Measuring Muon Flux in the Lower Stratosphere

Ben Wilson

Introduction

In Summer 2017 I was awarded the £250 John Rayson Award to fund a project to send a homemade muon particle detector to an altitude of almost 30km in order to measure how the count rate changes with altitude. I sent the detector up using a high-altitude balloon – an enormous latex sphere about one and a half metres in diameter, filled with almost two thousand litres of helium. The project took over a year to complete, with the work carried out in my spare time and almost entirely from my bedroom. The balloon was finally launched, and the payload recovered, on 14th September 2018.

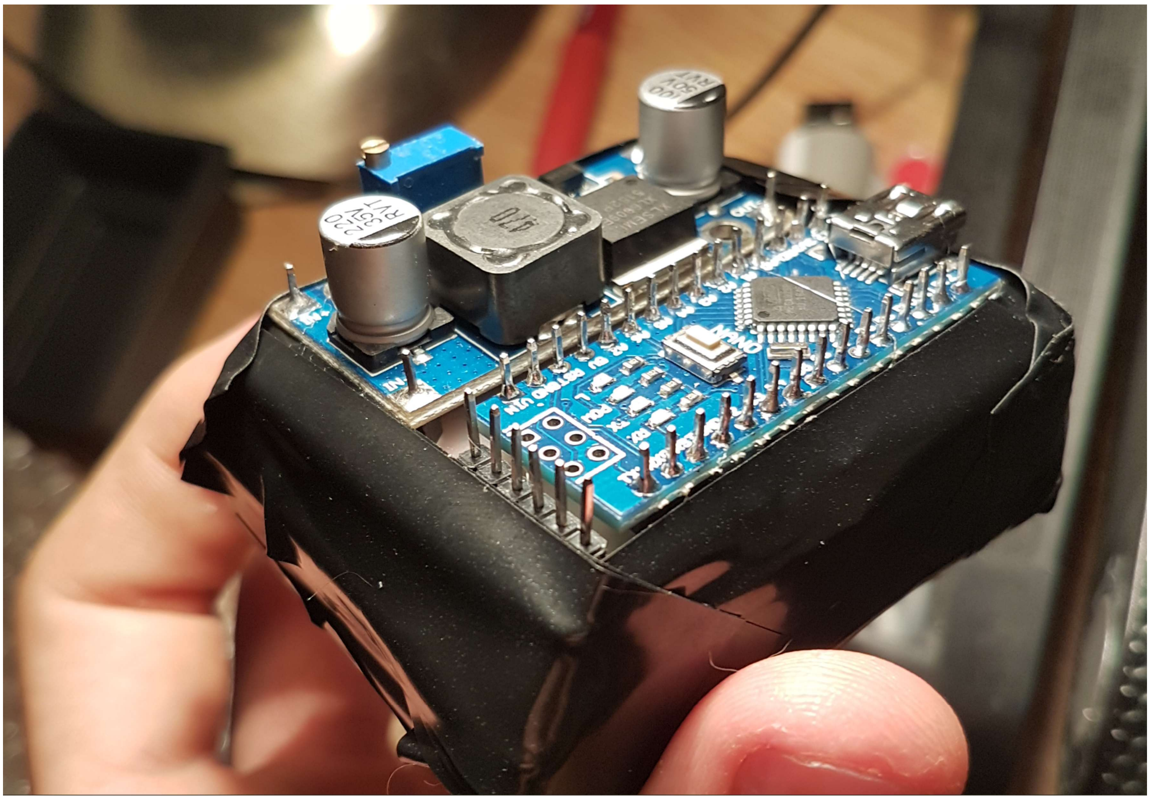
Above: The moment the balloon was launched.

The Science

Muons are subatomic particles that are much like electrons, but are much heavier and decay extremely quickly (with a half-life of 2.2 microseconds). The Earth is constantly bathed in high-energy cosmic rays, produced in part by distant supernovas. These rays interact with molecules in the atmosphere, producing many exotic particles, including muons. Those particles then rain down on the Earth.

The main interaction region for cosmic rays – the place where most muons are produced – is between 10 and 20 kilometres, because the atmosphere is extremely thin if you go any higher up, so there are few molecules to interact with. Since muons decay as they approach the Earth, the number of muons observed should decrease at lower altitudes[1].Therefore, the muon count rate should increase from a minimum at the Earth's surface, peak at around 20km[2], then begin to decrease. This means a high-altitude balloon (HAB) can go high enough to see the count rate turn over.

The muon detector is based on a design in a 2016 paper (arXiv:1606.01196). I had finished it before applying for the Rayson award, so I won't cover it in detail. The detector contains a special material called scintillator plastic, which is highly effective at absorbing muons and converting their energy to light (photons). It uses a solid-state photon detector called a silicon photomultiplier, which produces a current proportional to the number of photons that hit it. The device then amplifies, prolongs and measures this signal.

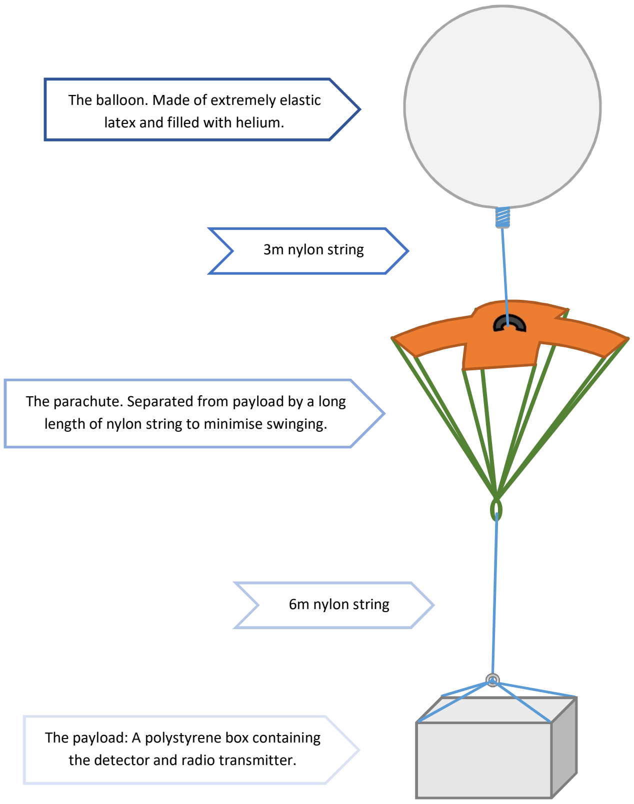


Above: The muon detector. The tape blocks ambient light from reaching the scintillator.

1. In fact, muons are a great example of Einstein's theory of special relativity in action. If you calculate the distance travelled by these muons classically, based on their speed of 99% of the speed of light, you would expect most to travel less than a kilometre before decaying. However, many are detected at the Earth's surface. This apparent paradox is resolved due to relativistic time dilation allowing the muons to survive for longer. Alternatively, from the muons' perspective, length contraction reduces the apparent distance they travel.
2. This peak is called the Regener-Pfotzer (or RP) maximum.

How It Works

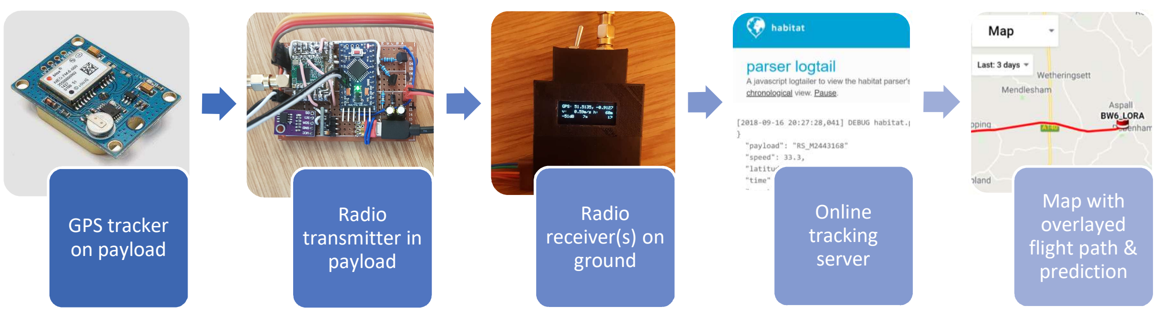
Below: The basic launch assembly.



The physics principles at work are fairly simple. A large balloon is inflated with helium, which, being less dense than air, generates an upthrust. This lifts the entire apparatus. As the balloon rises, the atmospheric pressure reduces, so it inflates further until it pops. The payload begins to fall, and a parachute attached between the payload and the balloon then opens up, slowing the payload's descent.

Unfortunately, if you simply put the muon detector in a box and send it up, you're never going to see it again. Tracking equipment is an absolute must – the payload can travel many kilometres over the ground in its flight. As described in the flow chart below, tracking is done via radio transmission of GPS coordinates down to a receiver on the ground, which uploads them to a website that can then predict the landing position.

Sounds fairly straightforward, right? To some extent, it is. In fact, there exists kits that contain all the necessary parts pre-made and well-tested. The problem is that these kits are extremely expensive, and I was working on a budget. In addition, as I had done with the muon detector, I was aiming to make as many parts as possible for this project in my bedroom. This called for me to create and test my own communication equipment and parachute.



Above: The five steps in the tracking process.

The Electronics

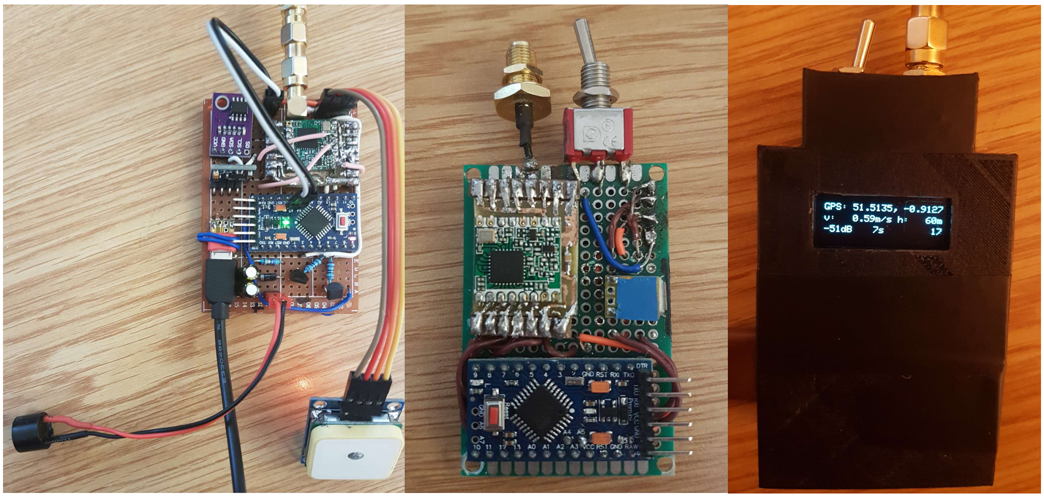
Modules

The first thing I had to do was figure out what kind of radio to use. The website of UKHAS[1] (the UK High Altitude Society) describes several types. The standard, well-tested method is to use a relatively cheap transmitter, sending data according to a radio protocol called RTTY. Unfortunately, since this was mostly used for radio in the past and is now only used by amateurs, receivers are effectively antiques and go for hundreds of pounds on eBay. That went slightly against my budgeting aims. There is another way to receive the same signals, using devices that plug into a computer called Software Defined Radio (SDR) dongles. These range in price from around £20-200. Unfortunately, the cheaper ones are either untested or unreliable at the long ranges required for high-altitude ballooning, and spending £200 was not ideal.

Luckily, there is a third method of transmission available that is gaining popularity but has only come into use relatively recently. It involves using electronic chips that can cost as little as £11, which transmit according to a protocol known as LoRa – standing for Long Range. Most similar radio modules do not have good enough range to use, but this protocol can allow for transmission over hundreds of kilometres if used effectively. I decided to choose this option.

Other modules I had to buy were a GPS receiver, a temperature sensor, a magnetometer, a voltage regulator and an OLED screen. The GPS receiver was, of course, used to track the payload's position during the flight. The muon detector's count rate depends on temperature (photons are also produced by thermal fluctuations in the scintillator) and angle (as this changes the vertically-facing cross-sectional area, and muons mostly travel straight down), hence the addition of the temperature sensor and magnetometer. The voltage regulator was used to efficiently step down the 5V power supply to the 3.3V required for the other components in the payload, and the screen was used in the receiver.

Finally, I needed a microcontroller[2] for both the radio transmitter and the receiver. I used the Arduino Pro Mini, a compact board which runs at 3.3V.

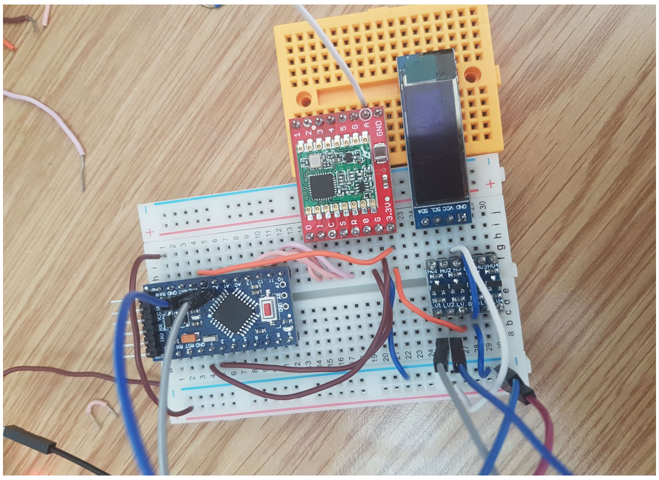


Above left: The transmission electronics. Clockwise from bottom right: GPS board, buzzer, USB input, magnetometer, temperature sensor, antenna output, radio chip, Arduino Pro Mini.
Above middle: The receiver electronics. Arduino Pro Mini at bottom, radio chip at mid left, USB input at mid right, antenna input and on switch at top, OLED screen on reverse side.
Above right: Receiver in case, with display showing last received packet information.

1. Their website is at ukhas.org.uk. It contains guidance about various aspects of high-altitude ballooning.
2. A microcontroller is a chip in a circuit that can be programmed from a computer to run any code, making it extremely versatile.

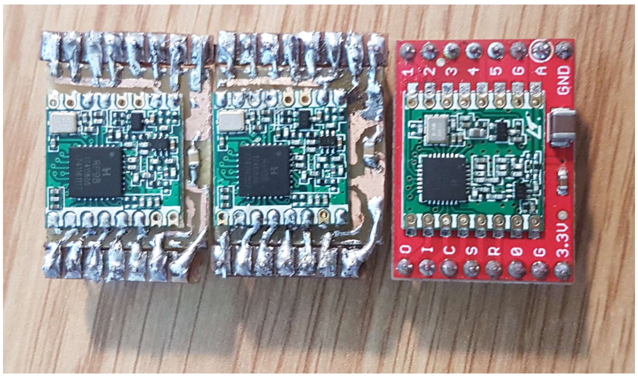
Creation

Before making soldering the components to a circuit board, I used breadboard to prototype (see right). This allowed me to test each of the modules individually. The GPS was hardest to set up, as I had to write code to listen in to a stream of binary data from the GPS module, searching through data packets for messages with the information I needed (latitude, longitude, altitude, ground speed). After this, I could test the components all together, ensuring that data was being sent reliably over radio. Once I confirmed everything was operational, I soldered the components to a piece of prototyping PCB with a grid of copper-plated holes. I then began to test the radio. I hand-made a yagi antenna[1] and attempted to test the signal strength. Unfortunately, the range was very disappointing: the signal didn't go nearly far enough to track the payload. To attempt to fix the problem, I bought a commercial yagi antenna and tried that instead, but obtained no better range than before. I eventually realised to my frustration that the radio chips that I was using were not, in fact, LoRa capable – I was using the RFM69HCW, but needed the RFM98W.



Above: The prototype receiver, on breadboard. The piece of white wire above the red radio module is serving as an antenna.

So, I went to search for RFM98 chips. Within a reasonable price range, they were only available in SMT configuration – that is, I only got the small green chip with metal contacts, rather than an entire board with holes for pins. My solution to this was to etch some small pieces of copper circuit board I had lying around, place a strip of Veroboard[2] either side, and solder everything together. This ended up with two inelegant but functional boards.



Above: Original RFM69HCW board on the right, 2x RFM98W boards cobbled together in its likeness on the left.

The signal strength was then much better: I had reception for over 2km on the ground, even when pointing the antenna in the wrong direction. This might not seem like enough, but signals can actually travel a lot further when communicating with HABs than they do on the ground, due to the line of sight communication – there are no trees, hills or houses to block the radio waves.

The last step was writing a script in Python[3] for my computer, which listened over a USB port for messages from the receiver, then uploaded them to a tracking website[4].

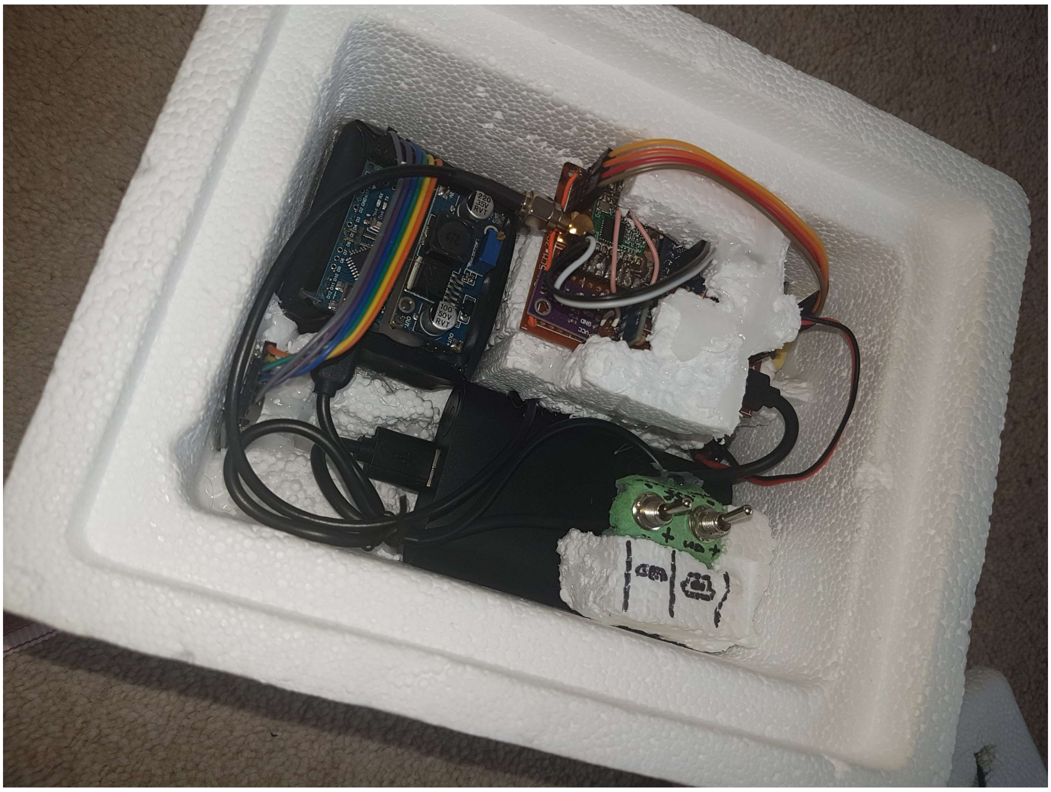
1. A type of highly directional antenna that you'd recognise from television receivers on houses.
2. A type of prototyping circuit board, using strips of copper plating with holes for pins in a similar layout to breadboards.
3. A popular and convenient programming language.
4. The website is habitat.habhub.org. Habhub is an excellent site used by practically all of the worldwide HAB community and has tools to predict your flight path days in advance from weather data, calculate burst altitudes and flight times, predict the landing site live during the flight from GPS data, and more. These open-source tools are developed by enthusiasts in the community.

Notes

Theoretically, my transmissions could also be heard by automatic and manned stationary receivers dotted around the UK, which could then also upload the data to the server if I didn't catch messages. However, due to my atypical setup, as well as some necessary changes the day before the launch, I ended up being the only one able to successfully receive and upload data for almost all of the flight.

Many, many hours and days were spent debugging and/or fixing the electronics and software. I've skimmed over several issues due to the space that would be taken explaining them. The most time consuming was a hard-to-trace problem with a solder contact on the handmade radio chips that caused the transmission to cut out after 0-2 packets were sent.

One important factor in the radio communication was staying legal. The 434MHz frequency band I was working in was unlicensed, but there were still restrictions in its use. In order to keep within power and duty cycle regulations, whilst maintaining a great enough range, the data rate had to be so low that it took around 17 seconds to transmit a single packet of around 65 bytes. For context, that's over a million times slower than the average UK WiFi speed!



Above: The payload, complete with all electronics. Muon detector top left, transmission circuitry top right, battery back and power switches bottom left.

The Parachute

Above Left: The newspaper prototype.
Above Right: The completed parachute. Bright colours for easy relocation.

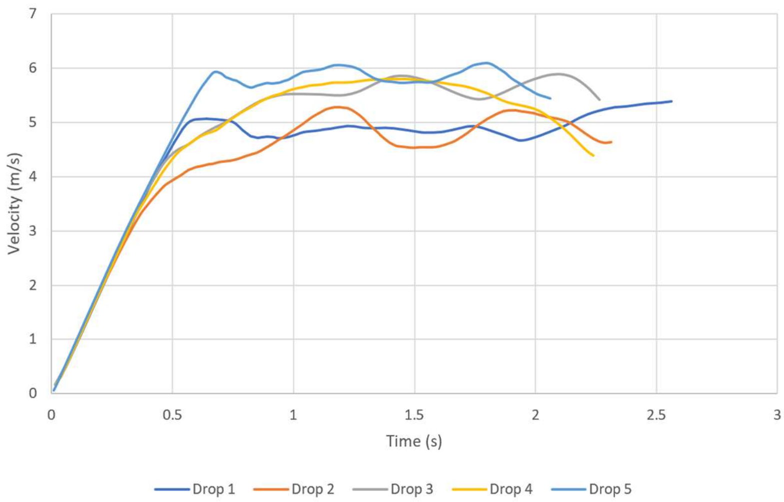
Explanation

It's inadvisable to simply gamble that your payload – travelling in freefall at 45 mph – will not land on a person, or on that person's house, car, or pet. Unfortunately, short of launching in Iceland, there's not much that can be done to avoid civilisation at the landing site. It's very important, both because of this and in order to protect the electronics in the payload from impact damage, to have the payload falling at safe speeds. However, it's also a bad idea to for the payload to fall too slowly, or it's likely to drift for long distances and land somewhere in the ocean. Consequently, the target descent velocity is between 5 and 7 m/s.

Construction

Using online instructions[1] I made a cross form parachute. I calculated the scale factor I would have to reduce the online version's size by in order to get the correct lift, made a test parachute out of newspaper, then moved on to making one out of strong materials. I used two panels of ripstop nylon for the canopy, gave them a wide hem on the longer sides, stitched them in an X shape, inserted paracord into the hem, stitched it to the fabric, and finally stitched an attachment loop on the top. This was done mostly by my grandma, using a sewing machine. Two sections of heat-shrink tubing were used to form the end loop, allowing for final cord length adjustments. A tape-covered cardboard separator was used to minimise entanglement.

Below: Parachute drop velocity-time graph. One drop's data was omitted as the parachute and payload hit the tower on the way down.



Testing

I emailed the local (Henley) fire department and was given permission to use their tower, as it was the tallest place around to use for drop tests. I took advantage of the accelerometer in my phone, downloading an app[2] that allowed me to record and export its data in order to calculate its vertical velocity. I placed it in a padded box with the same total mass as my payload, and with the help of three firefighters, it was dropped a distance of around 10 metres, a total of 6 times. The terminal velocity was found to be between 4.8 and 5.8 m/s – easily acceptable.

1. Tutorial found at www.nakka-rocketry.net.
2. Physics Toolbox Suite (free version) on the Google Play app store for Android.

Launch Day

The Theory

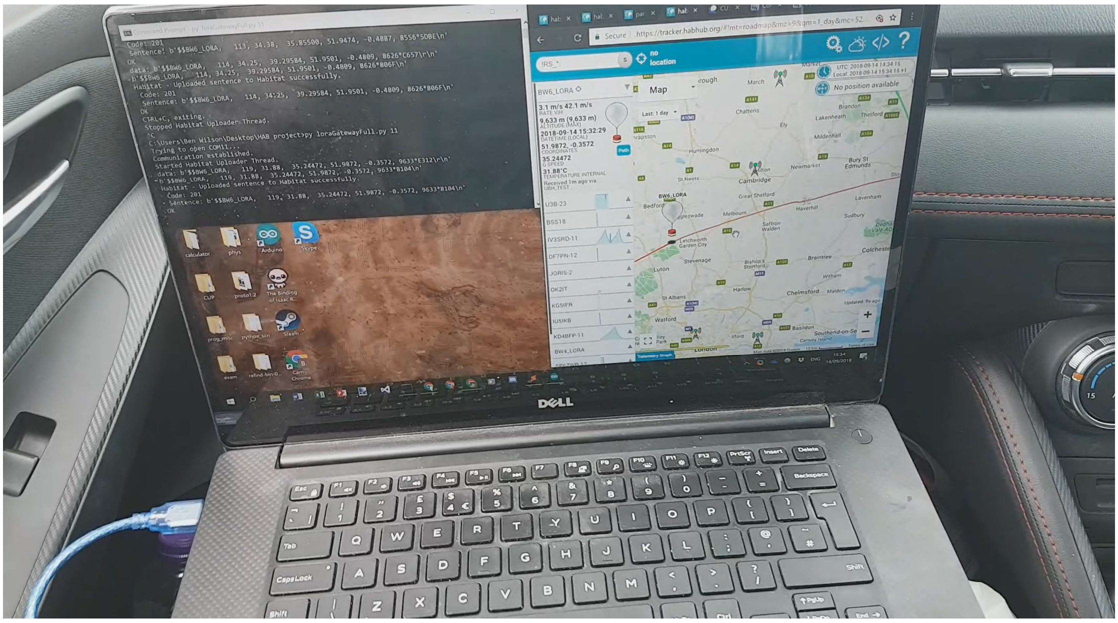
30 days prior to the day of the flight, permission should be gained from the Civil Aviation Authority (CAA), and a document called a NOTAM is issued one day before the launch before to notify pilots of the flight hazard. The predicted flight path needs to be periodically checked during the days before the launch to ensure the payload is safely away from oceans, cities, and CAA-restricted zones given in the NOTAM. Then, on the day:

- The telemetry equipment is checked – does it have a GPS lock? Is it uploading?
- The payload, parachute and balloon are connected with nylon string.
- The balloon is filled up with a calculated amount of helium. Weights are attached with a safety line to figure out when the correct lift force is reached. Several people are required for holding the balloon down, controlling the helium supply, and protecting the balloon from too much stress and wind, ensuring it doesn't burst prematurely.
- A final telemetry check is carried out.
- The balloon is released – time to sprint to the car and start driving to the predicted landing site!
- While in the car, the balloon is tracked by yourself and by others, and the predicted landing site is updated correspondingly. Having others help track significantly increases the chances you'll receive the signal and be able to recover the payload.

Above: The process of filling the balloon. Gloves are worn to avoid damaging the latex with oils from our skin, and the sheet is used to stabilise the balloon against wind.

- This process continues. When near the predicted landing site, it's best to get to some high ground, from which you can track the payload's final descent, get an accurate prediction of where it'll land, and hop in the car to see if you can watch it hit the ground.
- If you don't see it land, track it from the ground, first by rough GPS coordinates, then (especially if GPS fix is lost) by using a directional (yagi) antenna: you observe how the signal strength changes with the direction you point it, and attempt to zone in on it that way.
- Retrieve the payload!

Of course, with an atypical, homemade, first-time flight, things weren't going to go that smoothly.



Above: My laptop, about 20 minutes post-launch. The right-hand window shows the balloon position and its flight path prediction. The top-left window shows radio messages and their upload statuses.

The Reality

Months before the launch, I did several days of work experience at European Astrotech – who do launches fairly frequently – where I helped them with a separate launch, learning for my own one. I ended up using their Westcott site to launch from, which had permanent CAA permission and only required a NOTAM.

- I tested the telemetry. After a small amount of configuration, data was being successfully uploaded to the Internet server by both my receiver and theirs.
- We began filling the balloon with few hitches. It was a fairly windy day, making it hard to measure lift, so we overfilled the balloon to err on the side of safety, as it would then travel a shorter distance.
- I checked that the balloon was still sending its GPS data and let go of the balloon. I, my mum, and my grandma got in the car to begin the chase. I set up the receiver with an antenna and my laptop, gave myself a portable WiFi hotspot from my phone, and tried uploading the radio messages to the server… to find it wasn't working. I was receiving data on my receiver but the server refused to accept it[1]. This prevented me from using the website's live map for landing predictions, and prevented others from helping me track with their own antennas.
- Quite panicked, I spent several minutes writing a script in Python to fix the issue, getting the server to accept the data again. I could now track the balloon with the website again, but tracking was now almost entirely in my own hands[2].
- At 12km, the balloon lost its GPS lock, as the GPS was set to pedestrian mode – making it cut out for 'safety' over a certain height. After the launch I discovered the range could have been increased, but only to 18km, at which point GPS shuts off for military reasons.
- As the balloon travelled further, and my small car-mount antenna lost signal, I replaced it with my yagi antenna, stuck partially out of the car window.
- We drove for over an hour without knowing the payload's location, hoping it would follow the predicted flight path.

1. The problem was a previously-unseen issue with the checksum – a number added to each message calculated from data within the message itself, which the sender and receiver calculate independently and compare, to see if the transmission has been corrupted. The server's checksum calculation algorithm (unlike mine) ignored spaces at the end of the message, and some had been indirectly added in due to necessary last-minute changes. The Python script I wrote stripped the checksum off the end of the message and replaced it with another, calculated in the same way as the server.
2. Occasional messages came through without trailing spaces, which others could upload without errors, but for the majority of the flight I was alone in tracking the payload.

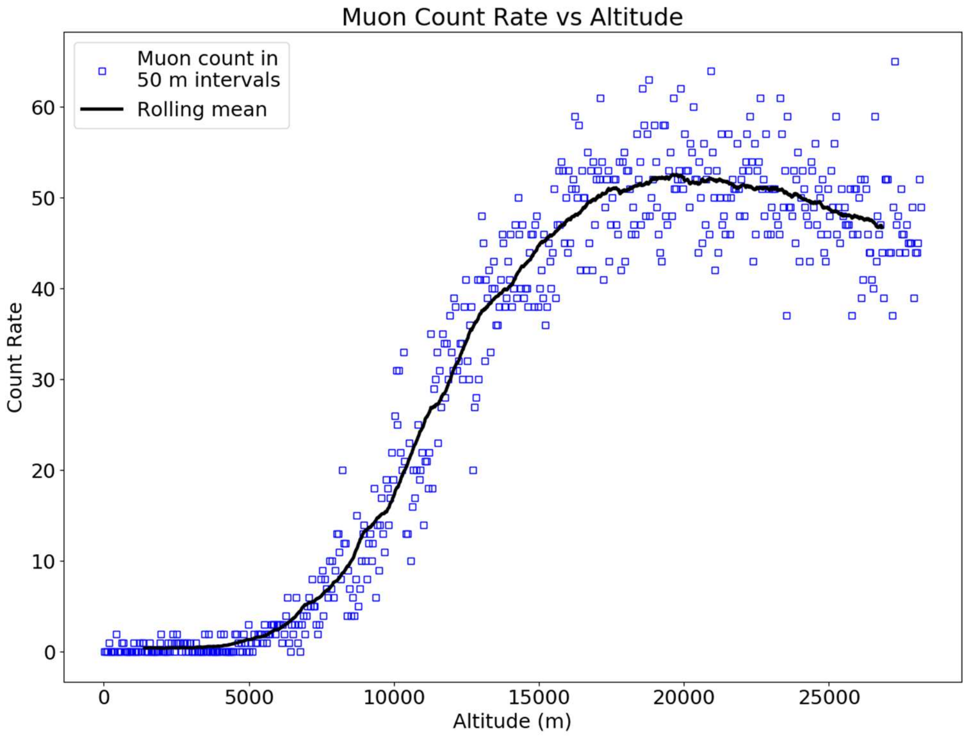
- Eventually I received a packet with GPS lock, saying the payload had deviated by around 20km from its predicted flight path and was at 10km height. The GPS lock was then lost for a long time. This was worrying, as it raised concerns that the payload would land without a GPS fix, in which case the range would be significantly decreased and the payload would be almost impossible to find.
- Finally, as hope was fading, a new GPS packet was received, showing the payload to be almost exactly on its original path and at around 10km altitude again. As it turned out, the previous coordinates had been extremely inaccurate, and the payload went on to land around Debenham – not far from its original predicted landing site.
- Despite driving from almost the moment of launch, we approached Debenham 10 minutes after the landing. Stopping at high ground nearby, I checked the signal direction, finding an extremely strong signal that suggested I had line of sight.

Above: Consulting the radio in the field before Debenham. The payload was found by the ploughed field seen in the distance, on the right-hand side.

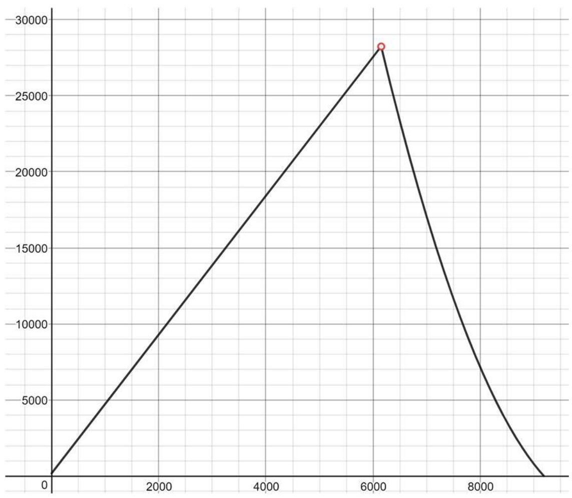
- We drove to the field the signal was coming from, searched for a few minutes, and quickly found the payload dangling from a tree next to the field. Luckily, we had brought a long pole and pruning scissors, letting us cut it down, recovering the electronics, which were intact and safe inside the box.
- With a successful mission, we celebrated in the local pub!

Below: The payload (left) and its parachute (right), stuck in a tree.

The Results



The output of the project is the graph above. To make it, I first reconstructed the altitude profile of the flight, since I only had data below 12km. Luckily, HAB flights have a fairly consistent shape for their altitude-time graphs, and curve-fitting the available data yielded a graph with a sensible profile and burst altitude (28.3km). I wrote a Python script to go through the timestamp for all muon detection events, find the corresponding altitude, split them into 50m intervals, and calculate the count rate for each interval.



$y_1 \sim a x_1 + b$

STATISTICS

$r^2 = 0.9995$

$r = 0.9998$

RESIDUALS

e_5 plot

PARAMETERS

$a = 4.56285$ $\quad b = 172.96$

$y_2 \sim a x_2^2 + b x_2 + c$

STATISTICS

$R^2 = 1$

RESIDUALS

e_2 plot

PARAMETERS

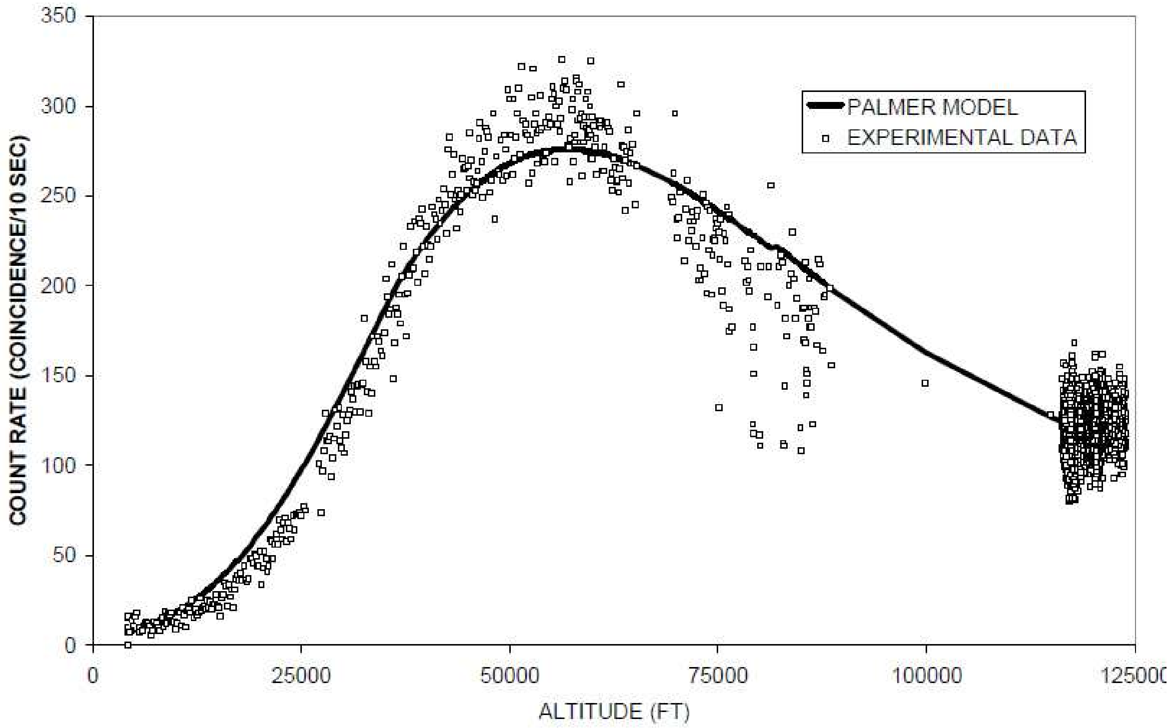
$a = 0.00177208$ $\quad b = -36.4785$

$c = 185566$

Above Left: The graph of altitude (m) against time (s). Created on Desmos graphing calculator.
Above Right: The fitting curves, with correlation coefficients and parameter values. Also calculated in Desmos.

For multiple reasons (the altitude reconstruction, rotation of the payload during the flight[1], limited sensitivity of my detector), the data is only qualitative. However, the graph agrees with both the theoretical curve shape and existing studies very closely, and the peak in count rate at about 20km is clear. With the resources and budget available to me, I consider the experiment to be a thorough success.

Below: Count rate and theoretical model curve against altitude, from the West Virginia University High Altitude Cosmic Radiation (HACR) Detector Payload Summary and Flight Science Report (2007).



1. Once I found that the data transmission rate had to be extremely slow, I removed the data sent from the magnetometer – partly because the angle would be changing far too quickly for meaningful data to be given, and partly to reduce the message size for faster transmission. Instead I assumed the random motion would lead to an approximately uniform vertical cross-sectional area on average.

Costs

Below is a breakdown of the costs of the HAB segment of the project (since the muon detector was already built at the time of receiving the John Rayson award). The detector cost below £100 thanks to several companies who generously donated the more exotic and expensive components.

Category	Description	Quantity	Total cost	Notes
Launch day costs	800g Hwoyee balloon, helium cylinder	1	£ 100.00	Bought directly from European Astrotech - not entire helium cylinder used, so cheaper than direct hire.
Materials	1mx1.5m 3.8oz ripstop nylon	1	£ 3.45	Bright orange strong fabric for parachute canopy.
	12.5m 2mm braided nylon cord	1	£ 1.19	For parachute-payload and parachute-balloon links.
	31m 550 7-strand nylon paracord	1	£ 5.99	Parachute lines.
	180m spool strong nylon thread	1	£ 2.99	Threading for parachute.
Payload	Polystyrene box	2	£ 7.95	Payload housing. 2 bought for material put inside to wedge components in place and in case one was ruined.
	Aluminium adhesive reflective tape	1	£ 2.29	Thermal insulation.
	Hand warmer	1	£ 1.99	Placed inside payload to combat lost heat.
Radio equipment	50cm SMA cable	1	£ 2.39	For 1/4 wave antenna on payload.
	SMA male/male coupler connector	1	£ 4.20	
	UHF/VHF magnetic car mount antenna	1	£ 2.41	
	SMA perpendicular pin connector	2	£ 2.95	
	434MHz Yagi antenna	1	£ 32.82	
Electronics	Arduino Pro Mini w/ headers	2	£ 10.50	A small form-factor 3.3V microcontroller.
	FTDI USB serial adapter modules	3	£ 9.00	For communication between computer and Arduinos. 3 minimum quantity.
	RFM69HCW 434MHz breakout boards	2	£ 19.98	Shorter-range radio chips that were later replaced.
	LoRa TRX 434MHz SMT chip	3	£ 33.96	One extra bought due to long delivery times in case one broke. One did go broke, so this was a good idea!
	Ublox NEO-7M-00 GPS module	1	£ 8.00	
	LM75A temperature sensor	1	£ 4.69	
	HMC5883L triple axis magnetometer	1	£ 4.85	
	Micro USB connector breakout board	5	£ 3.30	For powering electronics. 5 minimum quantity.
	OLED display	2	£ 9.99	For receiver display. 2 minimum quantity.
	2600mAh power bank	1	£ 3.99	Power supply for radio receiver.
	5200mAh power bank	1	£ 6.99	For payload electronics (transmitter & muon detector)
	5V to 3.3V linear regulator	5	£ 2.33	For lowering voltage efficiently in payload.
	Electrolytic decoupling capacitors	10	£ 0.99	Voltage smoothing in payload.
	Mini SPDT switches	5	£ 3.95	1 used in radio, 2 in payload. 5 minimum quantity.
	Total costs		**£ 293.14**	

Final Thoughts

There are two main things I took away from the combined muon detector and HAB project.

The first is that, if you're willing to reach out, it's amazing how many people are willing to help. Every individual or company in the following list was immensely helpful, whether by donating parts, giving guidance, or otherwise offering support:

- Sammy Graham at European Astrotech,
- Spencer Axani at MIT,
- Edel Cashman, applications engineer at Sensl,
- Ian Shipsey, head of particle physics at Oxford University,
- Adrian Rayson, benefactor of the award,
- The companies Sensl and Eljen, which donated parts,
- Several Abingdon members of staff, who offered advice and access to some of the school's physics and DT equipment,
- Henley Fire Station, who made drop testing possible,
- And – of course – my grandma, who helped make the parachute, and my mum, who drove around the country for 10 hours on launch day.

To begin with, I was extremely tentative about bothering people by sending an email asking for guidance. Over the course of the project, my confidence only grew and grew as almost everybody who I contacted responded with enthusiasm.

The second is the value of perseverance. There were countless times in the last two and a half years that I ran into roadblocks, and more than one occasion when I worked on something for days or weeks, only to have to re-do everything when it went wrong. With the backdrop of A-levels, as well as UK and US university applications, there were times when I became highly stressed, and when I felt like I was getting nowhere and that I should quit. However, I always kept going – sometimes after two weeks' break, sometimes by moving onto a different aspect of the project. Without perseverance, I never would have finished the project, and with it, I've learned how much I can accomplish if given enough time.

I would recommend to anyone to try to start their own long-term project. Not necessarily something as STEM-based; just something that will take time and tenacity to finish. In years' time, you'll look back, and you'll see just what you can do if you put your mind to it.