A Mathematician's Apogee

Last summer, with the help of an IMA Small Grant, Paul Shepherd spent 10 days in the Nevada Desert as part of a team of UK researchers searching for signs of life in the stratosphere. Working alongside astrobiologists from NASA, and with a group of rocket enthusiasts, the team built a self-contained testing laboratory and launched it into the stratosphere. This paper describes the highs and lows of the expedition, discussing the various aspects of mathematics, biology, chemistry, physics, engineering, telecommunications, computing and rocketry encountered along the way. It also goes a long way towards proving that what goes up … must indeed come down … somewhere … and quite possibly with a bang!

The Background

It started innocently enough. Having met Dr Oliver de Peyer (Ol) and Dr Melissa Grant (Mel) whilst participating in the *National Endowment for Science, Technology and the Arts (NESTA) Crucible* inter-disciplinary programme for early career researchers back in 2008, I was invited to get involved in their consequent NESTA-funded research project to put a biological experiment on a helium balloon and launch it over the UK to see if they could detect any living organisms high up in the atmosphere. The higher up you go, the less air there is per cubic metre, and so the less chance you have of finding any organisms in a given sample volume. The endeavour was analogous to panning for gold, hunting through huge quantities of fluid in search of a tiny speck of interest, and the mission was therefore named 'High Altitude Bioprospecting' or 'HAB' for short.

HAB needed someone with expertise in structural analysis to help design lab equipment light and strong enough to perform when slung underneath a balloon; knowledge of rapid prototyping *3D printer* technologies to actually build the specially shaped components for their equipment; and skills as a software programmer to help control the equipment once in flight. Obviously only a mathematician would have such an all-round and transferrable skill-set, and I was happy to agree to help out where I could. Over the next two years the project went through a number of indiscriminate changes in direction, until I finally found myself on a flight to the USA to meet researchers from NASA, about to spend ten days in a motorhome in the middle of a desert to launch a rocket into space!

The Motivation

Although it sounded like a lot of fun, there was (also) a serious side to our endeavour. If we were successful in finding life in the upper reaches of our planet's atmosphere it would have huge repercussions throughout the field of astrobiology. We were searching for *extremophiles*, organisms which thrive in extreme environments that are uninhabitable for most life found on earth. You may be familiar with the organisms which colonise deep-ocean hydrothermal vents and manage to survive huge pressures and temperatures in the mineral-rich waters at the bottom of the ocean. However, the extremophiles we were hunting would be capable of living high up where there is very little atmosphere but lots of UV radiation. These levels of radiation would certainly be harmful to humans, and would cause mutations in our cells leading to skin-cancer. So if life can be found in these types of environments, it must have evolved a method of either preventing, or more likely repairing, cell damage caused by UV radiation, and could possibly lead to the development of techniques to allow similar repairs on human cells. We were searching for a cure for cancer!

There was also a strong desire by the HAB team to use the project to promote the public understanding of science. The rocket enthusiasts we were collaborating with, the '*Rocket Mavericks*', were engaged in a STEM education programme in collaboration with the Discovery Channel, and had invited a team of high-school students to get involved in the design and construction of the rockets that we were going to use. The HAB team, with the help of Dr Rachel Brazil of NESTA, organised a competition for 16-18 year old science students across the UK, to search for two lucky winners who would join Rachel and ourselves on the trip and play an active part in the mission. After filtering over a hundred applications and inviting six finalists to a selection day in London, Joe Campion from Nuneaton, and Rainbow Lo from Wimbledon, were finally selected and joined us in the desert. They learned all about building and flying rockets, as well as getting involved in our research by measuring and recording the background distribution of biological contamination. The whole HAB team also took part in a number of art projects, kept diaries, and recorded their experiences with photos and videos, and I certainly intend to use the material I gathered as part of my own STEM outreach work.

The Location

Dealing with the usual two dimensions first, the site of our launch was the *Black Rock* desert in north-west Nevada, USA, (40.8° N, 119.14° W). The main feature of this fascinating and unique landscape is a dry lakebed, known as the '*playa*', which extends 160km northeast of the nearest village, Gerlach, and has an area of over 2,600km^2. It is completely flat and barren, and has often been used for land-speed record attempts. Its remote location and uncontrolled airspace makes it ideal for launching rockets, since rockets are unlikely to interfere with any aircraft and falling debris is unlikely to damage anything, except perhaps the rocket 'launchees' themselves. That is not to say there have not been some near-misses in the past, especially with the railroad which skirts the playa, and a direct hit through the windscreen of a car, luckily empty at the time. However this remoteness also made the logistics of our trip rather complicated.

In the vertical dimension, our experimentation was to take place above the desert in the stratosphere at what is usually described as 'the edge of space'. It would not technically be 'in space' since it would not be crossing the *Karman Line*, an interesting mathematical limit which is used as the definition of where space begins. The higher you go, the thinner the atmosphere, and therefore in order to generate the same lift, an aircraft with a wing would have to travel faster and faster. The Karman Line marks the height limit whereby, in order to stay aloft, even a theoretically optimum aircraft wing would have to travel so fast that it would reach orbital velocity like a satellite. Whilst rockets can and do go higher than this line – the first being the German Second World War V2 rocket and the first amateur rocket having been launched from the very same Black Rock desert in 2004 – our rocket was only expected to reach an altitude of 40km. This is still much higher than the cruising altitude of commercial airliners, and meant that we required US Federal Aviation Administration (FAA) permission for our launch. A time-slot had been allocated one-month in advance and this dictated when we could launch our rocket, since during this window, all commercial aircraft would be re-routed away from the skies above us.

The Experiment

Most experiments which search for life in the stratosphere, including that of the *Astrobiology* team from *NASA Ames* we were working with, aim to capture a sample of air from the stratosphere, filter it to retain any solid particles, and then return the sample safely back to earth for analysis in the laboratory clean-room to identify whether any of the particles are from living organisms. This approach means that the actual equipment which is launched into the sky can be relatively simple, combining an inlet valve, pump, and some sort of filter and storage. The down-side however, is that despite all attempts to sterilise and clean the equipment, both before and after the flight, there is always a question-mark over whether any detected organisms really were present up in the stratosphere or whether they have been introduced through contamination on the ground afterwards.

HAB's approach was somewhat more ambitious. The idea behind our experiment was to perform in-flight testing of samples, to detect signs of life in-situ, therefore removing any possible contamination and truly signifying the presence of life in the stratosphere. The obvious down-side to this technique was the need for a much more complicated piece of equipment. The experiment, as shown in Figure 1, consisted of syringes to pull and push air around a system of tubes. The air was sucked into a sterile chamber and bubbled through detergent to break open any bacteria or spores present in the air to release their DNA. The mixture was incubated at 37°C using heated water piped around the outside of the chamber. An enzyme mix called *TwistDX* was then added, a recent innovation which can amplify specific segments of DNA at this low temperature, along with a dye called *PicoGreen* which binds to DNA and fluoresces at a wavelength of 520nm under turquoise (480nm) light supplied by an LED. A light sensor was then used to detect any fluorescence at the 520nm wavelength, therefore indicating the presence of DNA. The syringes were moved by connecting them to shape-memory-alloy (SMA) springs. We passed a current through the SMA springs, which heated them, causing them to contract. Since the SMA is slow to recover its original shape, these springs were used in pairs much like our own muscles, with one spring causing the plunger to withdraw from the syringe and another pulling in the opposite direction to push the plunger back in. More SMA springs were used to open and close valves in the tubing, so that for example by lifting the plunger air could be sucked into the main syringe through an inlet tube, and then the inlet tube could be closed off and the tube leading to the reaction chamber opened so that when the plunger was returned; the air went into the chamber instead of back out into the atmosphere.

Figure 1: HAB experiment during testing

The whole system was controlled by a small Single Board Computer (TITAN PC104 with ARM processor running Linux) and programmed via a combination of C and shell-script. The computer had digital outputs to control the SMA springs, Heater and LED and analogue inputs to record air temperature and pressure, reaction temperature and the level of 520nm fluorescence detected. An onboard radio modem allowed us to communicate and interact with the computer during flight and everything was powered by radio-controlled car type lithium battery packs which we had to keep a constant supply of by continual recharging from the motorhome batteries.

The Rocket

Our first experience of the Rocket Mavericks was when we arrived in a peaceful residential suburb of San Francisco, and we knew we had found the right house not because of the American accented ‘you have reached your destination’ announcement from the in-car GPS, but because of the large trailer containing a dismantled rocket launch gantry parked outside. Inside, the otherwise inconspicuous garage door, was an array of tools, nose-cones and stabiliser- fins, not to mention a centrifuge for making explosives. Tom Atchison (Tom) the head Maverick, handed around the heavy cylinder shown in Figure 2 of what felt like cement and told us, ‘don’t drop it, that’s what we call a ‘grain’, a high-power rocket propellant’. In answer to our worried and sceptical looks, he said ‘if you don’t believe me, wait until we throw one on the barbeque out in the desert and then you’ll see’, something which turned out not to be an idle threat!

This was the first opportunity to test whether the (still not finished) HAB would actually fit inside the rocket the Mavericks had constructed. Thankfully, despite the infamous problem of conversion between imperial and metric units, the answer, as shown in Figure 3, was a very tight ‘yes’. However, HAB was much larger than the Mavericks had been anticipating, which meant there was not enough room on the large rocket for both HAB and NASA’s experiment. The original plan had been to test-fly HAB on a (relatively) small rocket first, and then send both HAB and NASA’s experiment up together on a larger rocket.

In this way they could validate each other’s results and if HAB detected DNA it would be powerful evidence that anything the NASA capture-and-return equipment collected had indeed been found at altitude and not as a result of contamination on the ground. Since there was not room for both experiments in the larger rocket, the NASA team got the ‘P’ rocket to themselves, and HAB’s planned test-flight on the ‘O’ rocket became its only flight, so we adjusted our expectations of how high it might go accordingly.

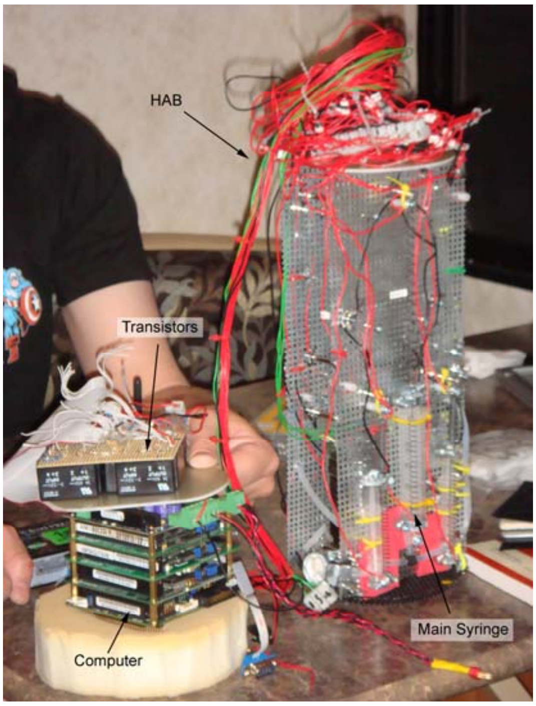


Figure 2: OI holding a Grain

Figure 3: HAB fit-test (left) with the IMA logo attached (right)

Rocket motors are classified by a letter of the alphabet to denote their total impulse on a logarithmic scale. An 'A' rocket motor can deliver up to 2.5 newton-seconds (Ns) of impulse, a 'B' motor can deliver twice this, a 'C' motor twice that of a 'B' motor, and so on, with each successive classification having twice the impulse of the previous. In the UK, non-commercial rockets usually go up to category K or L, although there has been one 'N' motor launched, which made the national news. HAB was to be launched on a twice-as-powerful 'O' motor, the same category as a cruise missile, with 40,960Ns total impulse provided by five of the cylindrical 'grains' we had passed around in the Mavericks' garage. The grains burn outwards from the hole up the middle, with the hole growing ever bigger until all the fuel is spent. The thrust each provides is proportional to the burning surface area, so as the grain burns, the surface area increases and the thrust increases. The exact nature of the way the thrust changes during the flight can be pre-determined by shaping (cutting grooves in) the hole up the centre of each grain.

With HAB successfully fit-tested, and the IMA logo safely attached to the rocket body with sellotape (see Figure 3), all that remained for us to do was to drive out into the desert, finish constructing HAB, program the on-board computer, sterilise everything, and wait for our flight window.

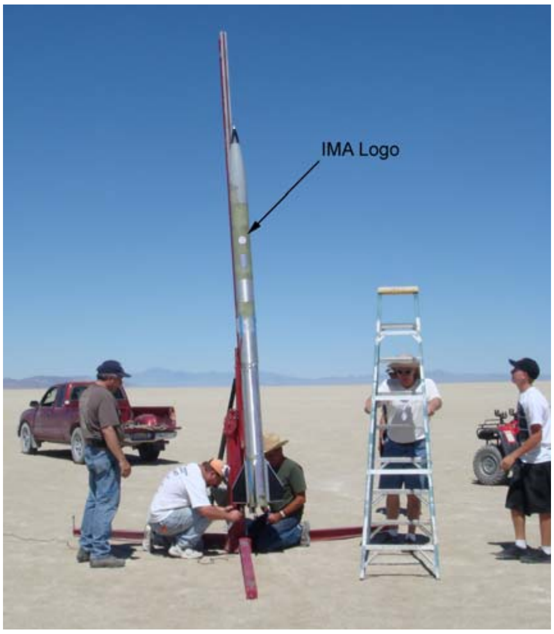


Figure 4: HAB on the launch-pad

The Launch

The HAB team had been working all through the night before, soldering, programming and battery-charging, with the noise from our motorhome generator keeping the majority of the camp awake too. Last minute problems with the Mavericks' launch and GPS location systems resulted in a mad rush to get everything ready in time to fly HAB before the FAA flight permission waiver expired at 3.30 pm.

We were rather worried that HAB's electronics might overheat in the >40°C desert sun whilst we waited for the Mavericks to make their preparations, but in the end everything seemed to come together and the rocket was assembled and attached to its launch rail (Figure 4).

Before any launch, a series of computer simulations need to be run to satisfy the requirements of the FAA and the insurers. A six degree-of-freedom problem is solved, taking into account location, wind and weather data, in order to model the trajectory of the rocket on its way up, and most importantly on its way down, to predict the eventual landing position. A Monte-Carlo simulation is run to calculate a three standard-deviation confidence interval for the problem, and the probability of causing a fatality (landing on a built-up area) needs to be less than 1 in 10 million before a launch can take place. Similarly, very strict protocols were in place for checking and re-checking each step in the preparation, with no mobile phones or radios allowed nearby in case they interfered with the launch control electronics. After a final visual check that there were no passing pedestrians, cars, trains or aeroplanes, countdown finally began around 3 pm on 19 July 2010.

Since one of my responsibilities had been to write the software to control HAB's various valves and syringes, I was allowed amongst the limited number of people at the forward command post during the launch. I had to start HAB's program running and monitor its progress. We were told if the rocket looked like it was coming towards us to 'get behind a car fast'. Unfortunately we would have less than a second to do so before the rocket travelled the 1km to where we were parked. Everyone else was standing well back – two and a half kilometres back to be precise. The countdown began at 20, 19, 18…it was held at 10 whilst I checked that all the equipment on board HAB was working correctly and gave the go ahead to continue,…9, 8, 7…, after 5 there was no going back – countdown would continue through to launch come what may, 3, 2, 1 … At zero, Ol pushed the launch button and watched 14 months of his hard work accelerate into the sky. With a flash, whoosh and the huge cloud of desert dust shown in Figure 5, the rocket took off and flew straight up into the air, accelerating at about 7g. It was easily visible as a trail of white smoke against the clear blue sky until, after only 8 seconds, the fuel was spent and it reached its maximum speed of about Mach 1.4. HAB then continued to rise, but ever more slowly as gravity began to take hold, and after what seemed like an eternity, but was only 42 seconds after launch, HAB reached its apogee, the highest point of its trajectory, 8km above the ground.

Figure 5: Lift-off, © Melissa Grant

What should have happened next was that one explosive charge would separate the motor booster section of the rocket from the part containing the experiment. These two sections would then float down to the ground separately, each under its own parachute, since they were too heavy to be controlled by one single parachute. The parachutes would be deployed via another small explosive charge which would eject a small drogue parachute, just big enough to catch sufficient air to pull out the main parachute. Opening a parachute at high altitude has minimal immediate effect, since there is not enough air up there to provide any drag, and so HAB was expected to accelerate downwards until reaching terminal velocity of about Mach 1.2. Once the atmosphere thickened sufficiently, HAB would quickly start to slow down and drop at a leisurely 15km/h, giving plenty of time to repeatedly suck in air and test it for signs of DNA, before being shut off and sealed to make sure detection took place at high altitude and not during the latter stages of descent.

That is what ‘should’ have happened. What ‘actually’ happened is that HAB fell back down to earth like a stone, hitting the playa floor nose-first and embedding the entirety of its 66cm long nose-cone into the ground before breaking in two, leaving the nose-cone buried and the rest of the fuselage lying on the floor with HAB inside (see Figure 6). Even the IMA logo had become detached and was lost forever! This was not quite what we had in mind when we said that it was important for our research to have impact.

Figure 6: Nose-cone buried (left) and excavated (middle) with the logo-less fuselage (right)

It seems that in all the rush to get HAB ready in time for its allocated time-slot, ‘someone’ forgot to pack the drogue parachute. Instead of a gentle controlled descent, HAB went ballistic until the main parachute eventually shook free, by which time it was travelling far too fast to deploy properly and was simply ripped and tangled up. It did provide some air-resistance, and kept the fuselage pointing more or less downwards, leading to a nose-first impact into the floor, but provided nowhere near enough drag to properly control the descent or cushion the impact sufficiently to protect the rocket’s valuable contents.

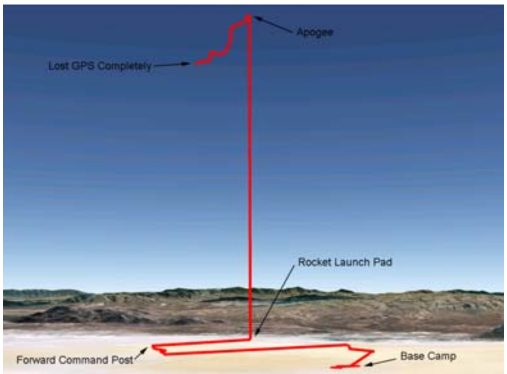
The nose-cone had to be dug out of the ground in order to leave the playa as we had found it, and it took a good half-an-hour with hammer and pliers back at camp to remove HAB from its snugly fitting rocket tube. We had packed all the solid, heavy parts of the equipment, such as the computer unit, battery packs and power transistors, in the bottom of the fuselage, with the lighter and more delicate syringes and SMA springs in the top towards the nose. This meant that on impact with the floor, all the heavy objects acted like a piston and rammed into the softer biology/chemistry parts, squashing them against the bulkhead. What started as a 40cm high metal frame with delicate springs, tubing and chemicals ended up as the crushed cylindrical lump with broken tubes and split syringes shown in Figure 7. We know from the data transmitted by HAB during flight that it captured air samples, but they were certainly lost to the desert wind on impact.

Figure 7: A rather squashed HAB

The Post-mortem

After plenty of philosophising, soul-searching and trying not to blame the Mavericks for the lack of drogue parachute, and after catching up on our much needed sleep, we picked through the debris to see what could be salvaged. There was surprisingly little damage to the computer itself and we tried to get it to talk to the laptop through its network port but without success. We were hoping to be able to download the log-file which kept a record of the flight and the successful actuations of syringes and valves to see how far through its routine of sampling and testing it had got before impact, but it showed no signs of life. HAB was officially pronounced dead at 10.06 am on 22 July.

The Mavericks' equipment came out of the incident somewhat better off than HAB. It seems that similar 'problems' have happened in the past and they have evolved a robust structural and software platform and are always prepared for the worst. Their guidance system reads GPS data, accelerations and barometric pressure from sensors and saves the data to on-board memory cards. This means that even if their electronics are physically damaged on impact, the memory cards can be removed from the rocket and are usually still readable.



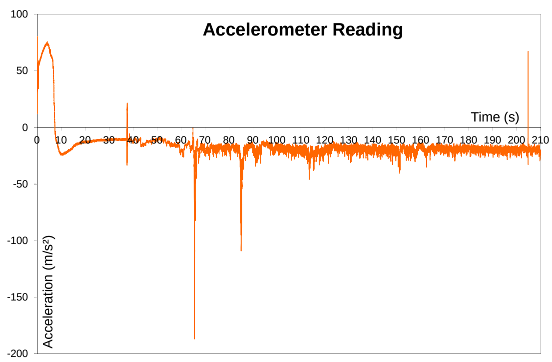
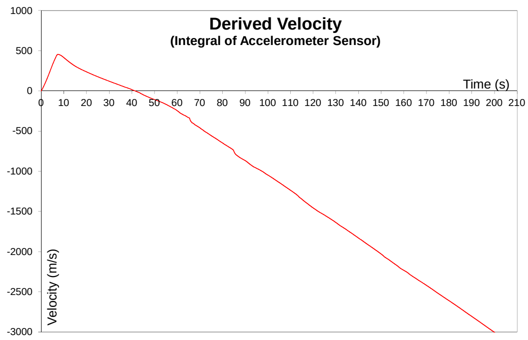


Figure 8: GPS flight path data Image © 2011 DigitalGlobe, Image USDA Farm Service Agency, © 2011 Google and Figure 9: Accelerometer data

GPS data is less accurate at high altitudes due to shallow vertical angles made between the receiver and the satellites. The high speed of travel also makes it difficult to acquire a lock as the rocket moves significantly between data samples. Data-files containing pre-calculated positions of all the satellites in the sky over a specified time-period can be pre-loaded onto the system to give the GPS a head-start in determining which satellites to look for, but in the rush to prepare HAB for launch there had not been enough time to do this. The *GPS data* stored on the memory card was successfully recovered from HAB but, as can be seen from Figure 8, it only gives approximate positional information.

More reliable is the acceleration data plotted in Figure 9. The Mavericks' guidance system includes an accelerometer similar to those found in modern mobile phones and games controllers. The rocket's acceleration was sampled 500 times every second with the results stored on the memory card for later interrogation. Since acceleration is the rate-of-change of velocity, we can derive an approximate velocity for the rocket by integrating the acceleration data with respect to time, as in Figure 10. Similarly, velocity is the rate-of-change of position, so if we integrate again with respect to time we get the values for the position of the rocket shown in Figure 11. If we assume that the acceleration of the rocket is purely vertical, then the speed we derive must be the vertical velocity of the rocket and thus the position is the altitude of the rocket above ground level.



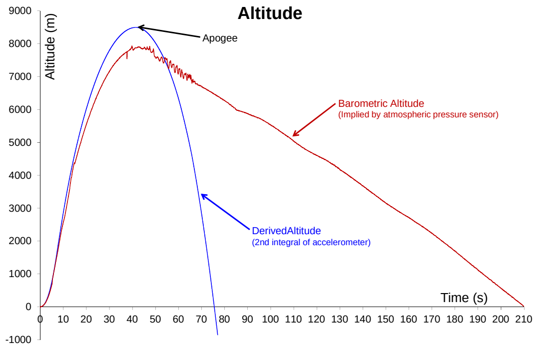


Figure 10: Velocity derived from acceleration and Figure 11: Altitude

This can be checked against the other variable the rocket's guidance system is measuring, the barometric pressure, also plotted in Figure 11 for comparison. There are issues with trying to read the atmospheric pressure around the rocket when it is travelling at such high speed, not least because it is difficult to get air inside the fuselage without affecting the stability of the flight. And the fact that the rocket breaks the sound barrier both on the way up and on the way down does not help either.

The two measures of altitude agree fairly well for the ascent. The accelerometer derived altitude is sensitive to drift-off as tiny errors accumulate, and the barometric altitude is sensitive to problems reading the pressure and in errors of calibration as base-line pressure can change with altitude. Nevertheless it can certainly be said that HAB made it to a slightly disappointing 8km above our heads before beginning its journey home. The altitude readings on the way back down show a very large discrepancy, mainly due to the fact that HAB was trailing a broken parachute behind it as it fell quickly to earth. This caused HAB to spin wildly and introduced accelerations which were not simply due to its downward motion. This same spiralling motion was responsible for the failure in GPS readings during the descent since the aerials were spinning wildly and were consequently unable to get a lock on any satellites. The barometric altitude reading is therefore our only guide as to what happened to HAB on the way down and shows a fairly steady fall until hitting the ground, coinciding with the huge spike in acceleration shown after 205 seconds. The gradient of the barometric altitude graph towards the end of the flight therefore gives us the best estimate of the speed at which HAB hit the ground. This works out to be about 630km/h (175m/s) or half the speed of sound, and goes some way to explaining how the nose-cone managed to bury itself so deeply into the ground and why HAB looked in such a sorry state when it was eventually removed from the fuselage. The interested reader may like to attempt to estimate what sort of deceleration HAB might have experienced when slowing from 175m/s to zero within the 66cm taken to bury the nose-cone – it certainly seems more than the 7g or so recorded by the accelerometer!

The Afterlife

We were all understandably a little disappointed that all our hard work and dreams of Nobel Prizes had been, quite literally, crushed. But we tried to pick ourselves up and make the most of what we had achieved. There were still two launches of the bigger rockets to look forward to, one for the Mavericks' 'Rockets in the Classroom' STEM project and the other to take the NASA team's biology sampling equipment, which is shown in Figure 12. Both were two-stage rockets with a 'P' booster section at the base and an entire 'O' section just like HAB on top. These were expected to go four or five times higher than HAB. We were able to help out with the preparations and made especially sure the drogue parachute was installed before launch.

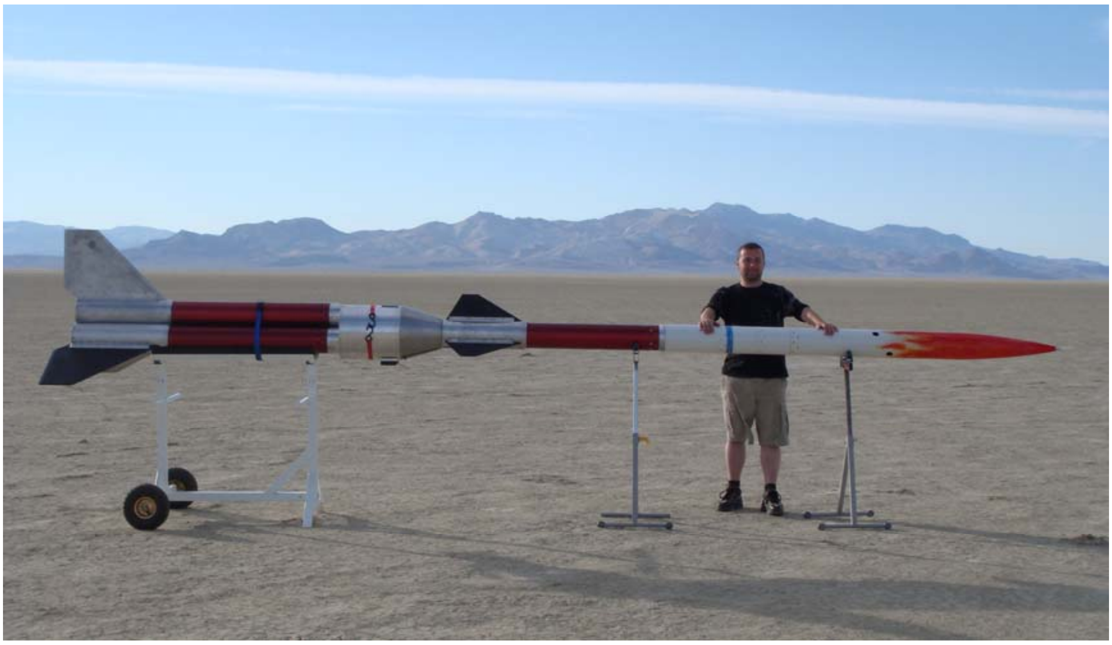


Figure 12: The 'P' rocket used by NASA

The Mavericks were rather apologetic over our 'little mishap' and tried to cheer us up by pointing out that we had 'certainly learned a lot about rocketry and designing experiments for lift-off'. And they generously invited us all back with the promise of a slot on an even bigger rocket next year. What they failed to realise is that they had just accelerated more than a year's hard work and the entirety of our hard-won research project budget into the sky at Mach 1.4 and then smashed it back down into the ground again at Mach 0.5. Still, all was not lost. We had all had great fun, learned a lot from our experience, and I now have a large collection of photos and videos to use as part of my STEM public engagement work.

In collaboration with artists Anna Dumitriu, Alex May and Kira O'Reilly the HAB team are developing an art installation to engage a wider audience in the science behind high-altitude bio-prospecting, and we are currently investigating options for an institution to host it. We have also made the *HAB flight-data* publicly available and it has already been used by other academics to help with their research. Similarly the data assessing background levels of biological contamination within the playa that the two school students collected has been passed on to the NASA team to help validate their research.

The remote-testing methodology of HAB, as opposed to the more established capture and return approach, has many other applications and we are keen to hear from anyone who might like to sponsor further research and development. We happened to be out in the desert just after the disastrous Florida oil spill, and we have been investigating whether there might be a use for Negative Altitude Bioprospecting (NAB), where simple remote sensing equipment could be sent to the bottom of the ocean or mounted on buoys to evaluate and monitor levels of pollutants.

And the search for further funding, to allow us to take the Mavericks up on their offer of a second launch, goes ever on. If there are any philanthropists out there who fancy a fortnight in a hot, dusty desert, please get in touch. After all, the IMA seem to have changed their logo since HAB was launched, so I will **have** to go back and do it all again with the new design (and some stronger sellotape), surely…?❑

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Acknowledgements

The author would like to thank the IMA and NESTA for their financial support, without which he would not have been able to take part in this exciting and, quite literally 'groundbreaking' project. He is also grateful to Lynn Rothschild and her team from NASA Ames, and the Rocket Mavericks, for their friendship, hospitality, and for taking the time to explain what was going on.

More details on the subjects marked in *italics* in this article, as well as photos, videos and the raw GPS and accelerometer data, are available on the author's website at http://people.bath.ac.uk/ps281/rockets/

Biography

After completing a degree in Mathematics at the University of Cambridge and a Phd in Structural Engineering at the University of Sheffield, Paul worked for eight years with consulting engineers Buro Happold, developing mathematical software solutions to complex engineering problems. He worked alongside some of the world's leading architects and was lucky enough to work on the design of the new London Olympic Stadium, if only for one afternoon. Paul is now a Research Fellow at the University of Bath, where he combines research into new computational methods for building design with a passion for promoting the public understanding of science, technology, engineering and mathematics.