Investigating the Structure of the Atmosphere

Ronan Laker

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Abstract

This report uses a weather balloon to send a payload to a height of 35km, whilst recording some characteristic variables of the atmosphere. An ultrasonic range finder was used to investigate the relationship between the speed of sound and temperature, with the conclusion that it followed the Newton-Laplace equation. Two more sensors were used to measure pressure, temperature, humidity and UV intensity. The relationship between these variables and altitude is investigated and clear layers are defined, corroborating with the standard atmospheric model.

1 Introduction

This project was completed over a period of 3 months, the full description of the building and launching process can be found at www.ronanlaker.com/high-altitude-balloon, along with video and pictures taken from the flight.

We aimed to record some characteristic variables of the atmosphere including speed of sound, pressure, temperature, humidity and UV intensity. The aim of this experiment is to classify different layers in the atmosphere using the temperature and UV intensity; investigate the relationship between each variable and altitude in order to gain greater insight into the atmosphere. The standard atmospheric model was used as a reference to prove the validity of our measurements.

2 Payload

The aim of this experiment was to measure some characteristic properties of the atmosphere at high altitudes. A weather balloon filled with helium was used to achieve this, which is a standard practice for a community known as UKHAS [1]. There is a wealth of literature online on how to launch such a balloon, so I will summarise only the points important to this report.

The package carried by the balloon is known as the payload, which needs to be as light as possible whilst carrying all the equipment needed for the experiment and its recovery. The most important item in the payload was the Raspberry Pi [2] with an add on board known as Pi in the Sky (PITS) created by David Akerman. This combination included all the equipment necessary to record the position of the balloon through a built in gps unit, and rely that information to the ground through via RTTY. This allows the position (including altitude) of the payload to be known, allowing it to be shown on a live map [3] along with a prediction of the landing site. This allowed the use of the Raspberry Pi V2 camera, I modified the code so that a picture would be taken every 10 seconds but not sent to the ground. This was done so as to not miss out on any data, as none can be taken whilst the image is sent to the ground via RTTY, which could take several minutes.

In order to send the telemetry string to the ground a wave ground plane antenna was made from collinear cable and copper wire arranged in an X shape. This sent a signal on the frequency 434.25MHz, as a series of undulating peaks separated by 650Hz. Although the signal itself is very weak (below 10mW by law), there is nothing to obstruct the signal, so many people around the country can track the payload. We could then pick up the signal from the ground through a Yagi antenna and an SDR (software defined radio), and decoded the sentence using dl-fldigi. Once the string is decoded, the information is uploaded to a server which then shows the balloon and all the information on a live map. This is the standard way of transmitting data via RTTY, this then allowed 17 different people to track our payload in flight from as far away as Holland (250 miles).

Different sensors were used to measure the characteristics of the atmosphere. The majority of the sensors used the i2c bus, a standard way of connecting a microcontroller (such as the raspberry Pi) to a sensor using only 4 connections. We used a BME280 manufactured by Bosch to record Pressure, Temperature and Relative Humidity. Support for this sensor was already included in the source files for the PITS board, so only the soldering of 4 wires was required. A small plastic cap was placed over the sensor in an attempt to shield it from the sunlight, which would increase the temperature giving false results.

The intensity of UV light was also of interest, since in theory it was thought that an increase would be detected as the payload travelled through the Ozone layer. First, I used a VEML6070 as it was described as a UV sensor. However, this was changed after discovery that the peak sensitivity for this sensor was 355nm, meaning that this sensor could only measure UVA (defined as 320-400nm) which was not blocked by the Ozone layer. After further research, it was decided that we would instead use the VEML6075, which advertised both UVA and UVB sensitivity. I modified the source code for the PITS to include this sensor. This was done by following the same basic structure as the BME280 support, more detail can be seen in the HAB guide [4] [5]. I chose to use an integration time of 50ms as this meant that the sensor would not become saturated with sunlight.

Another aim of this experiment was to measure how the speed of sound varied with altitude, in order to achieve this the HCSR04 was used. This is a small ultrasonic range finder, used to find the distance to objects by sending a small pulse (with a frequency of 40kHz) and recording the time take for the reflection to be received. I added support to the PITS source code, and modified the sensor to instead measure the speed of sound not distance. The payload was designed so that the HCSR04 pointed out of the box, towards a reflector 30cm away as seen in Fig 1.

Figure 1: Picture of the payload, highlighting the speed of sound experiment. The ultrasound sensor is point out towards to small metal disc.

3 Speed of Sound

3.1 Theory

Sound propagates as a series of compressions and rarefactions of the medium it is travelling through. In a fluid, sound propagates only as a longitudinal wave, meaning that the direction of displacement is the same as that of travel. The speed of sound is given by the Newton-Laplace equation [6], which shows that the speed of sound, c, is dependent on the density and the Bulk Modulus of the medium. It is reasonable to assume that air is an ideal gas, allowing the Newton-Laplace equation to become equation 1 using the ideal gas law.

$$c = \sqrt{\frac{\gamma k T}{m}}, \tag{1}$$

where γ is the ratio of heat capacities, k is the Boltzmann constant, T is the temperature of the gas (with units K) and m is the average mass of a single molecule in the medium. Air can be described as a diatomic gas (each molecule has two atoms i.e. O_2) meaning a γ of roughly 1.4. If we assume that the composition of the air stays roughly constant, then c is only dependent on the temperature of the air.

3.2 Interpreting False Results

The raw results of speed of sound with altitude can be seen in Fig 2, there are several anomalies to the general trend below 10km but these were expected. However, at 10750m the readings start to show values of $4.6ms^{-1}$, and above 15km the only readings are of this clearly wrong value. This is such a low value that it could not possibly be the actual speed of sound, I propose that the sensor could not detect up a return signal therefore just stopped timing and returned the same value consistently. The sensor did start working again when the balloon burst and the payload fell below 9438m, the same pattern is seen where a consistent bad result, then a transition period where it alternates between a real reading and no signal.

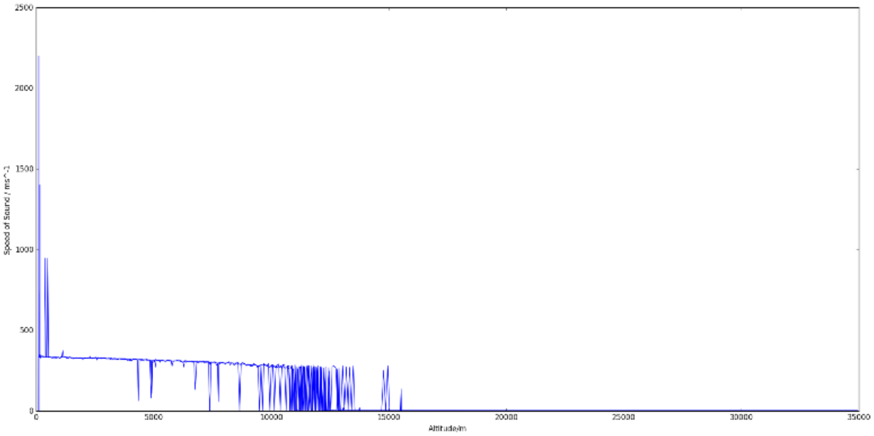


Figure 2: The raw results from the speed of sound experiment, can see obvious anomalies and the sensor fails at around 10km.

The temperature of the air could have been outside the operating temperature for sensor, however this is unlikely, as shown in section 6, the temperature rises in the stratosphere and the sensor still did not record real measurements. Another possibility is that strong winds could have interfered with the measurement, as seen in the path of the balloon, there is a complete change of direction at around 13km, which is associated with strong winds in the Jet stream. This could be the cause of the transition period as I have named it, where gusts of winds interrupted some of the measurements. However, there were strong winds at the launch, they can be heard in the video recording, and the speed of sound measurement still worked at this point.

I propose that the main cause of these results is due to the Sound Intensity Level (SIL) measured in Decibels (dB). This is a logarithmic scale of the intensity of the sound wave with respect to a reference, which is normally set at the threshold of human hearing. This is a useful scale as the range of human hearing is so large, and its definition at the source is seen in equation 2.

$$L_{i,src} = 10log_{10}\left(\frac{I_{src}}{I_0}\right), \tag{2}$$

where $L_{i,src}$ is the sound intensity level of the source in dB, I_{src} is the intensity of the source and I_0 is a reference intensity. When the payload moves through the atmosphere the value of I_0 varies in accordance to equation 3, which is basically as statement of what is the lowest intensity that can be heard at each point.

$$I_0 = \frac{P_0^2}{Z}, \qquad Z = \rho c, \tag{3}$$

where P_0 is the threshold of human hearing for sound pressure, defined as $20\mu Pa$. Z is the characteristic specific acoustic impedance, a measure of resistance to acoustic flow and ρ is the density of the medium. This means that I_0 increases with height, in other words the lowest intensity that can be heard increases with height. The density can be calculated from the Ideal gas law, as the payload measured both pressure and temperature. As mentioned, there is not a completed set of speed of sound results, so instead we must estimate c based on the relationship found in section 6.

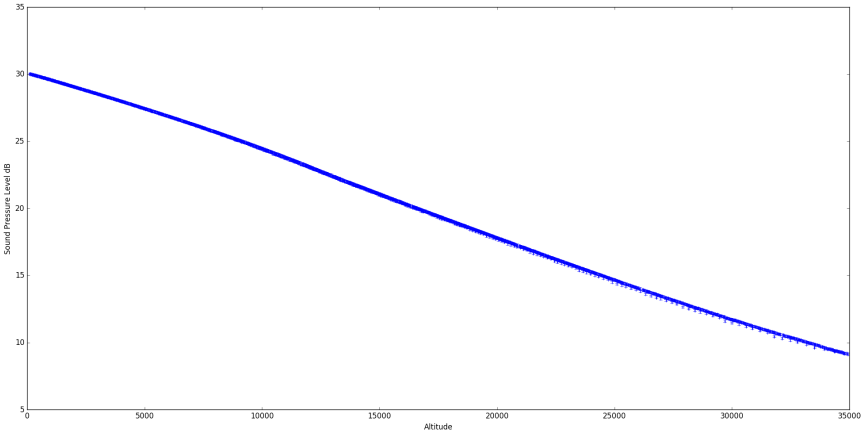


Figure 3: Sound Intensity Level at different heights. It is the change in dB that matters and not the absolute value. A change of 6dB at 10km, so 4 times quieter.

The intensity of the pulse sent out by the sensor is assumed to be constant, so now we can calculate the SIL at various points in the atmosphere. This is shown in Fig 3, the change in the values is more important than the absolute value which is arbitrary as I do not know the intensity of the sensor. This shows that at 10km, the point where results stopped working smoothly, there has been a drop of 6dB which means that the same pulse is 4 times quieter at this height. This I believe is a large enough change such that the microphone may have difficulty receiving the reflected pulse. This also works well with the transition period, as now the microphone is at its limit so is more susceptible to wind gusts. This SIL theory is also backed up by the video recording, at low altitudes the wind gusts can be heard, whereas at higher altitudes this is not the case even though we know there are strong winds. At the peak of the flight, there has been a change of 21dB which means that the same sound is 125 times quieter, so if there was a rock concert at 35km it would only be as loud as a hoover at sea level.

3.3 Analysis

Although the sensor stopped working past 10km, there were enough readings to still find a relationship between the speed of sound and temperature. After removing some clearly anomalous results, the results were plotted as shown in Fig 4. This shows a linear correlation as predicted by the theory, the line gradient was calculated to be $706.9 \pm 9.5 m^2 s^{-2} K^{-1}$ with an intercept of $-93000 \pm 2500 m^2 s^{-2}$. Assuming a γ of 1.4 and using equation 1 then the mean molecular mass is $2.73 \pm 0.04 \times 10^{-26} kg$, which differs from the normal value of air of $4.8 \times 10^{-26} kg$. The graph also shows that the results spread out as the temperature decreases, this could be the effect of cold temperature on the sensor.

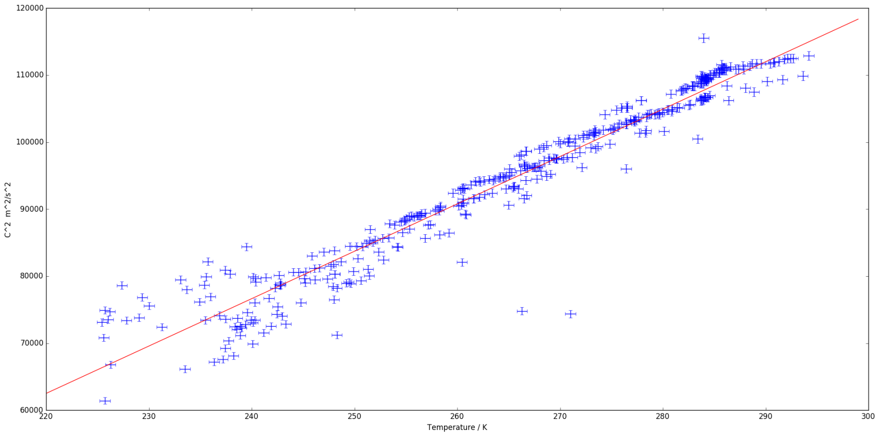


Figure 4: Shows speed of sound squared versus temperature. A linear correlation is fitted with a gradient of $706.9 \pm 9.5 m^2 s^{-2} K^{-1}$

To improve this experiment I would use a more powerful speaker to transmit the sound signal, so that the reducing of SIL with height does not mean that the microphone cannot pick up the reflected pulse. Another example I have found of this particular experiment uses a Dictaphone and a normal speaker that transmits a sine wave [7], the difference in peaks is analysed later to find the speed of sound.

4 Pressure

In order to maintain hydrostatic equilibrium, the upwards force created by a pressure gradient must balance the effect of gravity acting downwards, resulting in equation 4.

$$\frac{\mathrm{d}P}{\mathrm{d}h} = -\rho g, \tag{4}$$

where h is the altitude, and g is gravitational constant. This can be transformed using the ideal gas law and integrating to give equation 5, which shows that pressure should reduce in an exponential fashion as altitude increases.

The results can be seen in Fig 5, which shows that the lowest pressure was 820Pa at 34930m as opposed to 101kPa at sea level. This also shows an exponential decrease with altitude, however a more concrete confirmation of this is seen when ln(P) is plotted in Fig 6. This produces a linear correlation with a gradient of $-1.438 \pm 0.001 \times 10^{-4} m^{-1}$ and an intercept of 4.709 ± 0.002. The curve seems to bend away from the curve, this is the effect of temperature reducing until 15km then increasing. This

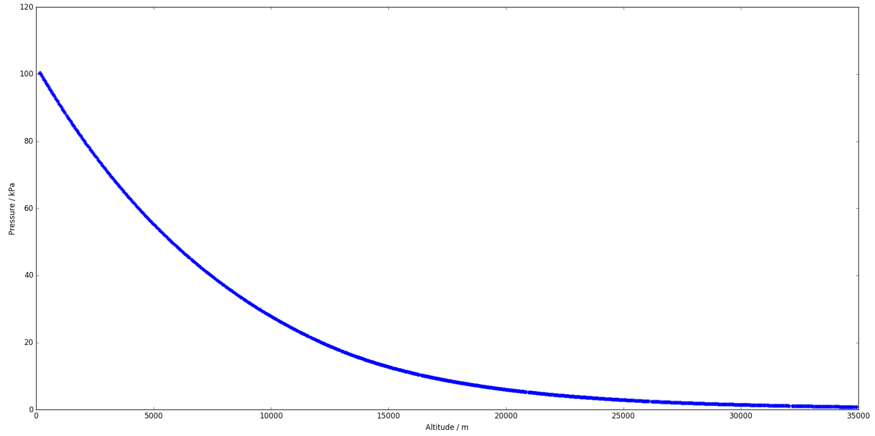


Figure 5: Shows how pressure varies with altitude, clearly showing an exponential decay.

is a minor effect so will be ignored for these purposes. Using equation 5 the theoretical gradient of the graph is calculated to be $-1.46 \times 10^{-4} m^{-1}$, using 234K, the temperature of the cross over point. This is close to the measured value, maybe the small deviation is due to the minor effect of temperature.

$$P = P_0 e^{-\frac{mgh}{kT}} \tag{5}$$

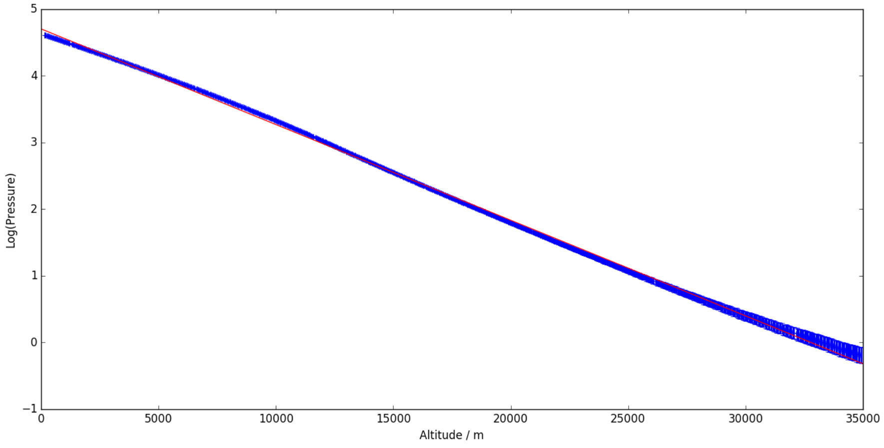
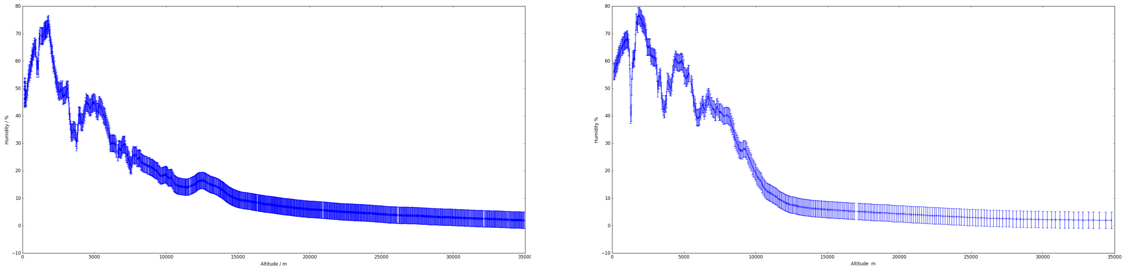


Figure 6: Shows the natural log of pressure against altitude, with a linear correlation. Slight deviation from this trend is due to the effect of temperature.

5 Humidity

The BME280 sensor measures the Relative Humidity (RH) which is a measure of how much water content there is compared to the maximum possible amount the air could hold. In general I would predict that the RH would decrease with increasing altitude, as most weather systems (high humidity) happen below 6000m [8].

The results taken when ascending are shown in Fig 7a and the result for the descending payload are shown in Fig 7b. The most obvious feature of these graphs are the peaks in humidity due to the



(a) Ascending

(b) Descending

Figure 7: Shows the humidity readings for both the ascending and descending payload, so a contrast can be seen at around 12km.

(a) 1706m

(b) 4738m

(c) 12388m

Figure 8: Shows several pictures taken by the payload, that highlight the different cloud layers.

low level clouds at 1700m. The RH peaks at $73 \pm 3\%$, with a temperature of 11^oC, meaning that these clouds were condensed water droplets. This is corroborated by the picture taken by the payload in Fig 8a, which shows the view from inside the dense cloud. A more interesting feature is seen around 12km, the ascending humidity graph shows a deviation from the clear trend of decreasing humidity. The picture at 4738m (Fig 8b) shows the thick clouds below, but also some less dense clouds above, the picture taken from 12388m (Fig 8c) shows that the deviation in RH is due to these high altitude clouds which appear to be of the Cirrus variety. However, the temperature at this point is -47.6^oC so these clouds are formed of ice crystals instead. This deviation at 12km is not seen when the payload descends, which further supports the idea that it is caused by high altitude clouds, which it did not pass through on the way down.

6 Temperature

The lowest layer of the atmosphere is known as the Troposphere, it extends to an average of 12km with a lower altitude at the poles. This region includes almost all of Earths water vapour, thus most weather originates in this layer. The temperature in this layer decreases with increasing altitude. The surface of the Earth is warmed by the Sun, this then causes a parcel of warm air to rise. This means the parcel adiabatically cools as it rises, the rate at which it does is called the lapse rate. This can depend on whether the air is saturated or not, and will be discussed later. The next layer of the atmosphere is known as the Stratosphere, which extends to 50km. This contains a higher concentration of ozone, which absorbs UV radiation from the Sun. This heats the layer, and means that temperature rises with altitude in this region, contradictory to many peoples belief. The boundary between these two layers is known as the Tropopause, where temperature is roughly constant due to the having little mixing of air.

The measurements for the ascending payload can be seen in Fig 9. The coldest temperature was -48.7 ± 0.5^oC at a height of 13263m, this does fit the standard atmospheric model (SAM) which says

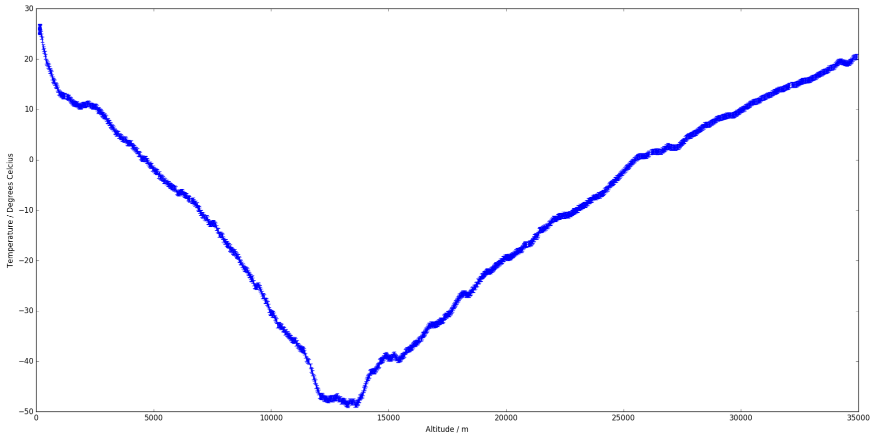


Figure 9: Shows the temperature versus altitude. There is heating from the Sun that seems to inflate the results past 20km.

the lowest temperature is around -51^oC in the Tropopause. The troposphere is defined as the layer where temperature decreases, therefore from our data this is up to the height of 12050m agreeing with the SAM. The tropopause is therefore found between 12050m and 13700m where the temperature is roughly stable at around -47^oC. The payload extended into the Stratosphere up to a height of 35km, which would put it above the Ozone layer at around 20-30km high. This is also evident from the results, as in the Stratosphere temperature rises with height, as predicted from the absorption of UV radiation in this layer. The temperature at 35km is around 20^oC, this is not an accurate reading as the true value should still be below zero. This is due to the heating of the Sun, as the sensor was placed on the top of the payload. Although an effort was made to shield the sensor from the Sun, this was clearly not entirely effective.

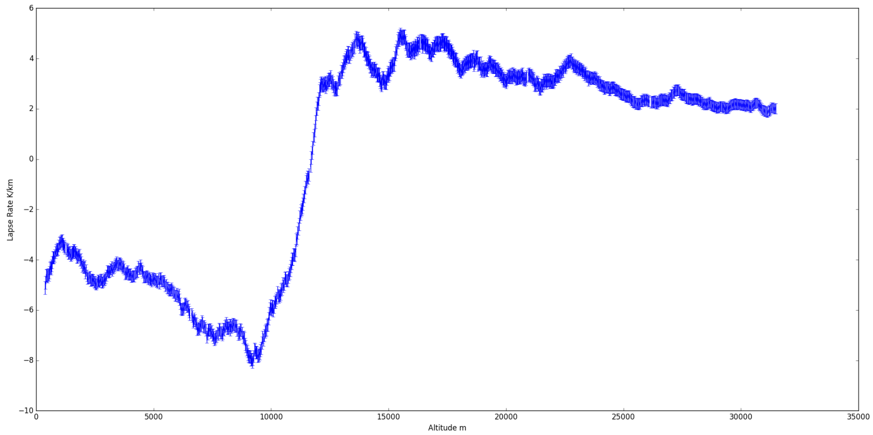


Figure 10: Shows the lapse rate, i.e the gradient, of the temperature profile.

As mentioned before the lapse rate is rate of cooling in the atmosphere with respect to altitude. The lapse rate of dry air is around 9.8K/km, whilst the lapse rate for moist is has an average of 5.5K/km. Fig 10 shows the lapse rate as a function of height, this is essentially the gradient of Fig 9. The lapse rate starts off at around -5K/km when the height is below 5000m, this is the lapse rate for moist air as from the humidity readings in fig this is where the moist air is situated. As the height increases above 5000m the lapse rate begins to decrease to a minimum of -8K/km. This is more like the lapse rate for dry air of 9.8K/km, which from Fig 10 does seem to be true. The lapse rate in the Stratosphere is smaller than the absolute value in the Troposphere. This is possibly due to the heating by UV absorption not being as strong as the convection in the Troposphere.

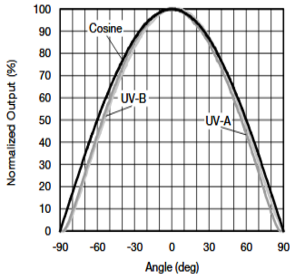


Figure 11: Graphs from the datasheet of the VEML6075 showing how the angle of the Sun would reduce the intensity reading.

7 Ultraviolet

As mentioned in section 6 the Ozone content in the Stratosphere absorbs UV radiation, therefore as the payload travelled through the Ozone layer there should be an increase in the amount of UV light detected. Estimates I researched suggested that 90% of UVB, wavelengths between 280−320nm, is absorbed by the Ozone layer whilst UVA (320−400nm) is not blocked at all.

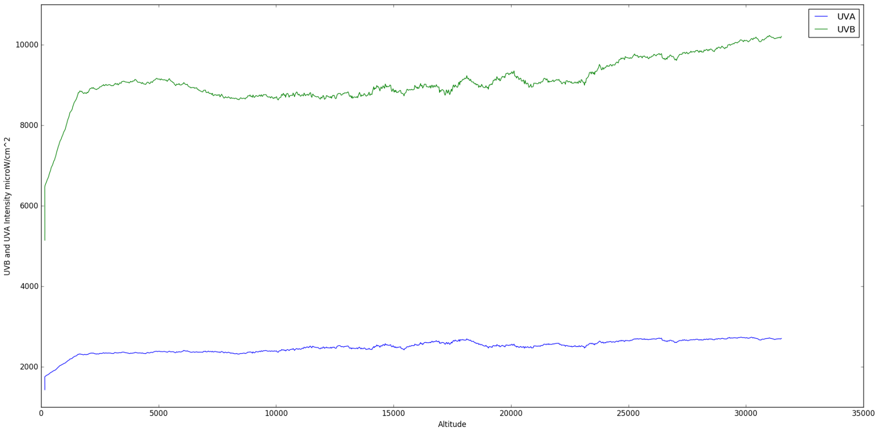
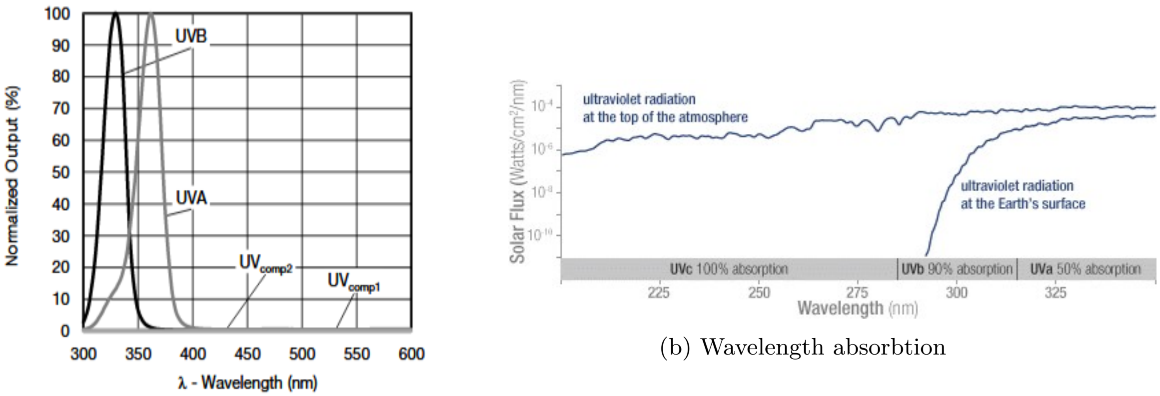


Figure 12: Shows a 100 point moving average of the UV intensity results, in order to smooth out and see a pattern.

The readings from the sensor during the flight are very variable, with large changes between two consecutive measurements. This is due to the swinging motion of the payload as it ascended meaning the angle to the sun change, this affects the reading as shown in Fig 11. To get around this problem a 100 point moving average was taken in order to smooth out the results as shown in Fig 12.

This does show an increase in UVB after 12km, as expected. However, this is only an increase of 17% much less than expected. The UVA reading also increased by 8% between 12km and 35km which



(b) Wavelength absorbtion

(a) Wavelength measured

Figure 13: A shows that the peak wavelength measured is around 320nm. B shows that this wavelength is not absorbed as much as thought prior to the flight.

does show that UVB increased more significantly. The answer to why there is such a small increase is found in the datasheet and shown in Fig 13a. This shows that the sensor is actually measuring UVB at a peak wavelength of around 320nm, this the sensor is measuring right at the top edge of the UVB definition. Fig 13b shows the actual change in flux between the surface and top of the atmosphere for each wavelength, which shows that the largest change in intensity is actually at the bottom end of the UVB band and complete absorption of the UVC band. An improvement would be to measure the UVC flux instead, as this is completely absorbed by the Ozone layer, so a dramatic change in readings. However, since there is no UVC at the surface there may not be a sensor that uses the i2c bus.

8 Conclusion

One purpose of this experiment was to classify the layers of the atmosphere. This was done using the temperature and UV data, which allowed the classification of the Troposphere and the Stratosphere as well as the Tropopause. An improvement to this would be to measure UVC intensity to the exact location of the Ozone layer can be determined, as the sensor used was not suitable for this purpose. Another aim was to investigate the relationship between speed of sound and temperature, which showed that it obeyed the Newton-Laplace equation. Although the sensor stopped working above 10km, there was still enough data to gain a conclusion and in fact this error gave more insight into the way sound propagates at high altitudes.

References

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