, schools and university societies worldwide have been launching similar projects primarily to capture images and video footage from great heights. The general idea is to use a balloon filled with helium to carry a payload box, usually constructed from a high density foam, containing cameras, GPS devices and other equipment up to heights in excess of 30km. As the pressure of the atmosphere decreases with altitude, the balloon expands, eventually bursting at its maximum altitude, which is determined by its 'burst radius'. During the descent a parachute is deployed to slow the payload to a safe landing speed. Once the payload has landed, the user utilises the onboard GPS devices to locate and recover the data collected.

The aim of the project was to learn how real scientific projects; with fixed requirements, budgets and timescales, are carried out. The primary specifications were to image the curvature of the Earth, collect pressure and temperature readings as a function of altitude and track latitude, longitude and altitude as a function of time. Secondary specifications were to capture high definition video, collect humidity readings and achieve a live download of data. The budget was £500 and the launch was to be carried out either week commencing 4 April or 2 May 2011. A simulation of the atmosphere and the balloon's behaviour within it would also be written. It would be used to produce atmospheric models for comparison with the measured parameters as well as predict the probable path and landing spot of the balloon based on high altitude winds. Finally, as much publicity as possible would be generated in order to further the interests of the department, university and science in general. This was achieved through a website, press releases and sponsorship of equipment.

Note. Throughout this paper reference is made to 'the balloon'. This refers to the entire system of balloon, payload and parachute during the whole duration of the flight. Any exceptions to this will be made clear at the time.

2. Theory

The main theoretical work involved simulating the balloon flight, allowing for predictions of the majority of the measurable parameters to be made.

2.1. **Temperature.** The atmosphere is made up of different layers each with their own characteristics. This means the overall temperature profile of the atmosphere is far from straightforward. From ground level the balloon passes through the troposphere and the stratosphere. The boundary between the two is known as the tropopause. This maintains a fairly fixed temperature of ~220K, with values decreasing linearly from ground level at a rate known as the lapse rate σ_l [1]. The temperature T at an altitude h in the troposphere is:

$$T = T_0 - \sigma_l h \tag{1}$$

where T_0 is the surface temperature. The tropopause is defined as the point at which the lapse rate reaches zero, i.e. where the atmosphere becomes isothermal [1]. The altitude this takes place varies from just under 10km at the poles to close to 20km at the equator [1]. It can also be disturbed by high intensity thunderstorms. For the next 10km the temperature remains isothermal, after which the stratosphere begins and temperatures actually *increase* to ~270K at the stratopause, an altitude of 50km [1]. The is due to UV absorption in the ozone layer. The linear temperature rate in this region is known as the gain rate, σ_g. The temperature T at an altitude h in the stratosphere is:

$$T = T_T + \sigma_g(h - h_T) \tag{2}$$

where T_T is the temperature and h_T is the altitude of the tropopause. Meteorological balloons have maximum altitudes of 30-40km, so only the troposphere and stratosphere need to be considered. The temperature readings taken by the balloon allow for these regions of the atmosphere to be identified and measured. The expected temperature profile can be seen in figure 1.

2.2. **Pressure.** How the pressure of both the atmosphere and the helium within the balloon change as a function of altitude are given by starting with the equation for hydrostatic support:

$$\frac{dP}{dr} = -\frac{GM}{r^2}\rho_r \tag{3}$$

where P is pressure, r is height above the Earth's surface, G is the gravitational constant, M is the mass of the Earth and ρ_r is the density of air at that height [2]. If:

$$\rho = \frac{P\mu}{k_B T}$$

where k_B is the Boltzmann constant and μ is the mean molecular mass then equation (3) can be rewritten as:

$$\frac{dP}{P} = -\frac{dr}{H} \tag{4}$$

where:

$$H = \frac{k_b T}{g\mu}$$

and the acceleration due to gravity $g = \frac{GM}{r^2}$. Integrating equation (4) and rearranging gives:

$$P = P_0 e^{-\frac{h}{H}} \tag{5}$$

where P_0 is the surface pressure. The expected trend can be seen in figure 2. The pressure readings made by the balloon allow for the accuracy of this simple model to be determined. The altitude of the balloon can be derived from equation (5) if the pressure and temperature are known at that height. However, if the temperature is unknown, equations (1) or (2) can be substituted in instead. This does require the current atmospheric 'sphere' (e.g troposphere, stratosphere) to be known. Rearranging equation (5) gives:

$$h = -ln\left(\frac{P}{P_0}\right)\frac{k_B T}{g\mu} \tag{6}$$

Using the tropopause temperature T_T in equation (6) gives the altitude h in the tropopause for a given pressure P. Substituting in equation (2) for T gives:

$$h = -ln\left(\frac{P}{P_0}\right)\frac{k_B}{g\mu}(T_T - \sigma_g(h - h_T))$$

Rearranging gives the altitude h in the stratosphere at a given pressure P to be:

$$h = \frac{-ln\left(\frac{P}{P_0}\right)\frac{k_B}{g\mu}(T_T - \sigma_g h_T)}{1 + ln\left(\frac{P}{P_0}\right)\frac{k_B}{g\mu}\sigma_g} \tag{7}$$

Similarly substituting equation (1) for T gives the altitude h in the troposphere at a given pressure P to be:

$$h = \frac{-ln\left(\frac{P}{P_0}\right)\frac{k_B}{g\mu}T_0}{1 - ln\left(\frac{P}{P_0}\right)\frac{k_B}{g\mu}\sigma_l} \tag{8}$$

During the ascent, the balloon will expand as the atmospheric pressure decreases with altitude. Rearranging the equation for the volume of a sphere and gives:

$$R = \sqrt[3]{\frac{3}{4\pi}\frac{m_{He}}{\rho_{He}}} \tag{9}$$

where the volume of helium $V_{He} = m_{He}/\rho_{He}$, where m_{He} is the total mass and ρ_{He} is the density of helium in the balloon. This is the model for balloon expansion used in the simulation. Once the balloon exceeds its burst radius, the ascent phase ends; the parachute opens and the descent begins.

2.3. **Force.** The balloon is affected by the gravitational force F_g of the Earth, buoyancy force F_b from the helium and a drag force F_d from the surrounding air. The gravitational acceleration decreases with increasing altitude, so F_g at a given altitude h is:

$$F_g = mg_0 \left(\frac{r_\oplus}{r_\oplus + h} \right)^2 \tag{10}$$

where m is the complete mass of the balloon; payload, balloon and helium included; g_0 is the gravitational acceleration at the Earth's surface and $r_\oplus$ is the mean radius of the Earth [3].

$$F_b = \rho_{air} g_h V_{He} \tag{11}$$

where ρ_{air} is the density of the atmosphere and g_h is the acceleration due to gravity at a given altitude, as inferred from equation (10) [4]. By assuming equal pressure between the air of the atmosphere and helium within the balloon equation (11) can be rewritten as:

$$F_b = g_h \frac{\mu_{air}}{\mu_{He}} m_{He} \tag{12}$$

Therefore, F_b is a constant dependent on the amount of helium used.

$$F_d = \frac{1}{2} C_D \rho v^2 A \tag{13}$$

where C_D is the drag coefficient of the balloon or parachute, ρ is the density of the medium it is travelling through, v is the velocity of the object and A is the cross-sectional area [5]. The main uncertainty in the drag force, which in turn affects the entire simulation, is the drag coefficient C_D. Values are available for standard objects such as a 'smooth sphere' or 'Boeing 747', but ultimately the only way of achieving an accurate value is through experimental measurement of the drag force generated. The data generated by the flight can be used to accurately determine the drag coefficient for both the balloon and parachute used and update the simulations to produce the best possible predictions.

The three forces are combined with the mass of the balloon to give the resultant acceleration at a particular time. This produces a velocity causing a change in altitude. This altitude profile as function of time is required to produce predictions for both temperature and pressure, as well as the duration and profile of the flight itself. The resultant force F is:

$$F = F_b \mp F_g \mp F_d \tag{14}$$

The $\mp$ represent how the resultant force changes during the flight. On the ascent, the upward buoyancy force provided by the balloon is reduced by the effect of gravity and drag. During the descent $F_b = 0$. As the same negative value of g_0 is used for the whole simulation (-9.81ms^{-2}), for the descent, F_d is *added* to the increase the deceleration on the way down.

3. The Simulation

The aim of the simulation was to provide models of the atmosphere which could be compared with the values recorded during the balloon flight. It would also be used to predict the behaviour of the balloon in order to determine the required equipment, balloon type, amount of helium, etc. Finally, it would act as a guide to the path of the balloon during the flight and give some idea of its landing location. All of this was successfully produced via an Excel spreadsheet.

3.1. **Method.** The simulation advanced in time-steps of 1 second. At time $t = 0$, the initial surface conditions for pressure, temperature, air and helium density, balloon radius, acceleration, velocity, drag force, height and position were set. As time advanced, these values then changed accordingly. Pressure changed as per equation (5). Temperature followed linear models as described in section 2.1; decreasing linearly until the tropopause, then remaining constant before increasing again in the stratosphere. Altitude was gained and lost as a result of the forces at work in equation (14) and the balloon swelled and eventually burst as a result of equation (9). A number of `if` statements were required to change the dimensions and formulae during the flight on certain events. For example, on the descent phase the source of drag changed from that of the balloon to the parachute, needing an updated area and drag coefficient.

The above enabled the profiles of temperature and pressure as functions of altitude, as well as altitude as a function of time to be predicted. In order to produce a flight and landing predictor weather data collected by an external source was needed. Ultimately all that was required was data on wind speed and direction at high altitudes, which can be very different to that experienced on the ground. It was eventually sourced from the US National Oceanic and Atmospheric Administration and their Operational Model Archive and Distribution System [6]. The data was requested by writing a unique URL; specifying the time from the latest forecast to the launch, the altitudes required and the area of sky to be covered. The data used had an accuracy of 1 square degree, sufficient area for a whole flight, so just one forecast needed to be downloaded and modelled. The URL request produced the data via HTML in separate files for wind speed north/south and east/west in ms^{-1}. The speeds were given as a function of pressure, so another file was provided to convert these into altitudes. The forecast extended from ground level to just above 30km. With the speeds already separated into the x and y directions, it was simply a matter of using extensive `if` statements to allocate the speeds to the appropriate altitudes before summing the distance travelled at each time-step. The simulation was already in time-steps of 1 second therefore speed in that interval was equivalent to the distance travelled. To produce a track the east/west distances and north/south distances were plotted onto the x and y axes respectively before being superimposed on a map of the area, as seen in figure 3.

3.2. **Predictions.** The profiles of temperature, pressure and altitude as a function of time can be seen in figures 1 and 2. They are based on using a 1600g balloon with a drag coefficient of 0.1 (C_D of a 'smooth sphere' [7]) filled with $3.5m^3$ of helium lifting a payload of 1.7kg. On the descent only the mass of the payload is included, suspended under a square parachute of area $0.75m^-2$ with a drag coefficient of 0.75 (C_D of a 'parasheet' [8]). The linear temperature profile is clear to see, with values decreasing to the tropopause temperature of 220K at an altitude of 10km. The peak in the centre of the plot is where temperatures have begun to rise again upon entering the stratosphere. The sudden drop indicates the start of the descent phase, in line with the drop in altitude. The profile then reverses, albeit much quicker than the ascent. It is a similar story with the exponential pressure profile, where it decreases until the balloon's burst point at an altitude of 38km. From either altitude plots the balloon is predicted to reach its maximum altitude after 1 hour and 44 minutes before touching down for a total flight time of 2 hours and 19 minutes.

The flight and landing prediction for a launch from the proposed launch site (Surprise View car park, on Hathersage Road, near Grindleford in Derbyshire) at midday on 20 May 2011 is shown in figure 3. It is imposed on top of a prediction for the same day by a predictor produced by Cambridge University Space Flight (CUSF), a university society specialising in high altitude

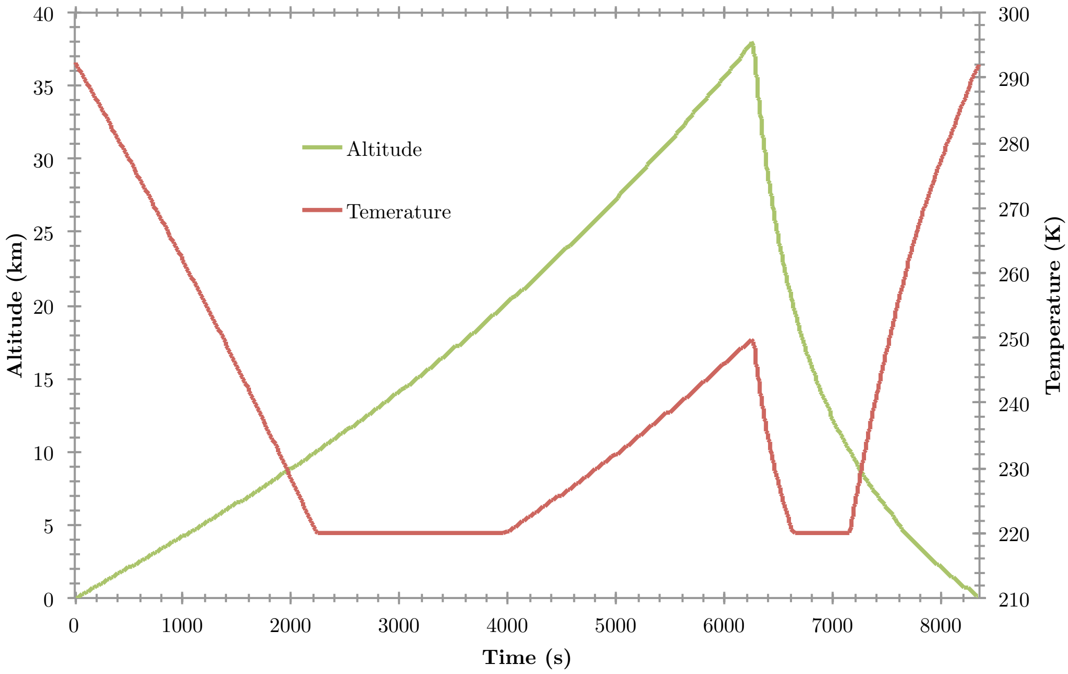

FIGURE 1. Predicted temperature and altitude profiles as functions of time

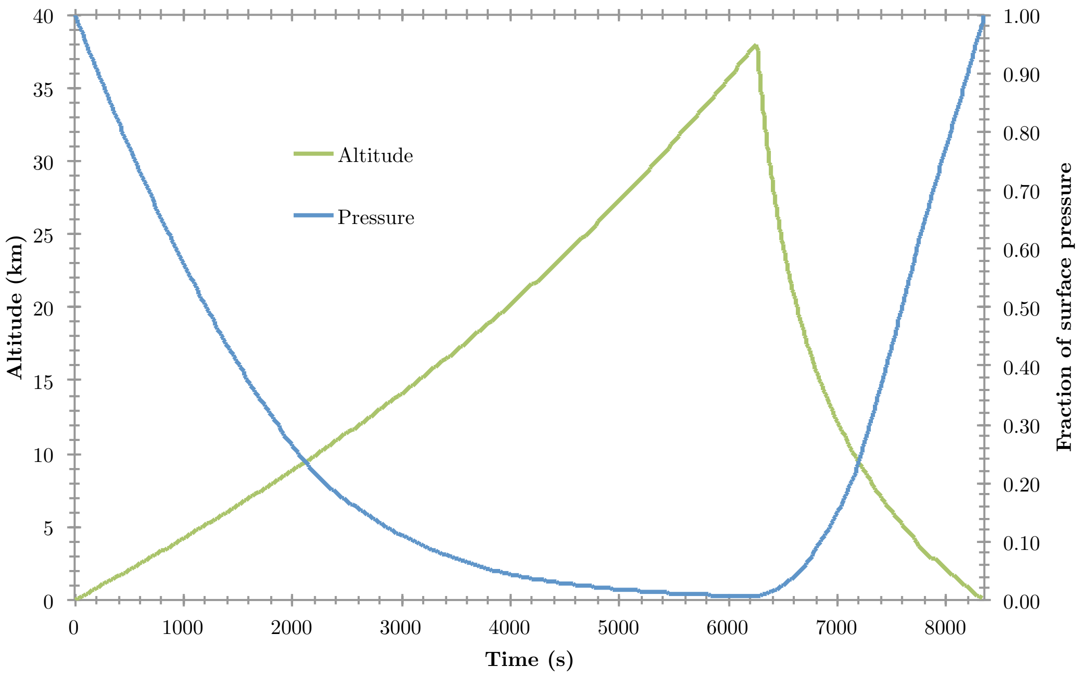

FIGURE 2. Predicted pressure and altitude profiles as functions of time

balloon flights [9]. They source their weather data from the same location and produce a plot based upon launch location and predicted rates of ascent and decent. This has to be an average value from both, in which the speeds can vary considerably. The tracks are similar in shape but the both stages of the CUSF prediction are much shorter. Also, the total length of the CUSF flight is only 1 hour and 53 minutes, whereas the average ascent and descent rate and maximum altitude used are the same in both simulations. The numbers in the CUSF prediction just do not add up. However, the relatively unknown drag coefficients used in the Excel simulation play a big part in the result. More drag on the ascent with less on the descent would bring the two predictions closer together. Results from the actual launch will confirm or discount this prospect.

4. The Balloon

With a budget of £500, a balloon had to be designed, constructed, launched and recovered capable of imaging the curvature of the Earth, taking temperature and pressure readings as a

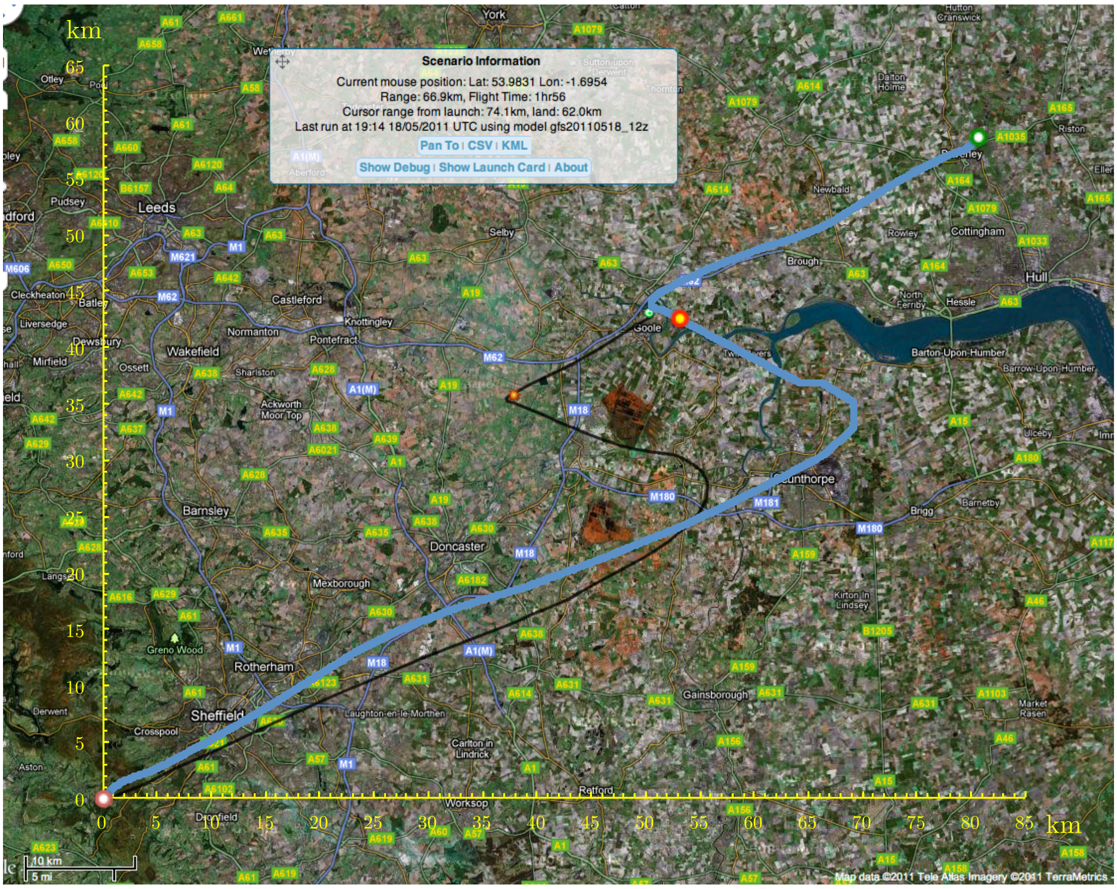

Figure 3. The flight and landing prediction (blue) with the prediction from the CUSF predictor (black) for a launch at midday on 20 May 2011. The red and white circle is the launch point, red and yellow markers are burst points and green and white circles are landing points.

function of altitude and logging its entire journey as latitude, longitude and altitude as a function of time. As well as meeting the required aims, back-ups for each system also had to be sought where possible. Realistically, the amount of launches possible was going to be limited on the budget and timescale, hence the need for back-up systems to ensure data was collected and the payload recovered. The predictions produced by the simulation also influenced the purchases made. The total cost for one launch was £676.22 and a full breakdown of the costs can be found in appendix 1.

4.1. **Payload Equipment.** The most important part of the payload was the system to allow for recovery upon landing, so this item was decided upon first. The majority of other similar projects [10] had used live radio tracking by building and programming an onboard microcomputer to control a GPS radio transmitter along with other components in the payload. This would then allow tracking from a ground radio station. This was discounted due to cost (ground receivers are ~£300) and a lack of time and expertise required to design and build such a device. Instead, a more 'off the shelf' approach had to be taken with all of the required devices. For the recovery system, the primary device was a Xexun TR102-2. This device used GPS to pinpoint its location before sending that information via text message (SMS) over the mobile phone network to a predetermined handset. The coordinates could then be used in an online mapping service to locate the payload. The back-up system used an iPhone installed with the Viewranger application which gave it similar capabilities to the Xexun. As well as transmitting its location, the iPhone also stored position information which could be recovered after the launch. These devices had SIM cards from different network providers to maximise the chance of picking up a signal.

The next item to consider was the imaging equipment. The primary aim was to capture a still image, with the secondary aim of high definition video. Both of these capabilities were met. A Canon A430 was programmed using the Canon Hack Development Kit (CHDK) to take a photograph every ten seconds during the flight whilst a Tachyon XC HD sports video camera was used to record video footage. The remaining devices required were those to take atmospheric and position readings. A Garmin eTrex H was used to log position information as a function of time. The iPhone would act as a limited back-up to this as its GPS would not work over the full altitude range of the flight. Although there are many GPS devices that log position information, there are a limited number that work at a sufficient altitude. Most are limited to an altitude of 18km as this is the limit of civilian airspace. Thankfully a list of GPS receivers that do work above this altitude has been compiled by high altitude balloon enthusiasts [11]. The iPhone is absent from this list so should not work above 18km. Pressure readings were taken with an MSR145 data-logger. An all-in-one enclosed device, it also recorded three-axis acceleration and temperature, although not over the required range (only down to 263K). From theory and the simulation temperatures were expected to drop to 220K. Instead, it was used to monitor internal temperatures of the payload. Data was extracted via USB connection upon recovery. External temperatures were recorded with a Lascar EL-USB-TC data-logger equipped with a thermocouple temperature probe (capable of recording temperatures down to 73K) and humidity with a Lascar EL-USB-2 data-logger. Again, this had the ability to record temperature but not in the required range (only down to 238K) and both devices stored their data before extraction via USB upon recovery. In order to achieve the live download of data a Vaisala RS80 radiosonde was also purchased. Used daily by meteorological agencies all over the world to measure temperature, pressure, humidity and windspeed at high altitudes, it transmited the recorded data live back to a radio receiver which was also obtained for the project. Connecting the receiver to a computer sound card, a piece of software called Sondemonitor was able to interpret the incoming data and produce real-time plots. However, the radiosonde was not built into the first payload and was destined to be used in a second launch, which unfortunately never took place.

4.2. **Payload Design.** The payload box was constructed from a variety of high density foams. A core cube of the highest density foam was constructed to hold the equipment securely and to maintain a temperature for efficient electrical functionality. It also allowed for precision access holes to be created in the sides for the cameras and sensors to sample the outside environment. The layout of the equipment within this central section can be seen in figure 4. The GPS devices were prioritised to be at the top in order for them to have the maximum satellite and signal access. The cube was then extended into a cigar shape by attaching flexible foam strips to the sides, as seen in figure 5. The idea was for this shape to produce a weather vane effect, where the payload would turn in line with the wind to give it more stability in order to take better quality photographs. The final shape was secured with plenty of strong orange tape to improve visibility and provide some waterproofing. Four small, flashing LED lights were also attached to the sides to aid in locating the payload in the dark as well as an internal buzzer powered by a 9v battery. A laminated contact sheet was attached to the lid for, in the event of being unable to locate the payload, a member of the public to contact the department. A University of Sheffield crest was attached to a boom in front of the Canon camera at a sufficient distance to allow for the logo and the background to be in focus. This was done to spark interest from the University after two PhD students from the Engineering Department published details of a similar project in January 2011 [12].

4.3. **Flight System.** The payload was suspended by high-strength cord below a parachute specifically designed for high altitude ballooning. This in turn was attached at the top to the neck of the balloon. The balloon used was a 1600g meteorological standard latex balloon. It had a radius of 1m on the ground which would grow to 5m at the top of its climb and was filled with 3.5m^3 of helium. From the simulation this was found to be sufficient to lift the required payload. Typically it is the size of a balloon that determines its maximum altitude. If a heavier payload is attached it simply takes longer to get there. 1600g was a compromise between cost (larger balloon, larger cost) and speed of ascent (limited battery life and data storage). Once the balloon burst, air rushing in under the parachute would cause it to open and reduce the speed of the falling payload to its terminal velocity. Again, from the simulation and taking into account the mass of the payload, a ground impact speed of 5ms^{-1} would be achieved with a parachute of area ~0.75m^2. The balloon was designed to completely shatter leaving no remnants to disrupt the function of the parachute. The weight of the payload and parachute was 1.7kg. With the balloon (1.6kg) and helium (~0.6kg) included the total mass m ~3.9kg.

4.4. **Testing.** All the components used in the launch were throughly tested where possible before use. Critical points that needed to be set out for the payload items were the set-up and configuration of the devices, battery life and data extraction. The Canon A430 had to be set-up with the CHDK software and ran continuously for several hours to ensure the camera took images at the correct interval and had sufficient battery life. The Tachyon was found to have sufficient battery life for the flight but the data extraction was not straightforward. If the device was turned off manually then the last file on the device would be corrupted. The solution was to either start and stop the video to create a new file or let the device run out of battery. The two

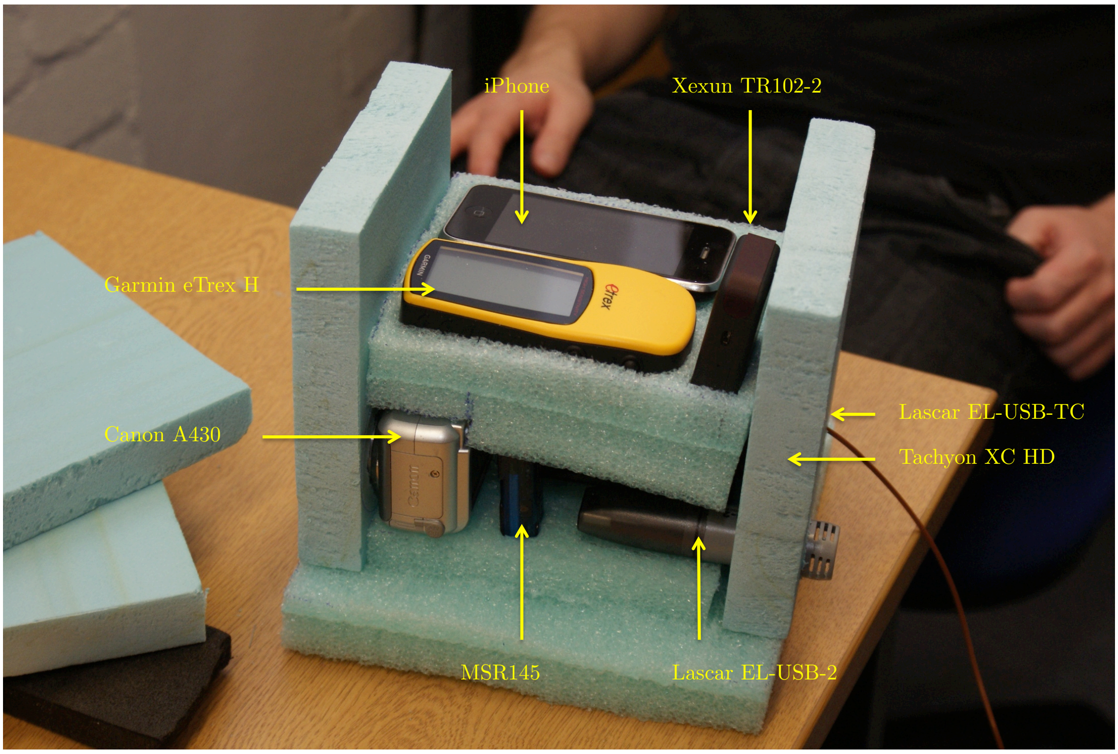

FIGURE 4. Layout of equipment in the central payload section.

FIGURE 5. Adding the flexible foam strips during the construction phase to give the payload its ’cigar’ shape and desired weather vane effect.

tracking devices had to be checked for accuracy and the method for obtaining their coordinates practised, as well as battery life. The Xexun communicated by SMS and the Viewranger application either by an application on another smartphone or via a webpage. Both of them had no problem accessing a GPS signal as long as they were outdoors. The data-loggers (Garmin, MSR and both Lascars) had to be checked for their sampling range, battery life and method of data extraction. They were placed in a freezer to simulate low temperature conditions and the MSR was ran in a deflated water bottle to simulate low pressure. All but the Garmin extracted data by USB and instead of wasting the budget on an expensive cable, one was wired by hand using instruction obtained from the internet. The insulation properties of the payload were found to be sufficient by placing a prototype box and the Lascar EL-USB-TC in a freezer for several hours and the function of the parachute was tested by dropping the payload (weighted to resemble the final contents) off the department roof.

4.5. **The Launch.** The launch took place on Friday 8 April 2011 from Surprise View Car Park on Hathersage Road near Grindleford in Derbyshire. An attempt the previous today had been aborted due to problems with Air Traffic Control. This resulted in the loss of a balloon and a large quantity of helium. Although permission for the launch at the site had been granted by the Civil Aviation Authority (see appendix 2 for certificate), they had not liaised sufficiently with the National Air Traffic Control Service who felt they did not have enough information to allow us to launch. An afternoon of telephone discussions with both parties resulted in the forwarding of the predicted flight path and altitude profile for their consideration. The next morning, the all clear was given. After fuelling the balloon and preparing the payload the two were attached before release. The ensure the balloon had been filled with a sufficient amount of helium to generate the lift required, 3 litres of water were used to act as counterweights. The amount required was derived from the simulation. After launch (figure 6), the balloon ascended as expected to the south-east. The pursuit followed, where during a stop on the outskirts of Nottingham the balloon was actually spotted nearing its maximum altitude (figure 7). Eventually, the balloon could no longer be seen indicating that it had burst. This meant there was now a half-hour wait for the payload to descend back to the ground. Once an SMS was received from the payload, the coordinates were inputted to Google Maps to give directions to the landing location some 16 miles away. The payload was found intact in a field 10km north of Melton Mowbray.

5. Analysis and Results

5.1. **Atmospheric Pressure.** The MSR145 was the sole device recording pressure and thankfully it worked perfectly, allowing the important events of the flight; launch, burst and landing, to be clearly identified. Burst occurred 1 hour and 56 minutes after launch when the pressure reached its minimum value. It then touched down when the pressure readings level off 2 hours and 29 minutes after launch. Using these timings, the drag coefficients of the balloon and the parachute were adjusted to allow the predictions to closely reflect the recorded profiles. The adjusted values were 0.125±0.0025 for the balloon and 0.655±0.0025 for the parachute. The error originates from the method to adjust the coefficients. The values were adjusted in steps of 0.005 until the burst and landing time in the simulation closely resembled the actual timings. The value for the balloon was fairly typical (the balloon was expected to have a greater drag than the 'smooth sphere' value of $C_D = 0.1$) but the parachute is less than expected (typical $C_D \sim 0.75$). The effective area of the parachute that actually causes drag is debatable and could be

FIGURE 6. Shortly after launch, showing the balloon, parachute and payload in their ascent configuration.

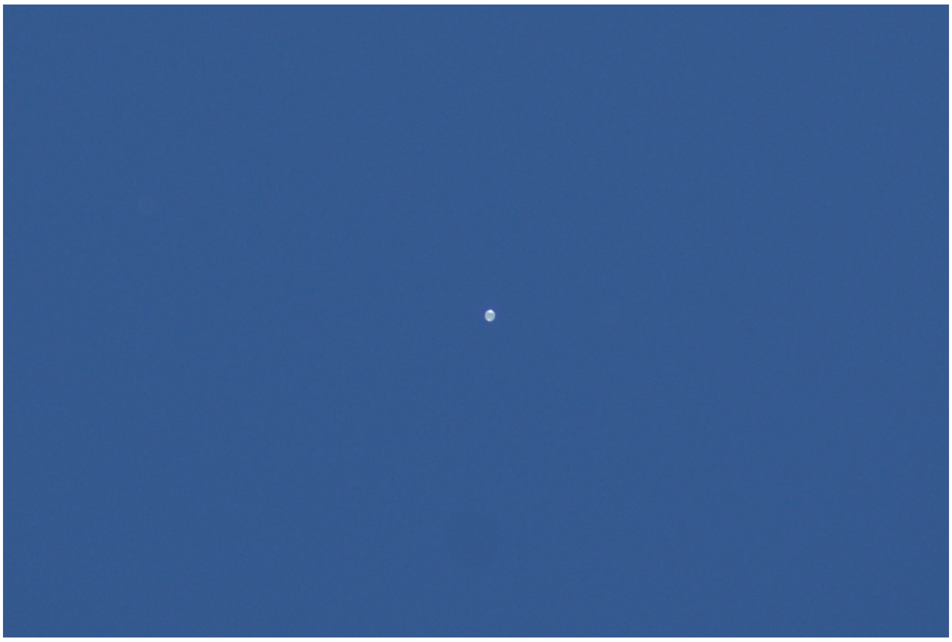

FIGURE 7. The balloon was spotted nearing its maximum altitude of ~40km just outside Nottingham. Moments later, the balloon disappeared, indicating it had burst.

the source of the discrepancy. These adjusted drag coefficients have been applied to the original predictions for the remainder of the report.

The recorded pressure in figure 8 shows a slightly steeper drop off, and reaches a burst pressure of just 230±250 Pa, within one error bar of the predicted 530 Pa at burst. The error here reflects the published accuracy of the MSR145. Using equations (6), (7) and (8) the pressure recordings were converted to altitudes, as seen in figure 9. The maximum altitude was calculated to be 45.3±9.1km. This error is based upon the minimum altitude possible considering the measurement accuracy of the MSR145. The steeper drop off and probable higher altitude reached reflect a faster rate of ascent than predicted. Adjusting the generally unknown drag coefficient in the simulation would allow this, but a more likely cause of the discrepancy is the expansion rate of the balloon. This decides at what altitude the balloon bursts and assumes a free expansion based upon equal pressure between the helium in the balloon and air in the atmosphere. The effect of the balloon could be to limit this, allowing the balloon to ascend higher before reaching its burst radius. A follow up study should investigate the effect of the balloon elasticity on the internal pressure.

5.2. **Atmospheric Temperature.** The primary atmospheric temperature recording device was the Lascar EL-USB-TC and its readings can be seen in blue in figure 10. The secondary device was the Lascar EL-USB-2 as shown in orange. This device's primary aim was to sample humidity, as it did not have the necessary range of temperature to sample the whole flight. It is included here for comparison, and to gain a precise initial ground temperature (292.5±0.5K). There is clearly a problem with the main Lascar device. The trend is the complete opposite of what was expected. The 'Adjusted' plot shown in red is a mirror image of the primary Lascar data, moved to start at the ground temperature recorded by the secondary Lascar. Although still not perfect, this profile clearly reflects the expected form. It follows the predicted (green) plot at the same lapse rate but flattens out much earlier. It steadily increases where the prediction states it should remain constant in the tropopause. There is still a well defined peak indicating the start of the stratosphere, at the same time as the prediction. It then falls and climbs at a very similar rate to the prediction on the descent. Although actual temperatures from the upper atmosphere cannot be gleaned from these measurements, the trend produced confirms that the location of the tropopause, stratosphere and burst point were correctly identified in the simulation. The fault with the primary Lascar has been traced to the thermocouple probe not bring fully inserted into the device prior to launch. The secondary Lascar EL-USB-2 also did not perform as expected. Although its sampling range extends down to 238K it did not go below 263K during the flight. In the supplied literature its accuracy of ±0.5K is only valid between 20% and 80% humidity. The humidity is much lower than this at high altitudes and so was potentially a source of the problem. For a future launch a fully capable secondary device would be sought.

5.3. **Photography.** Figure 11 is one of hundreds of photographs captured during the flight. Here the image is of the Yorkshire coastline, looking north-east out into the North Sea. Flamborough Head, the Humber Estuary and the city of Kingston-upon-Hull can all easily be seen. The Tachyon video camera was not as successful. After ~30 minutes into the flight condensation formed on the inside of the sealed lens as the temperature fell. This was still visible when the payload was recovered, so much of the video is unusable. As the Tachyon is marketed as a 'tough' sports camera, its lens is protected by a sealed plastic cover, leaving the air (and moisture) trapped inside liable to produce condensation when cooled. Removing this cap or simply

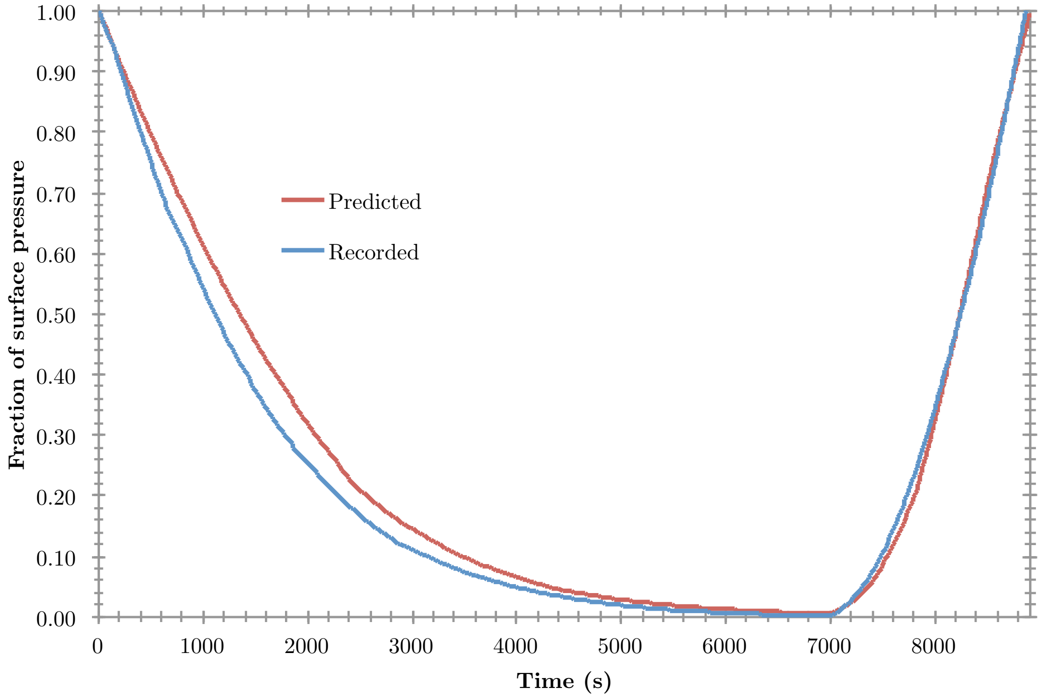

FIGURE 8. Showing the atmospheric pressure recorded by the MSR145 with the predicted atmospheric profile from the simulation.

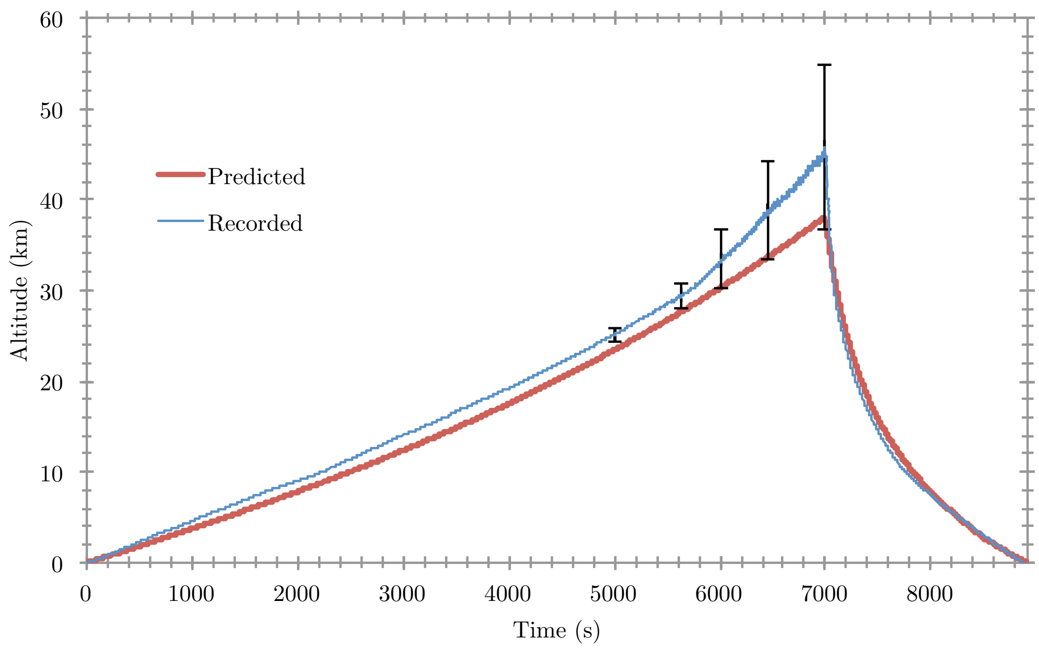

FIGURE 9. Altitude as a function of time derived from the MSR145 pressure values, shown with predicted altitude profile. Error bars reflect pressure accuracy of ±250 Pa.

drilling a small hole would allow the air to circulate and remove the moisture as the altitude increased.

5.4. **Flight.** The primary recording device for the flight was found to be turned off upon opening the payload after recovery. Examining the data revealed the Garmin had turned itself off soon after launch and provided no log of the flight path or altitude reached. However, after examining the iPhone it transpired that the Viewranger application had managed to record large amounts of the journey, in spite of the fact it was operating above its supposed maximum altitude of 18km. Pressure readings infer that it continued to record latitude and longitude points until an altitude of 20±0.4km. The recorded path can be seen in green in figure 12. Also included for reference are the location from where the balloon was observed to burst (red and yellow circle on the green line) and the landing spot (green and white circle). These fit perfectly with the recorded track. Although the position information appears correct, the altitude data was certainly incorrect, highlighting the limitations of the device. From the pressure readings, though, it is clear that the balloon reached at least the height expected, and potentially much higher. This could account for the additional drift to the south beyond either of the predictions. As the wind forecast only extends to 30km, accurate predictions above this altitude are difficult to achieve. The Garmin turning itself off was apparently pure bad luck as it has performed perfectly on numerous test runs. Potentially a button could have knocked during the flight, or it turned itself off due to inactivity in the build-up to launch. It was however very lucky that the iPhone performed better than expected, but disappointing that the maximum altitude has had to be inferred with a large error. The ideal scenario for a future launch would be to have two fully capable devices.

5.5. **Internal Temperature.** Figure 13 shows the internal temperature of the payload during the flight, as recorded by the MSR145. No prediction had been made for comparison, from testing and similar projects [10] it was assumed the insulation provided by the foam and heat generated by the electrical devices would be able to keep temperatures sufficiently high for everything in the payload to function correctly. It appears that this was more than sufficient. The temperature did not drop below 292 K (19°C) whilst in the upper regions of the atmosphere. Once on the descent, the temperature managed to drop lower, probably due to high velocity forcing cold air into the payload.

5.6. **Humidity.** Again, no predictions were made but the measurements made by the Lascar EL-USB-2 are unsurprising. Figure 13 shows how it decreases to 0% in the upper regions of the atmosphere, as expected. Humidity does not diminish with altitude directly, it is related to air density. At low densities (such as high altitudes) the air is not able to hold as much water. As humidity is quite localised and subject to change throughout the day, the higher landing value is not unexpected.

5.7. **Acceleration.** The MSR145 measured acceleration in units of g along three axes; x, y and z. From the orientation of the device in the payload, the x direction corresponds to longest horizontal axis, y to the vertical and z to shortest horizontal, as seen in figure 14. The results are displayed in figure 15. The highest acceleration is felt in the y direction, which is to be expected. It is in this vertical plane that the forces of gravity, buoyancy and drag are most focused. The x and z accelerations are pretty similar, most likely being cause by the payload swinging and turning in the wind. The is a notable increase in buffeting during the descent phase after ~7000s

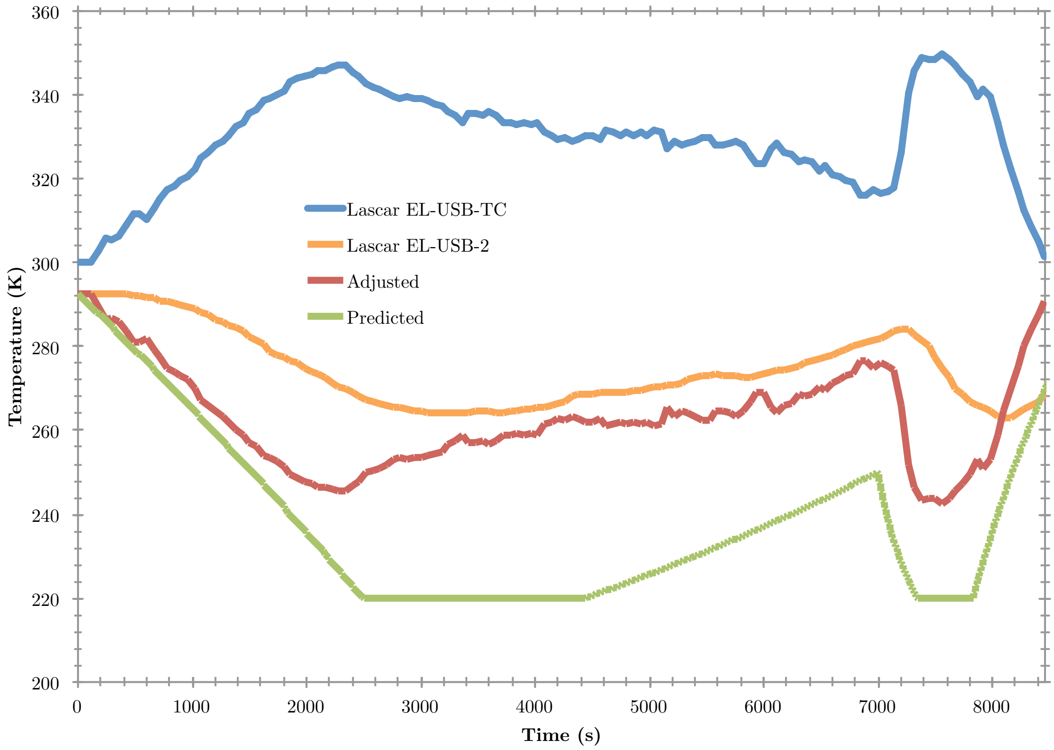

FIGURE 10. Showing the external temperatures recorded by both Lascar devices, an adjusted plot and the predicted temperature profile. The lower limit of the EL-USB-2 is 238K.

FIGURE 11. Image captured by the Canon A430 showing the Yorkshire coastline. Image was taken 1 hour and 55 minutes after launch, one minute before burst. Altitude is 44±8km.

and during the transit through the isothermal layer (~10-20km) between ~2000 and 4000s, as inferred from the pressure readings.

6. Summary of Results

The balloon was successfully launched and recovered. Burst occurred 1 hour and 56 minutes from launch with a total flight time of 2 hours and 29 minutes. Drag coefficients of 0.125±0.0025 and 0.655±0.0025 were determined for the balloon and parachute respectively. A maximum altitude of 45.3±9.1km was derived from pressure readings as the Garmin Etrex H position logger

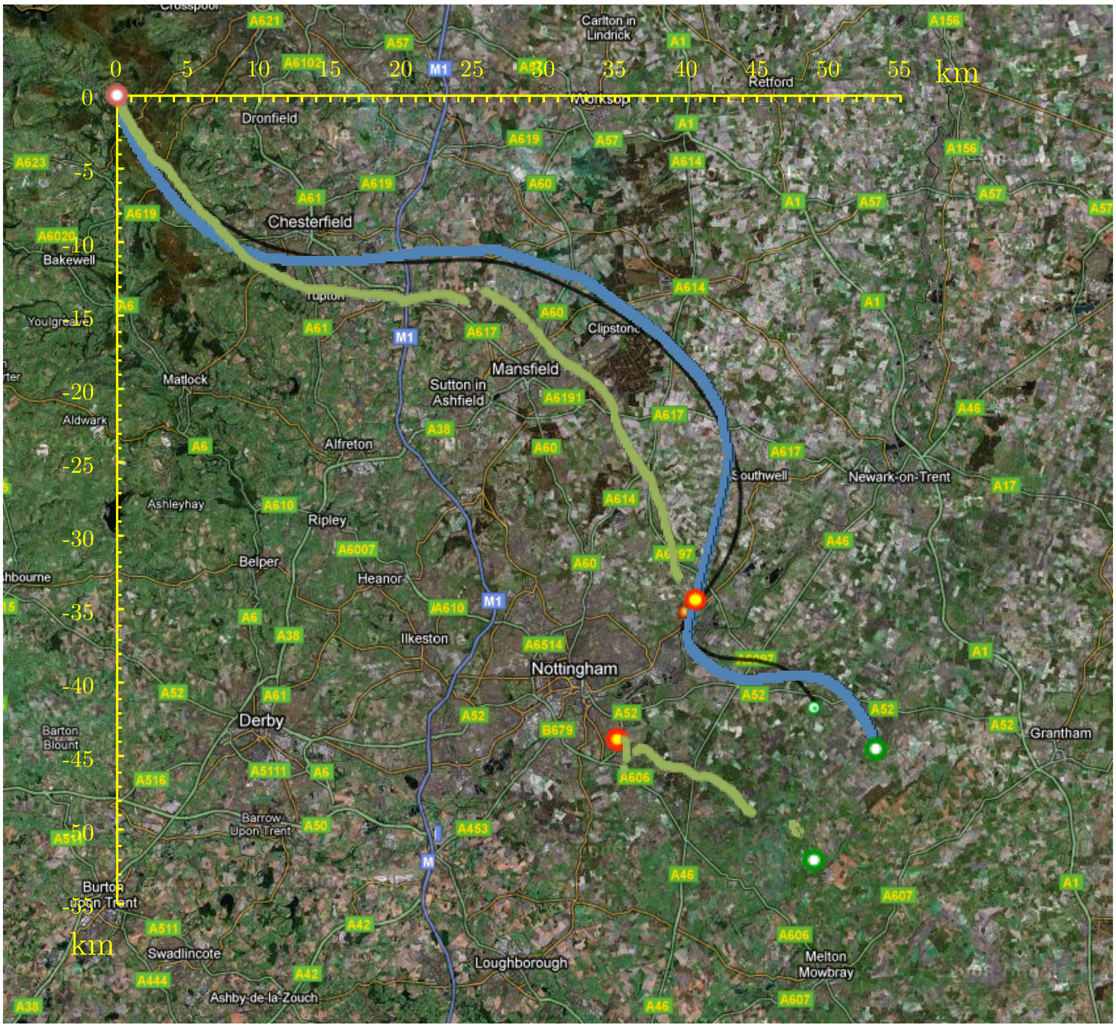

Figure 12. Flight paths for the launch at 1100 on 8 April 2011. Showing the CUSF prediction in black, the Excel simulation in blue and the recorded track in green. The red and white circle is the launch point, red and yellow markers are burst points and green and white circles are landing points. The bust and landing points for the recorded track are the actual sites as recorded on the day.

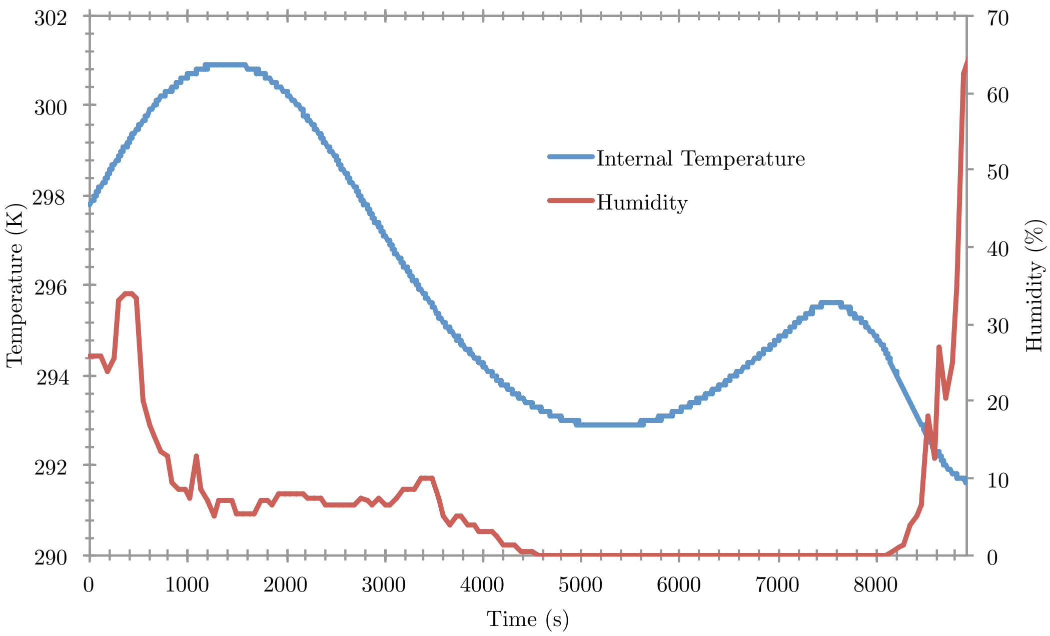

FIGURE 13. Showing the internal temperature of the payload as recorded by the MSR145 and the atmospheric humidity recorded by the Lascar EL-USB-2.

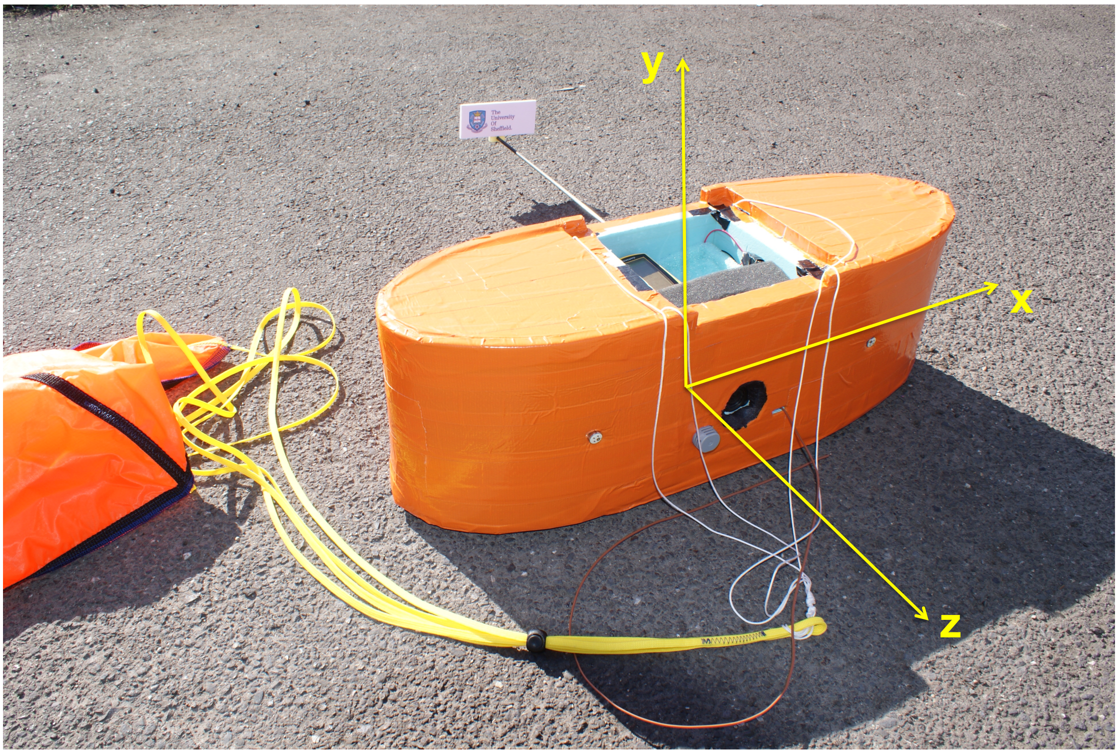

FIGURE 14. Showing the direction of acceleration axes in the MSR145 relative to the payload.

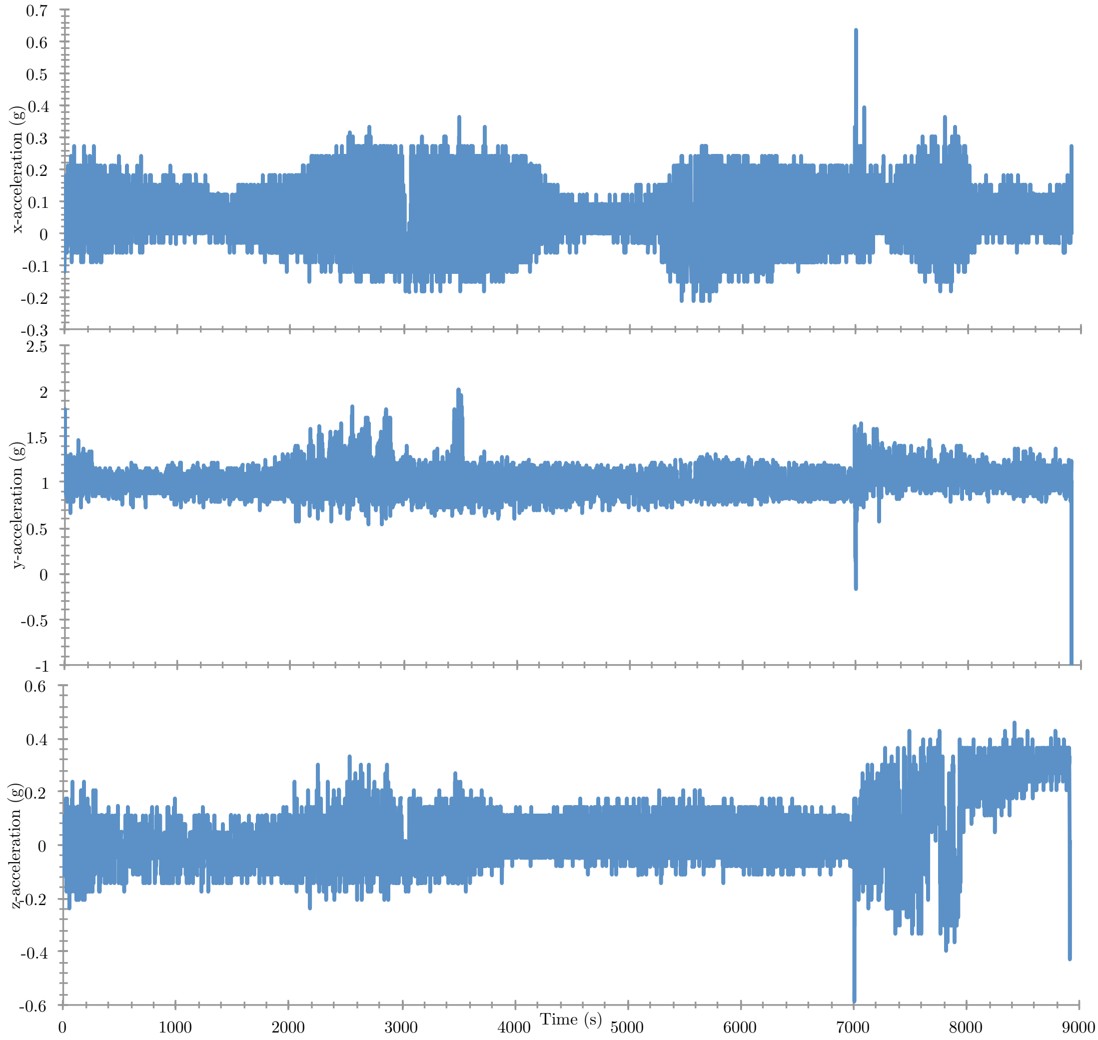

FIGURE 15. Three-axis acceleration as recorded by the MSR145. Top: x-acceleration. Centre: y-acceleration. Above: z-acceleration.

failed during the flight. The pressure profile also fit well with predictions. Temperature readings, although not correct values, show the expected trend through the atmosphere. The Canon A430 took excellent photographs throughout but the Tachyon developed condensation on the lens early on. Although the Garmin failed the Viewranger application on the iPhone was able to record much of the journey accurately, but not altitude. Internal temperature readings confirmed the suitability of the payload layout and construction in maintaining sufficient temperature. Humidity and acceleration readings were as expected.

7. Conclusions

Overall the project was a great success. A balloon was designed, built, launched and recovered whilst collecting data during its journey. Notable successes were the photography producing some stunning images, the pressure readings estimating an impressive maximum altitude and the iPhone performing well above its published limitations to allow a flight path to be produced. The simple, derived models of atmospheric pressure and temperature appear to fit well with measurements. The effect of the elasticity of the balloon would be the next stage in investigating this further. The partial or total failure of the Tachyon, Garmin and main Lascar device highlighted the importance of redundancies and perhaps the luck that was had in the rest of the payload working. A second launch, applying the lessons learnt from the first, would have been welcome but time, money and paperwork prevented this becoming a reality. The project was somewhat over budget, with the launch costing a total of £666.22. The overspend was partly due to loosing a balloon and a large amount of helium during the aborted launch. This amount would have been sufficient for two launches, making the spend per launch half of this. In terms of publicity, a press release has yet to be issued by the University but the website is already making an impact. An email has been received by a BBC production team looking to carry out their own balloon launch for a future series and are seeking advice on the matter.

8. Acknowledgements

This project has been one of the highlights of my university career and I struggle to think of another project I would have persevered with as much and maintained the same degree of enthusiasm for. I would like to thank the other members of my project group; Phillip Mahoney, Alex Mackie and Philip Carpenter for being excellent colleagues for who it has been a pleasure to work with. A big thanks also goes to the workshop staff, notably Pete Robinson and Trevor Gamble for their expertise and advice during the design and construction, as well as their assistance on the launch day(s). Dr Stuart Littlefair also deserves a mention for donating his old iPhone to the project. Finally, thank you to project supervisor Professor Vik Dhillon for his continued enthusiasm (often more than ours) and help throughout the project.

References

[1] M Allaby, Encyclopaedia of Weather and Climate, Volume 1, 2002, Infobase Publishing, p.47.
[2] V Dhillon, Stellar Structure and Evolution, 2010, The University of Sheffield.
[3] D Turcotte and G Schubert, Geodynamics, 2nd Edition, 2002, Cambridge University Press, p.212.
[4] R Serway, C Vuille and J Faughn, College Physics, Volume 10, 2008, Cengage Learning, p.285.
[5] H Smith, Illustrated Guide to Aerodynamics, 1992, McGraw-Hill Professional, p.65.
[6] National Oceanic and Atmospheric Administration, 2011, http://nomads.ncep.noaa.gov/.
[7] A Filippone, Advanced Topics in Aerodynamics, 2004, http://classic-web.archive.org/web/20070715171817/http://aerodyn.org/Drag/tables.html.
[8] Bethlehem-Centre School District, Parachute Design/Experimentation, 2001, http://www.bc.k12.pa.us/science_technology/Technology/3.6/Para%20Design%20is.htm.
[9] J Sowman and A Greig, Cambridge University Space Flight, 2011, http://habhub.org/predict/.
[10] R Harrison, The Icarus Project, 2011, http://www.robertharrison.org/icarus/.
[11] R Wallio, 2009, http://showcase.netins.net/web/wallio/GPSrcvrsvs60kft.htm.
[12] K Christie, The University of Sheffield, 2011, http://www.shef.ac.uk/mediacentre/2011/1834-video-earth-edge-space.html.