WUSAT-SOLSPEC REXUS 17 EXPERIMENT: MEASURING ATMOSPHERIC QUANTITIES OF OXYGEN AND SODIUM

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ABSTRACT

The WUSAT–SOLSPEC experiment was a proof of concept of a novel approach for analysing the characteristics of an atmosphere with regard to its habitability. Once validated the system could be used in the search for extra-terrestrial life by providing details of the compositions of exoplanet atmospheres.

The experiment comprised a free falling unit based on CubeSat specifications that measured the wavelengths of light absorbed by Na and O_2 in the atmosphere via solar spectroscopy. Using a wireless communication system, this data was sent to a ground station for analysis. As the free falling unit was unrecoverable, all of the data was transferred through the communication link.

The wireless communication link was successfully established and this was the first time such a link has been demonstrated on a REXUS mission. Data was received for 71 seconds after ejection. The solar spectroscopy instrument was unable to clearly distinguish the subtle trends in Na and O_2 with altitude due to light intensity variation. Light leakage within the optical system is the probable cause of the significant influence of light intensity variation in the results. Hence, further development is required to fully demonstrate the capabilities of solar spectroscopy for the analysis of an atmosphere from a free falling unit, however the experiment successfully illustrated the operation of all required subsystems and the principle of the optical measurement system.

1. INTRODUCTION

The presence of Na and O_2 within the atmospheres of exoplanets can provide an indication of their ability to support life. Most current methods of remote observation in expolanets register the presence of atmospheric elements, but not the corresponding altitude at which the levels are detected. These methods can therefore give misleading results. Water vapour in the upper atmosphere of a planet can be broken down by ultraviolet rays from the parent star, which from remote observation would indicate an oxygen rich atmosphere [1]. The altitude at which this oxygen is present, however, is too high to support life.

WUSAT-SOLSPEC was a CubeSat sized experiment that aimed to measure the levels of Na and O_2 with altitude in the atmosphere during free fall via solar spectroscopy. A CubeSat is formally defined as satellite units with dimensions 10cm x 10cm x 10cm (one litre volume) [2]. CubeSats provide increasing opportunities for access to space at reduced costs and with comparatively short development times which has opened up research opportunities to university students [3, 4]. The advantage of WUSAT-SOLSPEC is that it provides Na and O_2 profiles with altitude, showing if there is O_2 at ground level and therefore giving a better indication of the habitability of such a planet. It was primarily a proof of concept experiment. As the composition of the Earth's atmosphere is known, the intensity data collected by the experiment could be calibrated and eventually applied to other atmospheres.

WUSAT-SOLSPEC was launched on the REXUS-17 sounding rocket on 17th March 2015, from ESRANGE Space Centre, Kiruna. REXUS (Rocket EXperiments for University Students) is a programme provided by an agreement between the German Aerospace Center (DLR), Swedish National Space Board (SNSB) and the European Space Agency (ESA) enabling students to fly experiments on sounding rockets up to 90 km [5]. WUSAT-SOLSPEC was the first REXUS experiment to successfully transmit data over a communications link, live during free fall.

2. EXPERIMENT DESCRIPTION

2.1. Solar Spectroscopy Payload

The scientific objective of the experiment was to measure the relative concentrations of Na and O_2 in the atmosphere with altitude via solar spectroscopy. As light passes though the atmosphere, different wavelengths are absorbed by the gases present at different altitudes. By measuring the relative intensities of light at wavelengths corresponding to known substances, the variation of the concentration of the substances with altitude can be determined. This is the principle of solar spectroscopy.

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The WUSAT-SOLSPEC optical system performed solar spectroscopy with the use of a photodiode array and a set of optic filters. For each molecule measured there were two filters: a wide band and a narrow band filter. The wide band filtered photodiodes measured the background intensity, which could then be removed from the narrow band results, providing results adjusted for intensity.

2.2. System Overview

The WUSAT-SOLSPEC experiment comprised two distinct subassemblies, the Free Falling Unit (FFU) and the Rocket Mounted Unit (RMU). The FFU was responsible for taking the solar spectroscopy measurements and transmitting the results to the ground via a wireless communication link. The RMU served to contain the FFU during the ascent phase of the launch and actuate the ejection of the FFU at apogee. The experiment was mounted on the bulkhead underneath the nosecone of the REXUS rocket. The nosecone of the REXUS rocket was ejected prior to apogee at T+78 seconds, which enabled data collection before the FFU was ejected during the ascent phase of the launch. Whilst inside the RMU, the FFU communicated with the RMU, allowing the transmission of results to the ground via the REXUS service module telemetry. Electronics housed inside the RMU electronics box enabled this communication.

Figure 1 illustrates the full system design, both enclosed inside the nosecone and with the FFU separated from the RMU. Label 1 and 2 in Figure 1 show the FFU and RMU respectively, while label 3 denotes the RMU electronics box.

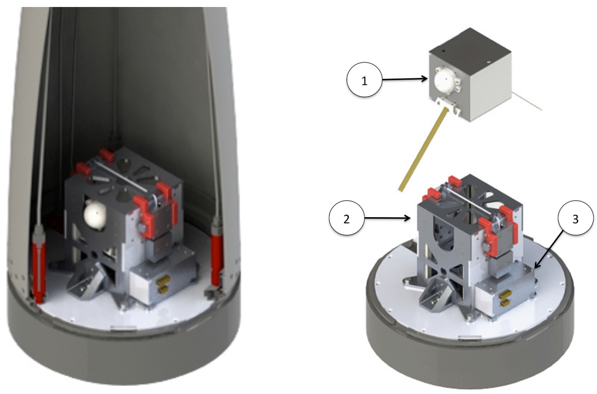

Figure 1. Illustration of experimental design

2.3. Mechanical Design

Both the RMU and FFU structures were manufactured from 7075-T6 Aluminium due to its preferential mechanical and manufacturing properties. Mass reduction was achieved with an iterative design process utilising static FEA analysis, resulting in a final mass of 4.8kg. This was distributed between the FFU and RMU at 1kg and 3.8 kg respectively.

The FFU construction utilised internal extruded bosses and countersunk M2 screws to hold the individual sides together. Two PCBs were mounted vertically with the use of aluminium rails, which improved resistance to vibration. The third PCB which was responsible for the optical measurements was mounted in a horizontal orientation due to its larger size. Thermal control was provided with the use of insulation and a heating element, ensuring the internal temperature was maintained well within the operating bounds of the electronic components. A composite material formed by wrapping Pyrogel® XT insulation with aluminised Mylar® film was selected as the insulating material due to its resistance to heat transfer through both conduction and radiation. The material was further wrapped in non-aluminised Mylar® film to ensure that the surface was not electronically conductive. Wrapping the insulation also prevented the escape of dust particles which could interfere with the optical system.

The optical system used to take the solar spectroscopy measurements was composed of two dome structures mounted on the outside of the structure. These held fibre optic cables that transported the ambient light into the internal structure. The geometry of the domes was designed to ensure light could be collected from all directions, preventing the attitude of the FFU from influencing the results. The fibre optic cables were fed into a barrel that housed the optic filters. These filtered the light into the required wavelengths for the photodiode array, responsible from taking the measurements. The internal structure of the FFU is demonstrated in Figure 2. Label 1 identifies the optic barrel, while label 2 illustrates the dome structure used to mount the optic fibres.

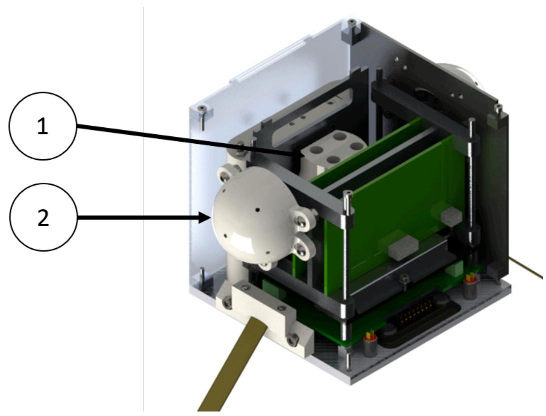

Figure 2. Internal structure of FFU

The RMU was a spring based ejection system, designed to achieve an ejection velocity of $1.5ms^{-1}$. The design was based on the ISIS-Pod and P-Pod CubeSat ejector concepts [6]. Four helical compression springs provided the ejection force, while Teflon rails were incorporated to ensure a low coefficient of friction between the FFU and RMU. The FFU was constrained inside the RMU with the use of a wire cable, enabling the ejection to be actuated with the use of two pyro-cutters. The construction of the wire and pyro-cutter mounting is illustrated in Figure 3. Labels 1 and 2 demonstrate the pyro-cutter and pyro-cutter mounting respectively. Label 3 illustrates the mounting system for the wire cable.

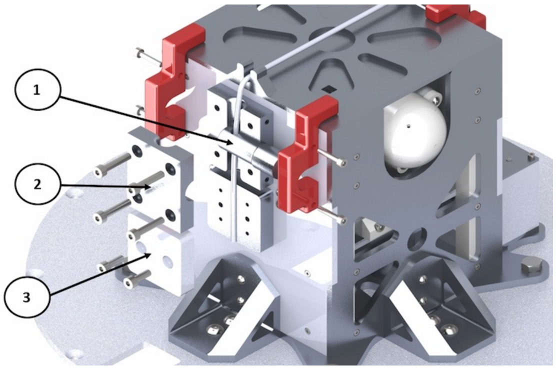

Figure 3. Illustration of pyro-cutter and wire mounting

The RMU contained an electronics box, which was of similar construction to the FFU and housed a PCB that provided power systems and communication between the REXUS service module and the FFU.

2.4. Electronic Design

The electronic system comprised three major subsystems: FFU, RMU and Ground Station (GS) as shown in Figure 4. The FFU performed scientific measurements and transmitted this information to the ground station via a wireless link during free fall, and through the RMU during the ascent of the rocket. The RMU provided an interface between the FFU and the rocket service module to deliver communications and power. The ground station decoded, analysed and stored the data received from both the RMU and FFU.

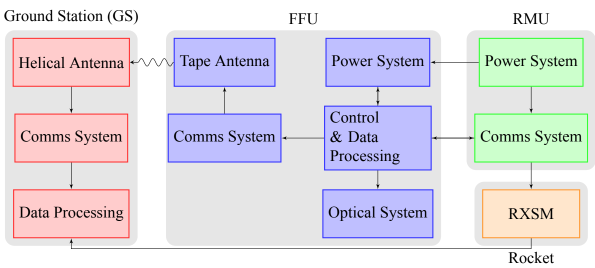

Figure 4. Electronic system architecture

The RMU downlink was utilised while the FFU was still within the rocket to ensure no interference occurred with the rockets communications systems.

The FFU was designed around a Microchip PIC® Microcontroller, which provided the ability to maintain an optimum internal environment, take the scientific measurements and apply a Forward Error Correction scheme to the communication downlink. An Easy Radio module and a RF amplifier were used to provide a FSK communication link to the ground in the unlicensed 433 MHz communication band. The FFU contained 4 SAFT NiMH batteries to power the unit during the free fall. The scientific readings were taken using a photodiode array in a trans-conductance amplifier topology. The photodiodes were combined with an optical system that using optical filters to select the absorption bands of interest.

The RMU contained a second microcontroller to allow the relay of data between the FFU and the ground station via the rockets communication systems. In addition it also served as a secondary mechanism to ensure radio silence while the FFU was within the rocket. The RMU contained DC-DC power converters to simplify the power system design of the FFU.

The ground station contained a receiving antenna and an Easy Radio module to demodulate the downlink from the FFU. The module was connected to a laptop to allow the data to be decoded and analysed.

2.5. Software

A custom piece of software was written for the FFU, RMU and Ground Station. The software developed enabled many of the functionality of the system with a focus on transmitting error free data to the ground station.

2.6. Communications System Design

The lack of FFU attitude control during free fall necessitated an antenna system that produced an approximate omnidirectional field to ensure consistent signal strength independent of orientation. A configuration using two monopole antennas with a 180° phase-shift between the monopoles was chosen. These antennas were angled at 45°, on opposite faces of the FFU, which provided a linear polarized signal with no major angles of low gain (see Figure 5). The antennas were constructed from steel tape measure in order to simplify both storage of the antennas prior to ejection, and deployment of the antennas upon ejection.

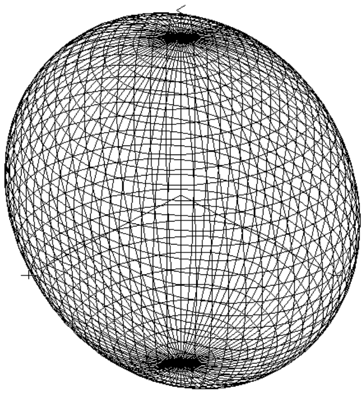

Figure 5 - EZNEC v5.0 simulation of FFU 3D gain pattern

A helical design was chosen for the receiving antenna in order to counter the signal polarisation variation as the FFU tumbled during descent. This allowed receiving of any polarization with a constant -3dB loss, while the exact dimensioning of the helical antenna (number of coils, diameter and spacing) determined the directionality and frequency of operation. Through calculation and simulation a four-turn design was chosen to provide sufficient gain to receive a signal at high altitude as well a beam-width that covered the entire trajectory during the FFU's descent.

To allow transport to Sweden the helical antennas were constructed from sheets of laser-cut acrylic. This allowed both accurate dimensioning and the ability to pack them flat.

Figure 6- Receiving helical antenna mounted at radar hill

3. DESIGN ANALYSIS

3.1. Thermal Analysis

Thermal modeling was carried out in order to ensure correct design of the thermal system (insulation and heater) to maintain the electrical components within operating temperature ranges. The analysis also aided the placement of the internal temperature sensor. Modeling was carried out using ESATAN-TMS® thermal modeling software, with simulations being run for the FFU and RMU with conditions before, during and after flight. The models of the FFU and RMU were simplified, showing only the main thermal components; heat sinks, insulation, PCB heat dissipation and the heater.

The first iteration of thermal analysis resulted in a change of components to obtain a wider operating temperature range. The final components were operational between minus 40ºC and plus 80ºC. The ESATAN-TMS simulations showed that internal temperatures of the FFU and RMU would remain within this critical temperature range during operation.

3.2. Trajectory Analysis

Trajectory analysis was required to ensure the FFU would not leave the SSC impact area and to provide a correlation between altitude and time to enable the optical results to be related to altitude. Local wind data on the day of flight was also incorporated into the model to guarantee that local wind conditions would not result in significant drift.

The aerodynamic forces generated on the FFU were predicted with the use of a theoretical model adopted from a model developed by the NASA Ames Research Center for predicting the trajectories of space debris [7]. The model considers one dimensional isentropic flow combined with correction factors for three dimensional effects to predict the aerodynamic forces produced on bluff bodies at high Mach numbers.

The aerodynamic forces could then be used in the formulation of three degree of freedom equations of motions, which were solved numerically with the use of the fourth order Runge-Kutta method. Incorporating local wind data into the model for the day of the flight resulted in a ground range of 26.8 Km after ejection. The maximum velocity was computed as 826 ms^{-1} relating to a Mach number of 1.95. Figure 7 demonstrates the trajectory represented in Google Earth.

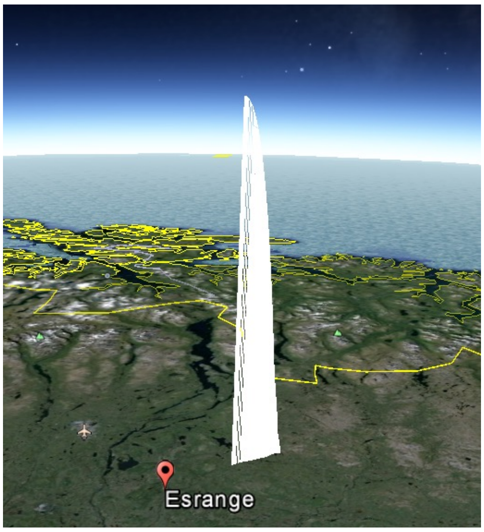

Figure 7. Trajectory represented in google Earth

3.3. Communication System Analysis

The link budget was an important analysis to ensure sufficient signal strength would be received. A model was created that determined the received signal strength with the altitude of the FFU. The model also predicted the variation in receiving antenna gain as the FFU descended. Therefore it could be ensured that the link margin was appropriate for the whole trajectory.

The Doppler shift generated during the descent of the FFU was also evaluated by analysing the results of the trajectory analysis. As the velocity became perpendicular to the line-of-sight of the receiver during the descent of the FFU, a maximum Doppler Shift of 1065Hz was predicted. This occurred at around 100 seconds after ejection. At this point the bit-time is still less than the coherence time, so the received signal should not be adversely affected by the Doppler shift.

4. QUALIFICATION TESTING

In order to receive a flight ticket WUSAT-SOLSPEC had to pass a number of qualification tests, verifying the experiments capability of withstanding the launch conditions safely.

4.1. Vacuum Testing

The FFU was vacuum tested at DLR, Oberpfaffenhofen. The assembly was exposed to a pressure low of 5×10^{-3} mbar, maintained for a duration of 2 minutes. Immediately following this test the FFU was disassembled and all parts were visually inspected, in particular the batteries and 3D printed components. The visual inspection showed that the low pressure had no impact on the structure or function of the FFU.

4.2. Vibration Testing

The RMU was vibration tested to a level of $12.7g_{RMS}$ with a frequency range of 20-2000Hz in the lateral and longitudinal axes. These parameters were defined by the REXUS programme to validate the experiment against the loads that would be experienced by the rocket.

No sign of damage or displacement was detected following these tests. A subsequent successful ejection test demonstrated that there was no significant deformation of the structure.

4.3. Thermal Testing

Thermal testing was undertaken in order to ensure the functionality of all hardware when exposed to external temperatures outside of the operational range of the electronic components.

Functional hot and cold tests were carried out at temperature extremes of 45ºC and -10ºC respectively. The hardware remained operational throughout all of the tests, and the physical results obtained for the FFU showed a discrepancy with the ESATAN-TMS model of only 5%.

5. RESULTS

5.1. Communications System

The wireless communications link was analysed using data collected by an SDR (Software Defined Radio). A spectrogram of the received signal demonstrates the side band signal strength and the frequency (see Figure 8).
Data packets were received for the first 71s of free fall, and this period was defined by strong signal strength and minimal frequency shift. At approximately 235s there was a sudden drop in signal strength and the received frequency started to decrease. The signal frequency reached a low of 400Hz below the transmission frequency. Signal was intermittent from this point onwards with the final signal received at approximately 520s on the spectrogram.

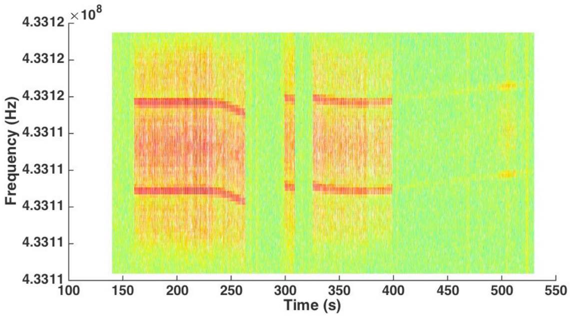

Figure 8. Spectrogram of received signal over SDR and plot of side-band power

5.2. Optical Data

Figure 9 shows the optical data collected in its raw form. The origin of the graph corresponds to the ejection of the REXUS-17 nosecone (T+78s). The ejection of the FFU corresponds to 66s in Figure 9. There are therefore two distinct data collection regions: the 0s to 66s region in which the FFU is contained within the RMU and the rocket is ascending, and 66s to 151s, when the FFU is in free fall.

Upon nosecone ejection the FFU was exposed to light and the optical readings rose from zero. The sinusoidal variation that can be seen within this region was due to the rotation of the rocket. Note that the lower optical readings in this period compared with those collected during free fall was due to the obstruction of the optical fibres by the RMU.

The linear portion of the graph (from 66s to 121s) represents the planned 15s delay between the ejection of the FFU and the transmission of data. The sinusoidal variation that can be seen from 81s to 151s (when the last data packet was received) was due to rotation of the FFU.

The raw data presented in Figure 9 was processed by averaging the readings obtained from the high and low sensitivity photodiodes for each optical filter and smoothing to remove the noise. To find the relative intensity level at the desired wavelength the narrowband was divided by the wideband reading and normalised. Note that Figure 9 shows that the higher sensitivity photodiodes saturated during the free fall. These readings were therefore discounted and the lower sensitivity readings used. The rocket trajectory data and FFU trajectory model were then combined in order to map the time from nosecone ejection to last received packet against altitude. Figure 10 shows the obtained Na and O_2 profiles.

The optical data does not show the expected trend. For example, the high concentration of Na above 80km corresponding to the sodium layer was not represented in the results. These variations present are most likely due to light intensity fluctuations, which can be seen in Figure 10. This is also evident in the disparity between the data obtained during the ascent (represented by the blue portion of the graph in Figure 10) and the free fall data (the red portion). It is suspected that imperfections in the 3D printed optical barrel that housed the photodiodes resulted in light leakage. This could have been additionally exacerbated by the uneven distribution of the fibre-optics. The variations hide any subtle change due to the changing substance levels and therefore the results cannot be considered valid. Although the measuring of light levels while in free fall through the use of the optical system was a success, the measurement system needs further refinement.

6. CONCLUSION

In conclusion, the design, manufacture and testing of WUSAT-SOLSPEC culminated in a successful launch campaign in March 2015. The primary objective of the project was to develop a functioning CubeSat unit which was fully achieved, with the system behaving as expected during the launch.

Communications with the REXUS rocket were maintained before ejection, and the FFU was ejected at the apogee of the REXUS rocket proving that the ejection mechanism functioned. The mechanical structure of both the FFU and the RMU was able to sufficiently protect the payload during launch and free fall, with a visual inspection of the RMU post-launch showing no measurable damage to the structure.

For the first time in any REXUS mission a live communications link was established between an FFU and a ground station during free-fall. Subject to some drop outs on this communications link, data about atmospheric levels of Na and O_2 was able to be collected during the free-fall of the FFU.

It should be noted that although there was not a strong trend in the scientific results collected, from an

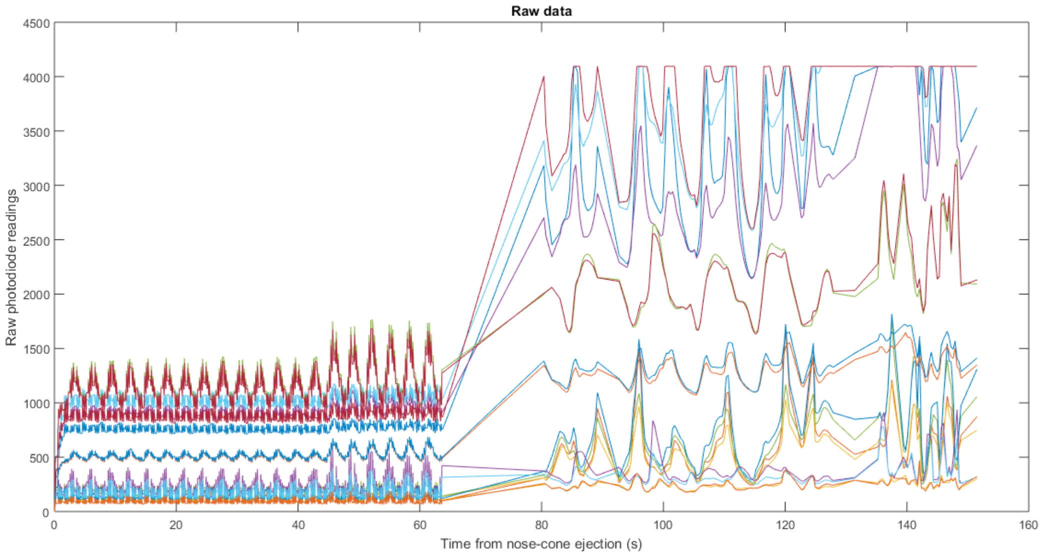

Figure 9. Raw optical data

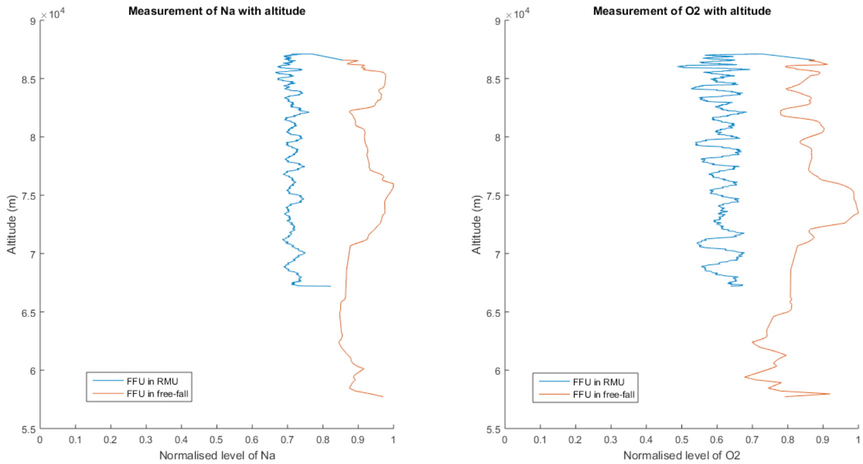

Figure 10. Normalised levels of Na and O_2 with altitude

engineering perspective the capability of the payload to collect data was more important than the quality of the data collected. The collection of data proved that the optical system designed and used was successful.

7. ACKNOWLEDGEMENTS

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