Final Science Report

Payload Title: Sheffield University Nova Balloon Lifted Telescope		
Institution: The University of Sheffield		
Payload Class: LARGE		Submit Date: 14.12.2018
Project Abstract: Sun surveillance from the ground is often difficult as the thick atmosphere of the Earth blocks and distorts much of the incoming light. Learning about the Sun is critical in modern society, when solar flares have the potential to cripple telecommunication and global navigation systems. In the UK alone, €22mn was invested in the Space Situational Awareness program emphasising the need to better understand and predict solar events. Project SunbYte (Sheffield University Nova Balloon Lifted Telescope) aims to revolutionise the industry of solar observations by using a high-altitude balloon to lift a telescope to an altitude of 25-35km, where SunbYte has the potential to capture images of much better quality. As the existing ground and space telescopes are large, complex and expensive, the number of scientists who have access to such resources are quite limited. Even though experimental studies using high-altitude balloon telescopes have been previously conducted, these are, in terms of cost, inaccessible to many mainstream research institutions across the world. Combining the latest practices in manufacturing, astrophysics science and engineering, the team aims to deliver a low cost high quality method of imaging the Sun. The experiment was launched on BEXUS 25 from ESRANGE, Sweden in Oct 2017 as part of the REXUS/BEXUS programme. This document will discuss the new design for launch on HASP based on the lessons learnt.		
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Nomenclature

3D	Three Dimensional
ADCS	Attitude Determination and Control System
CRC	Cyclic Redundancy Check
CME	Coronal Mass Ejection
CMOS	Complementary metal–oxide–semiconductor
DC	Direct Current
DOF	Degrees Of Freedom
ERF	Energy Rejection Filter
FCS	Frame Check Sequence
FEA	Finite Element Analysis
FOV	Field Of View
GPS	Global Positioning System
HASP	High Altitude Student Payload
PCB	Printed Circuit Board
RPi	Raspberry Pi
SSD	Solid State Drive
STEM	Science, Technology, Engineering and Maths
UK	United Kingdom
USA	The United States of America
USB	Universal Serial Bus
WBS	Work Breakdown Structure

Content

1.Introduction

1.1 Scientific/Technical Background

The Sun is the most important source of energy for the Earth and it is essential that we keep it under surveillance in order to understand how any changes will affect our planet.

In 1895, a solar coronal mass ejection hit the Earth's magnetosphere and caused Auroras to appear as far South as the Caribbean. In 1989, a geomagnetic storm took out much of Quebec's electricity grid plunging the country into chaos. If such an event were to occur nowadays, where delicate electronic devices a ect important aspects of our lives such as security, the outcome would be even more devastating. In 2012, there was a solar storm of equal magnitude as the one that occurred in 1895 but luckily missed the Earth. Given the impact of these threatening events former U.S. President Barack Obama issued an executive order calling for preparations against solar flares in October 2016 [1]. Solar storms are one of the most significant outer space threats to normal life - hence the need for development of low cost access to monitoring of the Sun is imperative.

1.2 Mission Statement

Current Earth-based solar telescopes are very expensive in part due to the large and costly equipment required for compensation of astronomical "seeing" (Refraction and scattering distortions caused by Earth's atmosphere). This reduces the quality of images taken. Whilst space-based telescopes can avoid astronomical seeing and astronomical extinction (absorption of electromagnetic radiation in the ultraviolet, X-ray and gamma wavelengths), these require expensive rocket launchers and are practically impossible to modify or modernise once launched into orbit.

Traditionally, the best solution has been to locate observatories as high as possible to minimise the thickness of atmosphere. Lucky imaging is also used to capture moments when the turbulent atmosphere has no overall effect. Combining these conventional ideas, project SunbYte aims to use high altitude balloons to hoist a telescope to the edges of the Earth's atmosphere at 36 km altitude. High frame rate with allow “lucky imaging” and further increase the probability of acquiring scientifically worthwhile images.

1.3 Experiment Objectives

1. Primary objective: Track and image the Sun.
2. Secondary objectives: Acquire focused solar images to demonstrate scientific potential.
3. Tertiary objectives: Promote and increase space engineering studies in "aerospace engineering" courses across the country.

1.4 Experiment Concept

Based on the objectives, a full list of derived function, performance, design and operational requirements can be found in this report.

In order to locate and track the Sun we have a tracking camera attached to the telescope tube:

This camera was connected to a Raspberry Pi (RPi), this will detect the bright disc of the Sun in the images using Python code developed with OpenCV. A neutral solar filter at the front of the cameras (99.99% absorption) would ensure that only the disc of the Sun is visible in images. Once the position of the Sun within the image is located, instructions are sent from the RPi to a Arduino motor controller to reposition the telescope so that the center of the Sun is at the center of the telescope.

A science data acquisition camera would be attached to the prime focus of the telescope tube, this will be connected to a different RPi via USB and expected to capture images of 1920x1080 up to ~1 FPS (limited by the processor speed of the RPi). The images would be saved to an SD card for post-flight analysis. The system would also run a focusing routine to check and adjust the telescope focus as it expands and cools due to temperature/pressure changes. This would be carried out by shifting the focus, taking a sample picture and comparing the image to determine which image is in better focus.
Lastly, during flight, a selection of highly cropped and reduced images from each camera would be intermittently transmitted to the ground station to manually verify target and focus of the telescope.

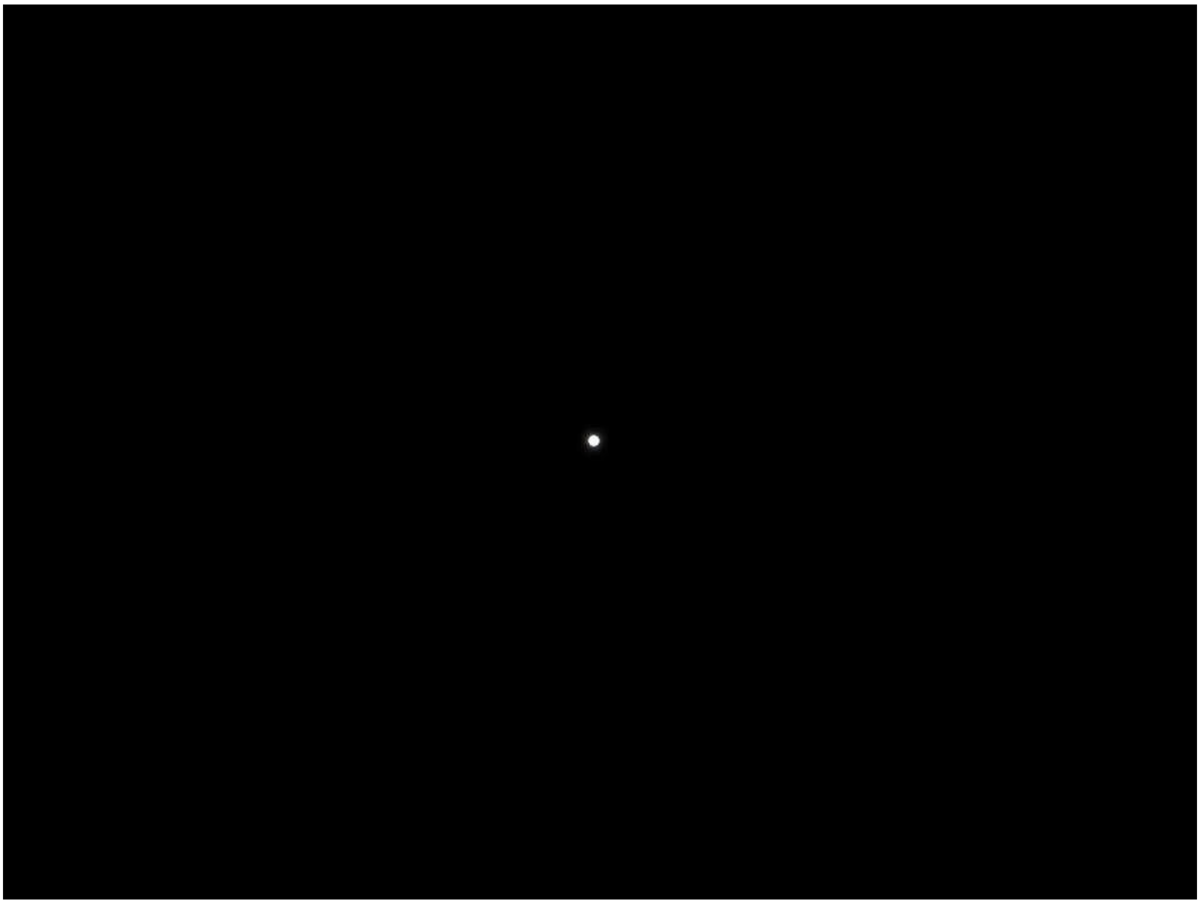

Figure 1.4.1 – Images of the sun as taken by a RPi Camera Module v2.1 with Baader Planetarium AstroSolar Solar Filter film. The disc of the sun is clear and easy to track.

1.5 Team Details

1.5.1 Contact point

Name:	Iakov Bobrov (team leader)
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Team E-mail:	SunbYte@sheffield.ac.uk

1.5.2 External support

Table 1.5.2.1 – External support

	**Name:** Dr. Viktor Fedun, Department of Automatic Control and Systems Engineering, PhD, The University of Sheffield (UK) **Role:** Academic Lead **Responsibilities:** Scientific and organisational support for funding and outreach purposes. Engages internal stakeholders and other departments.
	**Name:** Dr. Gary Verth, School of Mathematics and Statistics (SoMaS), PhD, The University of Sheffield (UK) **Role:** Scientific and organisational support **Responsibilities:** Scientific and organisational support for funding and outreach purposes. Engages internal stakeholders and other departments.
	**Name:** Yun-Hang Cho, Department of Civil Engineering, 2nd year PhD, The University of Sheffield (UK) **Role:** Mentor and Systems Engineer **Responsibilities:** Systems Engineering support and mentorship. Yun was previous team leader of SunbYte and lead the team to launch with the European Space Agency as part of REXUS/BEXUS program.

1.5.3 Current team members

Table 1.5.3.1 – Current team members

	**Name:** Iakov Bobrov, 3rd year BEng Aerospace Engineering with a Year in Industry and Private Pilot Instructions, The University of Sheffield (UK) **Role:** Project Leader **Responsibilities:** Overall project planning and management.
	**Name:** Gianni Heung, The University of Hong Kong (HK) **Role:** Electrical team leader **Responsibilities:** Electrical team management. Developed communication Tracking and Hardware systems.
	**Name:** George Robinson, 3rd year BEng Aerospace Engineering with a Year in Industry, The University of Sheffield (UK) **Role:** Mechanical team leader **Responsibilities:** Structure design and telescope integration. Mechanical team management.
	**Name:** Alex Hamilton, PhD student, The University of Hull (UK) **Role:** Optics team member **Responsibilities:** Optics System
	**Name:** Arthur Cunningham, 4th year MEng Aerospace Engineering, The University of Sheffield (UK) **Role:** Mechanical team member **Responsibilities:** Helped with the design and manufacture of the mechanical structure. Helped to implement the electrical systems.
	**Name:** Abdulla Omaruddin, 2nd year Automatic Control and Systems Engineering, The University of Sheffield (UK) **Role:** Electrical team member **Responsibilities:** Assisted in developing the software for the system. Worked on motor control and serial communication.

	**Name:** Federico Orrego Mendez, BEng Aerospace Engineering with a Year in Industry and Private Pilot Instructions, The University of Sheffield (UK) **Role:** Electrical and Mechanical team member **Responsibilities:** Design and manufacture of the sensors subsystem
	**Name:** Tom Holford, 4th year MEng Mechanical Engineering, The University of Sheffield (UK) **Role:** Mechanical team member **Responsibilities:** Development of structure. Designing and prototyping of components.
	**Name:** Sagar Shah, 2nd year MEng Aerospace Engineering, The University of Sheffield (UK) **Role:** Electrical team member **Responsibilities:** Ground Station System
	**Name:** Theo Glashier, 4th year MEng Mechanical Engineering, The University of Sheffield (UK) **Role:** Mechanical team member **Responsibilities:** Helped on the development of the payload initial prototype. My work was focused on motor/structure design and general CAD of the system.
	**Name:** Yadav Dosieah, The University of Sheffield (UK) **Role:** Electrical team member **Responsibilities:** Worked on the solar tracking.
	**Name:** Alexander Menzies, 4th year MEng Mechanical Engineering, The University of Sheffield (UK) **Role:** Mechanical team member **Responsibilities:** Helped on the development of the payload initial CAD design.

	**Name:** Joycelyn Fontanilla, 3rd year MEng Chemical Engineering, The University of Sheffield (UK) **Role:** First mechanical team leader **Responsibilities:** Helped on the development of the payload initial CAD design and prototype.
	**Name:** Andrew Baker, 2nd year MEng Aerospace Engineering, The University of Sheffield (UK) **Role:** Mechanical team member **Responsibilities:** Assisted with CAD design and manufacturing.

Demographics for every student who participated in the project since November 2017 can be found in the Appendix A.

1.5.4 Team organization

Figure 1.5.4.1 - Team organization chart

Team organization chart is shown in Figure 1.5.4.1. Project guidance is provided by Faculty Advisor and Mentor who was also the systems Engineer. Project leader is responsible for distributing task to leaders of each sub-team and overall management of the project. Project leader is responsible for ensuring each sub team meets their deadlines and objective. Each team leader allocates tasks and technical support to the members. End of each month, the project leader and sub-team leaders are producing a monthly report to present the progress of the project. This ensures all objective are met on time.

2. Experiment requirements and constraints

2.1 Functional Requirements

F1. The camera shall successfully track the Sun.
F2. The experiment shall image the Sun in the spectral line at 393 nm (K-Ca) or 656.28nm (H-alpha).

2.2 Performance Requirements

P1. The gimbal system shall direct the telescope towards the Sun with an accuracy of at least 1 arc minute.
P2. The telescopes diffraction limited resolution shall be within a value of 1.5 arcsecs.
P3. The Sun shall be imaged at a maximum rate of 40 fps.
P4. The experiment shall produce an output image with a resolution of 0.6 arcsec at the vacuum wavelength of H-alpha line core - 656.28nm.
P5. The maximum current drawn shall not exceed 2.5A.
P6. The supporting structure shall withstand a maximum compressive load of 200N.
P7. The tracking camera shall have a video resolution of no less than 640 by 480 pixels and 30 fps.

2.3 Design Requirements

D1. The experiment shall operate in the temperature profile of the HASP vehicle flight and launch.
D2. The experiment shall operate in the vibration profile of the HASP vehicle flight and launch.
D3. The experiment shall operate in the pressure profile of the HASP vehicle flight and launch.
D4. The experiment shall not disturb or harm the launch vehicle.
D5. The experiment shall not broadcast at a frequency prohibited in New Mexico.
D6. The diameter of the primary mirror shall not exceed 85 mm.
D7. The length of the telescope shall not exceed 380 mm.
D8. The mass of the experiment shall not exceed 20 kg.
D9. The maximum tolerance of any gearing has to be within 0.2 arc minute.
D10. The Sun sensor shall detect intensities of up to 100,000 lux.
D11. The supporting structure shall not twist by more than 0.1 degrees.
D12. The supporting beam shall not buckle under a safety factor of 2.
D13. The experiment shall be able to run for up to 20 hours.
D14. The datalogger shall able to receive signal and store it.
D15. The main computer shall able to communicate with the ground station
D16. The external focuser shall able to adjust focus up to 8mm.

2.4 Operational Requirements

O1. The experiment shall accept control of the focusing motor for manual focus if a command is sent.
O2. The experiment shall enter the searching pattern if the location of the Sun is not found according to the astronomical algorithm.
O3. The experiment shall transmit images to the ground when requested.
O4. The experiment shall cease to rotate on landing.
O5. The experiment shall be able to read data from a GPS device.

3. Project Planning

The project was managed on a day-to-day basis by the sub-team leaders. As principal participant, the team leader is responsible for overall project management and direction. The project will be supervised by the Academic Lead with mentoring support to conduct internal project reviews. This will highlight the progress made, and allow for planning and discussion for further advancement of the project.

The team leader is responsible for the successful running and delivery of the following tasks:

1. Meeting the contractual obligations of the project (financial, administrative, and scientific).
2. Monitoring the progress of the project and ensuring deliverables are met.
3. Organising, chairing and reporting of project meetings.
4. Ensuring good, timely communications between the members of the team and stakeholders.

At the operational level, each task has a responsible student lead (supported by an Academic Advisor when necessary). His/her main responsibility also includes understanding of other the other work carried out by their sub-team and how it fits within the project deliverables.

3.1 Schedule

3.1.1 Overall project Gantt Chart

The project can be divided into 7 main phases; these are shown in the table below alongside with non-productive periods, such as exams and holidays.

The table below explains some of the key activities taking place during each stage.

Phase	Name	Description
0	Concept	Develop concept and feasibility analysis of mission
A	Preliminary Design	Develop requirements and first design
B	Detailed Design	Build test prototypes to validate and develop design
C	Manufactruing	Manufacture, test and assembly of flight model
D	Integration	Integrate payload into launch vehicle
E	Launch	Launch activities, monitor status, downlink data, uplink commands
F	Post Processing	Analyse data and compare against industry standards

Figure 3.1.1.1 – Legend for Gantt Chart

Using the work breakdown structure, the Gantt chart below shows a detailed breakdown of the tasks undertaken by each sub-team during the current phase (detailed design) and the periods of when the activities began and will finish.

	2017			2018											
	October	November	December	January	February	March	April	May	June	July	August	September	October	November	December
Notes	Launch		Exam & Christmas Break					Exam & Summer Vacation							
Phase 0	Concept														
Phase A		Preliminary													
Phase B				Detialed Design											
Phase C						Manufacturing & Testing									
Phase D										Payload Integration with HASP - July 23 - July 28					
Phase E												Launch - September 2			
Phase F														Post processing	
Milestones					Revised Application/ Response to reviewer - due on Feb. 26		Preliminary Payload Specification & Integration Plan (PISP) - due on April 27		Final Payload Specification & Integration Plan (PISP) - due on June 22						Final Flight/Science Report

Figure 3.1.1.2 – Gantt Chart

3.1.2 Project planning by sub-team

Figure 3.1.2.1 shows the project plan for the mechanical team. No work is to take place during the exam periods. Spare days have been planned to account for possible delays.

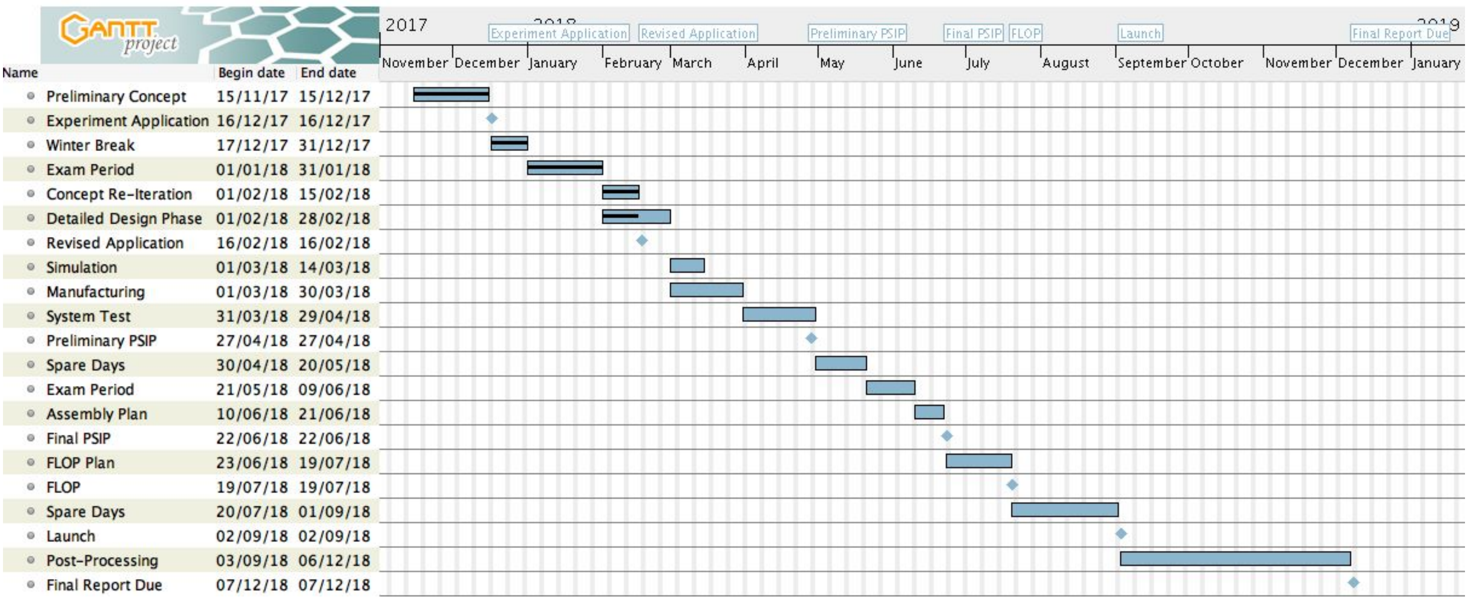


Figure 3.1.2.1 – Mechanical Team Gantt Chart

The Work Breakdown Structure is shown in Table 3.1.2.1, and details the allocation of sub-tasks and their estimated duration.

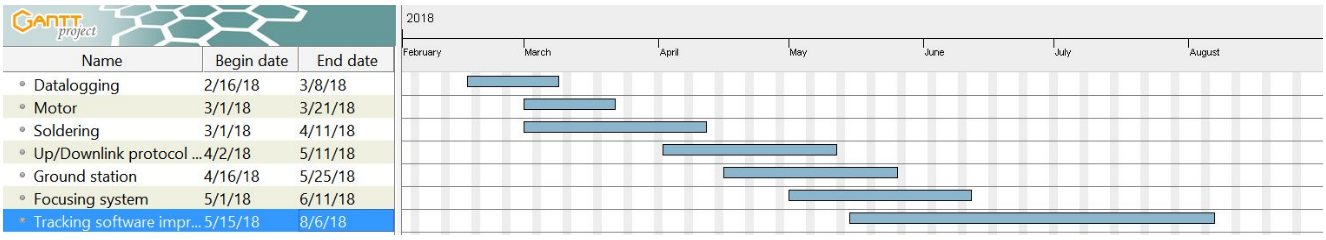


Figure 3.1.2.2– Electrical and Software Team Gantt Chart

Table 3.1.2.1 – Mechanical Team Work Breakdown Structure

Task	Details	Duration (Days)	Lead
Preliminary Concept		31	Joycelyn
Design Concept	Generation of preliminary design concept	20	Joycelyn
CAD Modelling	CAD Modelling in SOLIDWORKS of preliminary concept	11	Alexander
Concept Re-Iteration		15	Joycelyn
Design Concept	Feedback used to generate revised concept	7	Joycelyn
CAD Modelling	CAD Modelling in SOLIDWORKS of revised concept	8	Alexander
Detailed Design		28	Alexander
Engineering Drawings	Production of technical drawings in SOLIDWORKS for manufacturing	7	Brandon & George
Manufacturing Plan	Assigning manufacturing tasks, send requests to workshops for complex parts	14	Alexander
Purchasing	Ordering material (to be done in parallel to other tasks)	7	Joycelyn
Simulation		14	Brandon
Structural FEA	Analysis using ANSYS software	14	Brandon
Thermal FEA	Analysis using ANSYS software	14	Brandon
Manufacturing		30	Joycelyn
Manufacturing	Manufacturing of mechanical components, collection from workshops	25	Joycelyn
Assembly	Integration with electronics hardware	5	George
System Test	Full-functional test of the system	30	Iakov
Assembly Plan	Creation of assembly manuals and launch procedures for mechanical parts	12	George
Spare Days	Used in case of delays or for manufacturing/ordering spare parts	21 (Pre-FLOP) + 44 (Post- FLOP)	Joycelyn

Table 3.1.2.2 – Electrical/Software Team Work Breakdown Structure

Task	Details	Duration (Days)	Lead
Electronic Sub Team		61	Gianni
Focusing system	Developing an arduino code for focusing system	61	Gianni
Motor	Developing a stoppable telescope protection system	15	Gianni
Soldering	Soldering all parts together	10	Iakov
Data logging	Building the sensors to monitor the system performance	15	Gianni
Updown/ Download cable	Up/Downlink protocol development	45	Gianni
Software Sub Team		75	Alex
Tracking	Software improvement	75	Alex
Ground Station	Design a ground station that collects all real time data and displays it	61	Gianni/Alex

3.2 Risk

A list of safety, project and technical risks can be found in Appendix B. Risk Analysis. Actions to reduce these risks are stated where necessary.

4. Experiment description

Project can be split into five subsystems:

1. Optics
2. Electrical and Power System
3. Altitude Determination and Control System
4. Structure
5. Datalogger
6. Thermal System
7. Communication System

The payload is the telescope. Altitude Determination and Control System provides tracking of the Sun and moves the telescope to face the Sun. Electrical and Power System supplies power to the necessary modules. Communication System allows to transmit data to the system as well as receive it back to the ground station. Thermal System is responsible for keeping the system functionable at extreme temperatures and the Structure physically holds everything together.

4.1 Optics

4.1.1 Optics Introduction

1. Target considerations: The Sun subtends an angle of approximately 1,865 arc seconds (0.52 degrees) to an observer on the Earth. The diameter of the Sun is $1.392 * 10^9$ m (864,949 miles). The required resolution of 1 arc seconds therefore represents 373,151m (373.1 km, 231.96 miles) on the surface of the Sun.

2. Angle of view: The telescope will be limited to making observations of the Sun only and therefore it will be acceptable to use an optical system with a narrow field of view.

3. Limits to telescope resolution:
   a. Atmospheric distortion. At ground level, atmospheric distortion limits telescope resolution depending on altitude/location. Most Earth telescopes are limited by atmospheric distortion but within the HASP operating environment, atmospheric distortion is minimised because there is low pressure.

   b. Diffraction. The resolution of the telescope is limited by the size of the primary reflecting optic. This may be calculated as:
   $$\text{Angular resolution} = 1.22\ x\,\frac{wavelength}{optic\ diameter}$$

   c. Sensor and pixel size. The angle of view is limited by:
   $$\text{FoV} = arctan\left(\frac{sensor\ size}{focal\ length}\right)$$

   d. Likewise, sensor resolution is limited by:
   $$\text{Sensor resolution} = arctan\left(\frac{pixel\ spacing\ size}{focal\ length}\right)$$

4. Environmental considerations

- Temperature variations: It was expected that the telescope would suffer an extreme range of temperatures. Due consideration was given to thermal expansion (contraction) which may impact the primary and secondary mirror alignment as well as the positioning of the imaging sensor at the focal point of the telescope.

- Condensation of water vapour: Consideration was also given to the possibility that water vapour may condense on the optics at altitude due to low temperatures.

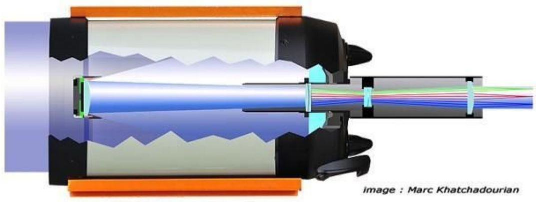
5. Solar energy reduction. Energy Rejection filter (ERF) to block the majority (99.99%) of light, especially in the UV and IR parts of the spectrum to protect optics and sensors.

4.1.2 Telescope Selection

4.1.2.1 Initial selection

Because of considerations outlined above, a cassegrain type telescope was considered due to long focal length with a compact length and volume. The telescope under consideration was the Meade ETX 90. This uses a Maksutov Cassegrain reflector design.

This design differs from the classic Cassegrain design by having a corrective negative lens at the front of the telescope to correct for the off-axis aberrations. The design has a relatively narrow field of view making it suitable for solar observations.



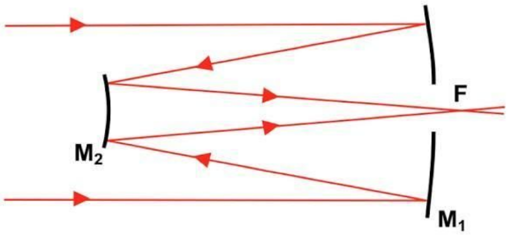


Figure 4.1.2.1.1 – Telescope configuration

A 90 mm primary optic offers a 0.032 arcsecond resolution for light 656 nm (H-alpha) and 0.019 arcsecond resolution for light 393 nm (K-Ca) based on calculations below (resolution is within the requirement of 1.5 arcsecs).

$$\text{Angular resolution} = 1.22\ x \frac{656.28nm}{90mm} = 0.032 \text{ arcsec}$$

$$\text{Angular resolution} = 1.22\ x \frac{393nm}{90mm} = 0.019 \text{ arcsec}$$

Other characteristics of Meade ETX-90:

- aperture: 90mm
- focal length: 1250mm
- focal ratio: f/13.9.

Meade ETX 90 and a sensor ZWO ASI 120MM Mini were selected in the beginning of the project and design of other systems was based on these components. However, a decision to select a different telescope was made for the following reasons:

1. Mechanical constraints. This telescope was too large for the mechanical constraints given by HASP.
2. Magnification of the telescope was too large to capture the entire Sun. In order to decrease it we tried to implement focal reducers which reduce the

focal length of a telescope, hence reducing the magnification factor. However, we could not find any focal reducers that allowed us to achieve the desired magnification. Image that could be taken with this telescope-sensor configuration can be seen below in Figure 4.1.2.1.2.

Figure 4.1.2.1.2 – Example of the image taken with a telescope Meade ETX-90 and a sensor ZWO ASI 120MM Mini, generated using website: http://www.skyatnightmagazine.com/astronomy-field-view-calculator

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4.1.2.2 Final selection

A William Optics Zenithstar 61 refracting telescope was then selected to resolve the outlined problems.

Figure 4.1.2.2.1 – William Optics Zenithstar 61

A 61 mm primary optic offers a 0.047 arcsecond resolution for light 656.28 nm (H-alpha) and 0.028 arcsecond resolution for light 393 nm (K-Ca) based on calculations below (resolution is within the requirement of 1.5 arcsecs).

$$\text{Angular resolution} = 1.22\, x \frac{656.28nm}{61mm} = 0.047 \text{ arcsec}$$
$$\text{Angular resolution} = 1.22\, x \frac{393nm}{61mm} = 0.028 \text{ arcsec}$$

Other characteristics of William Optics Zenithstar 61:

- aperture: 61mm
- focal length: 360mm
- focal ratio: f/5.9.

William Optics Zenithstar 61 in combination with the same sensor gives an image of the entire Sun in the field of view, as in Figure 4.1.2.2.2

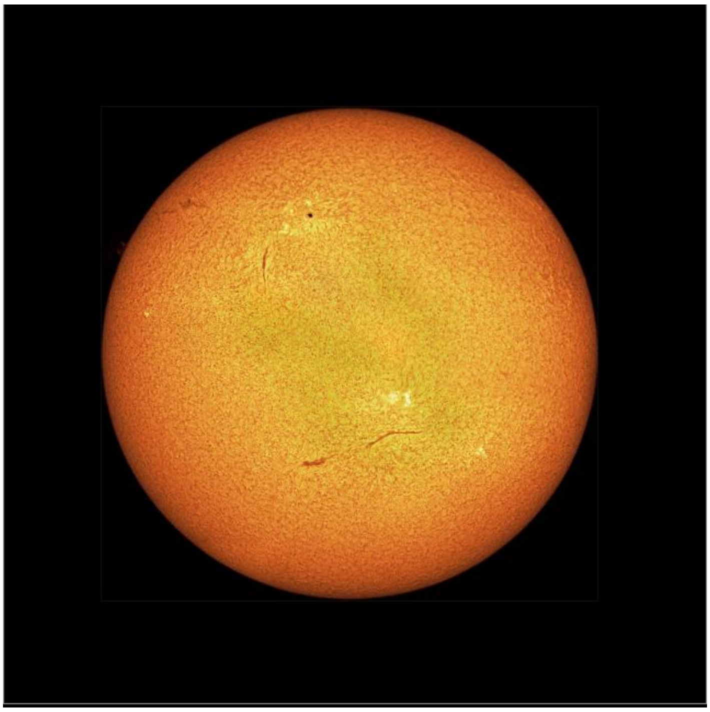


Figure 4.1.2.2.2 – Example of the image taken with a telescope William Optics Zenithstar 61 and a sensor ZWO ASI 120MM Mini, generated using website: http://www.skyatnightmagazine.com/astronomy-field-view-calculator

4.1.3 Filter selection

In order to evaluate the performance of the focus control, a resolution of <2 arcsec at the vacuum wavelength of H-alpha line core (656.28 nm) is required. The choice of the line is based on the following factors:

- The sensitivity of most CCD/CMOS cameras are close to its maximum at this wavelength;
- This wavelength is close to the peak of the Planck function, which approximately describes the solar radiation spectrum as a black body radiation with the effective temperature of 5700 K;
- H-alpha line core is formed mostly in the solar chromosphere with some lower corona influence, making it especially attractive for scientific applications;
- H-alpha line core etalons are commercially available as they are commonly used in amateur astronomy.
- The images produced will have a high range of contrast, with light and dark feature visible, which should be ideal for allowing the image to focus.

As an alternative, consideration has been given to the use of a CaK (394 nm ± 80 Å HBW) dielectric lens filter. This has the following considerations:

- A similar section of the spectrum to H-alpha, so suitable for most optical setups and cameras.
- Has a wider suitable bandpass, making it more suitable for shorter focal length setups. We could also "double stack" two filters to narrow the bandpass.
- Is cheaper, lighter and requires no power supply to maintain the correct bandpass.
- The CaK emission is mostly in the Chromosphere, overlapping H-alpha but ending higher in the solar atmosphere, this will show features like granulation, sunspots and faculae.

Figure 4.1.3.1 shows a comparison between the image of the Sun in the visible light and the images obtained using H-alpha and CaK filters.

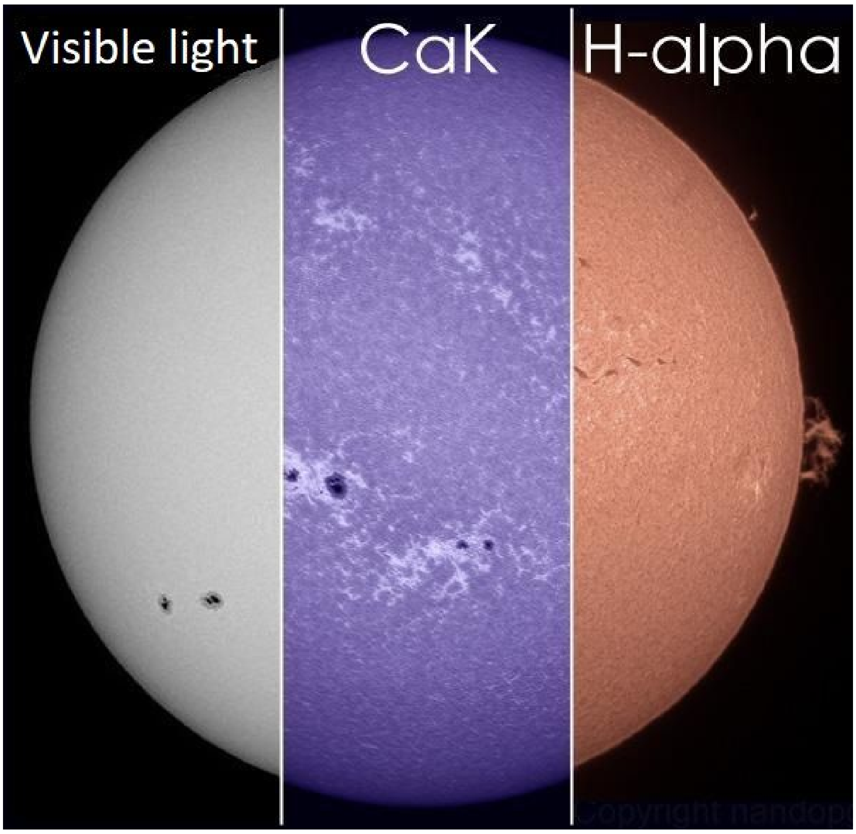


Figure 4.1.3.1 – Image of the Sun in visible light, Ca-K and H-alpha spectrum line.

As it can be seen, the white light shows little detail beyond sunspots, while the CaK and H-alpha filters show a good variety of details. [4]

4.1.4 Optical system Design

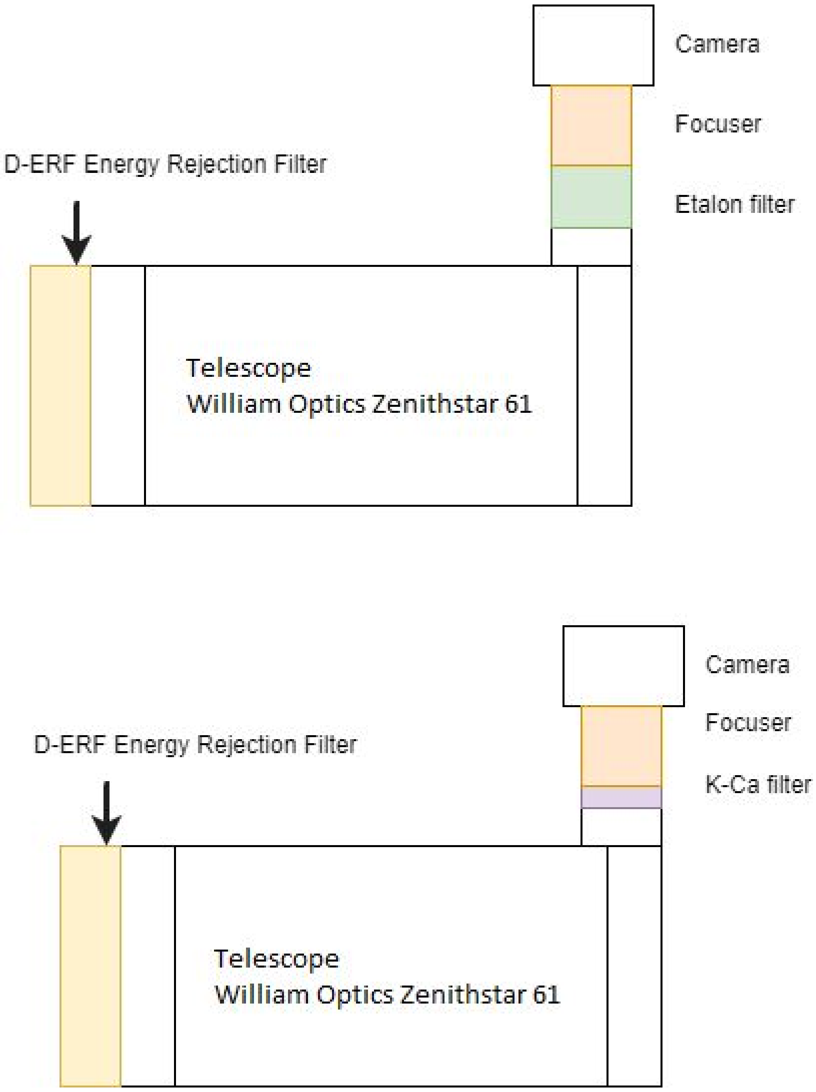


Figure 4.1.4.1 – Schematic of optical system

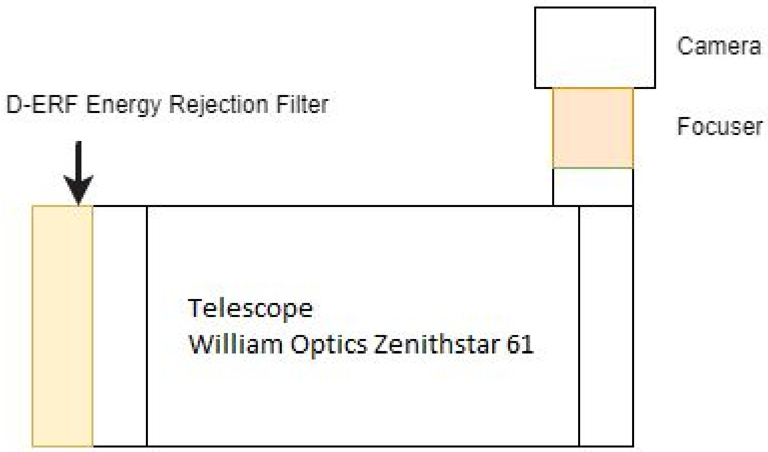
Figure 4.1.4.1 shows the optical design concepts, the upper diagram is the primary design of the system. Energy rejection filter is installed at the front end, it reduces the total flux into the telescope and thus protects the mirrors from heating up. The telescope is optically placed in the middle, etalon and focuser are attached on top of the viewfinder. The internal focuser moves the primary mirror, this is not used in flight because it requires good lubrication to get smooth movement, which cannot be guaranteed given the extreme variation of environment the telescope will be subjected to. Therefore an external helical focuser will be used. The scientific camera is placed at the end of the optical path to capture images.

One concern is the survival of the relatively expensive etalon filter, at high altitudes the extremely low temperature and pressure could cause damage and make it hard to maintain the correct temperature for the etalon to accurately fix on the correct bandpass, as an alternative, if vacuum tests show an issue a much simpler K-Calcium (K-Ca) lens filter can be used instead, This does not require a constant temperature to operate correctly hence eliminating the need for a power supply while also being lighter and more durable.

The allocation of the secondary design are shown in the bottom of Figure 4.1.4.1 Etalon filter is replaced by K-Ca filter.

Final optical system design

Solar observation in a certain wavelength makes the experiment much more complicated than if no filters are used. Etalons are bulky and require power and expensive electronics. Both filters discussed above would also ideally require some additional optics, that would push out tube length too far. Because our primary aim of the second iteration of SunbYte was to prove the concept, a decision to fly our experiment without any of the filters was made. Thus, Sun would be observed in visible light. The final optics setup is shown on the diagram below.



e 4.1.4.2 – Schematic of the final optical system

4.2 Electrical and Power System

4.2.1 Electrical System

Electronics Overview

The main goal of this project has been to develop a low-cost instrument that will allow us to study the Sun. Hence, the electronic components that have been selected are inexpensive and commercially off-the-shelf available with immense resources available online. The electronic circuitry was to provide a platform for the software that allows an effective tracking of the Sun and correct adjustment of the telescope. A set of tables, Table 4.2.1.1 and Table 4.2.2.2, has been produced to provide a list of components that were used highlighting their purposes as well as reasons as to why they were selected.

Electronics

As part of the specification supplied by HASP, the team was required to develop a serial communication interface with NASA's groundstation in order to have telemetry communication functionality in the system. The initial design consisted of only two Raspberry Pis. However, due to the processing speed of the Raspberry Pi, it was decided to split the task of the system into three systems instead.

Due to certain constraints, the team decided to distribute the function of system into three computers. Thus, the electronic system was simplified and became more robust, where each data recorded more than 2 copies within the system. Below, Figure 4.2.1.1 illustrates the 'Electrical Topology of the Sunbyte II'.

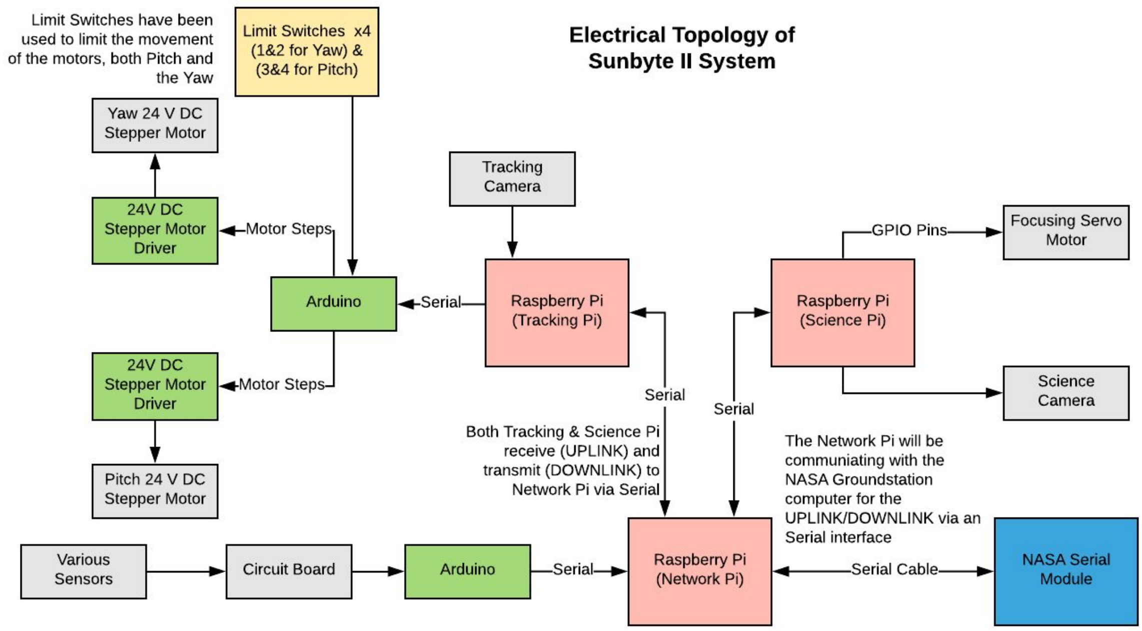


Figure 4.2.1.1 - Electrical Topology of the Sunbyte II system

As shown in the above figure, Figure 4.2.1.1, in its current state, the entire system is composed of three Raspberry Pis v3, two Arduinos for controlling the motors and sensors, two high resolution stepper motors for rotation of the gimbal and 2 CVK series drivers for controlling these motors, one focusing system including a high resolution stepper motor with a driver, 3 DC/DC converters and several sensors including pressure sensors, temperature sensors, and humidity sensors.

The first computer, Tracking Pi, was be responsible for performing the actual tracking of the Sun. It was connected to an Arduino Mega microcontroller in order to perform the movement of the two 24V stepper motors. The Tracking Pi would also send a unique string that would include the settings and parameters of the filters etc. via a serial link to the Network Pi, as shown in Figure 4.2.1.1

The second computer, Science Pi, was responsible for capturing the high-quality images via the Scientific camera, which was mounted at the back of the telescope, and focus the telescope using a servo motor every minute or so. The Science Pi would also produce a unique string containing the settings of the camera and the string of the compressed image. This string, as shown in Figure 4.2.1.1, was send via a serial link to the Network Pi.

Finally, the Network Pi was designed to obtain useful data such as the temperature, pressure, acceleration, etc. from an Arduino datalogger. The Network Pi was also receiving and storing the unique strings produced by the Science & Tracking Pi. A final string would be sent to the ground station as the downlink from the Network Pi. The final string would consist of the Arduino datalogger data and the string supplied by the Tracking and Science Pi. An additional functionality was added in order to perform the Uplink, whereby the team could send a unique hexadecimal value from the ground station in order to change the settings and parameters of the system. The hexadecimal value would be sent to either the Scientific or Tracking Pi through the Network Pi. This design ensured that the instrument has three independent processes that did not rely on each other. For example, in case the Tracking Pi failed, the team would at least be able to recover the data of the Arduino Datalogger.

Table 4.2.1.1: List of electronic components used in the system

Electronic Components	Purpose	Justification
Arduino Mega Microcontroller	2 Arduino Megas for the motor control and sensor data acquisition respectively.	Powerful processor and a reasonable number of I/O pins.
Raspberry Pi v3	3 Raspberry Pis used in the system: Tracking, Science, and Networking.	High computational power which is useful for tracking algorithm. Availability of I/O’s is also useful for telemetry communication with ground station.
Webcam Logitech C920	Used for tracking algorithm i.e. getting current position of the telescope.	Compatible with Linux and economical cost. Provides 1080P @ 30Hz.
ZWO ASI 120MM Mini	Used to capture the ‘high-quality’ images of the sun	Compatible with Linux and economical cost. Provides a high resolution of 1280x960
Stepper Motors - Oriental Motors	2 motors for the pitch and yaw respectively	Provides sufficient torque and accuracy for the task.

DC/DC Converter (to 5V)	Provides power to the 2 Arduino Microcontrollers and the 3 Raspberry Pis.	High efficiency to step down 30VDC from HASP to 5VDC
DC/DC Converter (to 24V)	Provide power to the 2 Stepper Motors	High efficiency to step down 30VDC from HASP to 24VDC
Real-time clock module	Essential for time stamping of the sensor data	Most reliable method of time-stamping

Table 4.2.1.2: List of sensors used in the system

Sensors	Purpose	Justification
GPS	Measure altitude with onboard sensor to avoid relying on uplink signal for HASP GPS position	Sensor to measure altitude up to 40 km above sea level
Thermocouple - Adafruit MAX31850	K-type thermocouple, used to measure temperature in a suitable range based on operation of SunbYte II	Gather data about the environment. Allows for multiple sensors on a single digital line.
Current Sensor	Measure current of high power components, such as heaters and stepper motors.	Used to control and monitor use of high power components
IMU	Measures the orientation of the system	Used to gather data about the flight profile

A complete list of the sensors can be found in the section 4.4 Datalogger.

Allocation of components in the eboxes

In order to minimise wiring across the two E-boxes, closely linked subsystems were placed on the same side. On the pitch motor side, tracking and gimbal motion required use of the Tracking Pi and Arduino Mega. Hence, these components were placed in the same 'shelf' along with the motor drivers used for both axis. On the parallel side, the Science Pi was placed on the top, with close proximity to the scientific camera. The second Arduino Mega was kept along the same shelf as the various sensors used for data acquisition. The Network Pi was located at the bottom in order to minimise the distance of communication cables coming from the opposite E-box. Additional layer space was designed in both boxes for future expansion to house solid state hard drives (SSD), additional DC/DC convertors or more sensors.

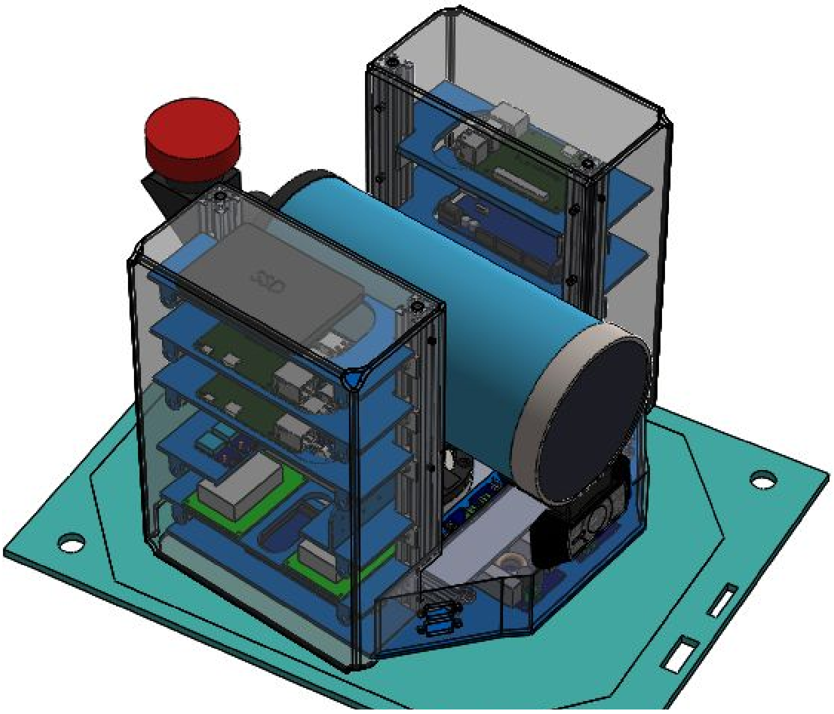


Figure 9.4.1 - Component allocation inside the side E-boxes.

4.2.2 Power System

Power Budget

A power distribution unit is being studied during the construction of the latest version of this document. Our preliminary power consumption details are given in the table Table 4.2.2.1.

Average power consumption (Current consumption): 36.73W (1.35A)

Table 4.2.2.1 – Power System Breakdown

	Voltage(V)	Current (A)	Power (Watt)	**Quantity**	**Total (W)**
Raspberry Pi 3	5	0.25	1.25	2	3
Arduino Mega	5	0.1	1	3	3
Electrical motors and Drivers	24	0.5	12	2	24
Tracking camera (HD PRO WEBCAM C920)	5	0.15	0.75	1	1.5
Focusing Motor	24V	0.2	12	1	12
Scientific camera (ZWO ASI120MM-S)	5	0.15	0.75	1	0.75
DC-DC converters (efficiency 95%)	24 or 5	N/A	0.35	2	0.7

Heating mats					
Wiring (10% of the total Power consumption)	N/A	N/A	0.165	N/A	3.343
Total	N/A	1.35A	N/A	N/A	36.73W

Values provided in the power table are rated values. It is now known from experience that the real power consumption is below those values which points out to the possibility of relying in the power management strategy described in this document.

The telescope actuation and image processing system consists of several components with the electrical power consumption roughly equally distributed among them. The system assumes two entry point coming from the balloon's batteries — from there the electrical power is brought to the parameters required by various components using DC-DC converters as it follows:

1. 1 converter 30/5 V for Arduino, Raspberry Pi, cameras and sensors,
2. 1 converter 30/24 V for motors

The DC/DC converters number is kept down by connecting multiple components in parallel if they share the same voltage parameters, the wiring is as shown in E-box Internal Circuit Design.

4.3 Attitude Determination and Control

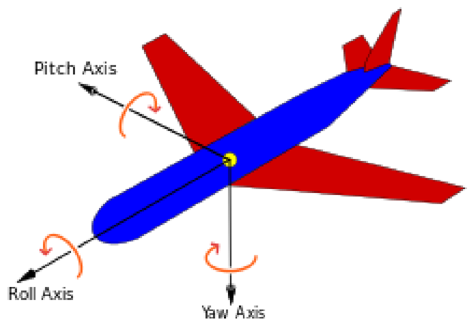
4.3.1 Solar Tracking

In this section, the software architecture as well as its supporting hardware are discussed. The hardware is only mentioned at an elevated level and only brought into view particularly if it has some limiting characteristics which needs to be circumvented. The software design concerns several directions:

1. Sun tracking system
2. Monitoring and diagnostics
3. Redundancy of hardware and software
4. The main tracking and control system
5. The data storage system

To successfully complete the experiment, a minimal setup consisting only of the Sun tracking and image processing needs to be present and able to function in fully autonomous manner. Given the challenging environmental conditions and the fact that physical access to the experimental setup during the flight is impossible, some redundancy as well as monitoring (through telemetry) should be implemented. This in turn requires the presence of the ground station systems which will allow manual (i.e. operator based) intervention using telemetry as well as in-flight data collection.

The solar tracking system is divided into two parts: sweeping, or identification of location of the Sun in 360 degrees, and the fine adjustment tracking system - accurate positioning. This functionality refers to both location and correction of the telescope's position until the Sun's center coincides with the center of the telescope camera.



4.3.1.1 Sweeping

During the first stage of tracking, sweeping was used to scan the sky for the Sun.
If the Sun is not identified by the Raspberry Pi, it instructs the Gimbal to rotate anticlockwise in the yaw axis until either the Sun is discovered or the yaw limiting switch is activated. When the switch is activated, the yaw motor reverses direction of rotation and the gimbal rotates clockwise to the starting position, after which the scanning mode activates again. This ensures that a full sweep of the sky is completed within two cycles with minimal logic and programming complexity.

In the pitch direction, if the Sun is not identified by the Raspberry Pi, it instructs the Gimbal to pitch down in the pitch axis until either the Sun is discovered or the lower pitch limiting switch is activated. On activation, the pitch motor will reverse direction and the gimbal pitches up about 40 degrees before the arduino returns control back to the Pi. This was compromise ensure that the tracking camera was able to scan the upper part of the sky whilst minimising the effect of hitting the lower switch.

4.3.1.2 Accurate positioning

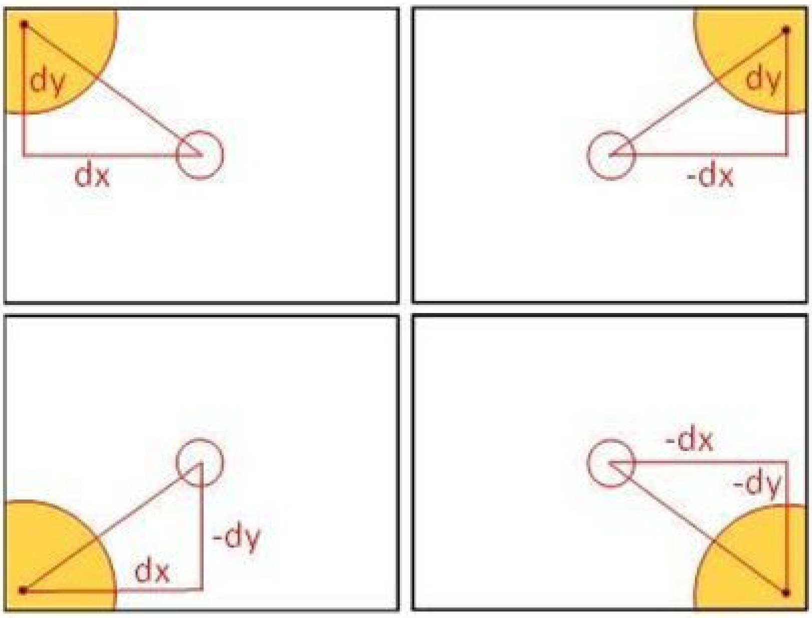


Figure 4.3.1.2.1 – Cases where the bright regions are detected with various possibilities.

The second stage of tracking occurs when the first stage positioning brings the Sun disc into the camera's field of view. At this stage, an algorithm looks for the brightest object in the space and ignores dimmer reflections provided that the approximate Sun brightness is pre-set. Once this is verified, the Raspberry Pi calculates the offset in orientation of the bright spot (the Sun) from the center of the image, translates those deflections into relative yaw and pitch angles and sends them to the Arduino controller (Figure 4.3.1.2.1 above). The Raspberry Pi maps those angles into steps movements required by the motors so as to reduce and possibly eliminate those offsets and hence centering the Sun at the image scope. The logic is better illustrated in the flowchart 4.3.1.2.2 below.

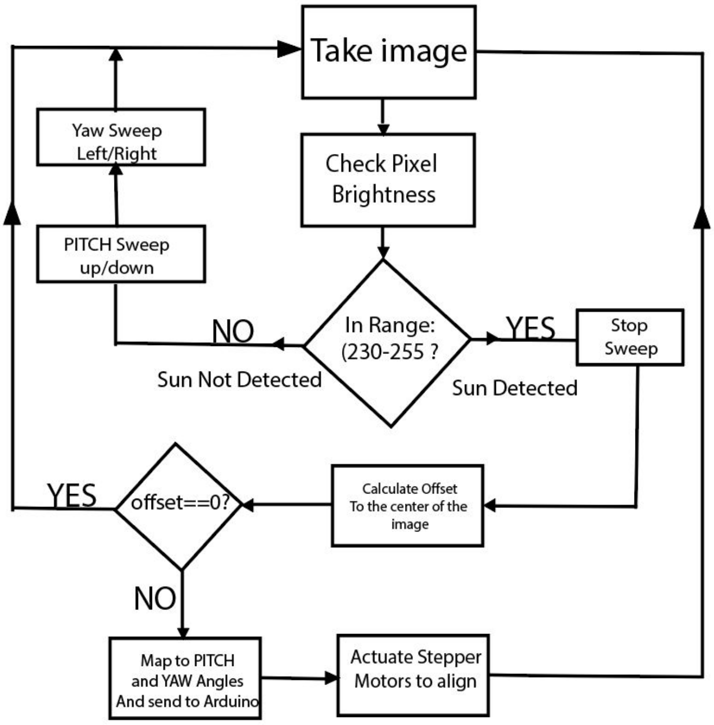


Figure 4.3.1.2.2 – Flowchart of the tracking algorithm

4.3.2 Monitoring and diagnostics

The diagnostics are going to be performed if during the monitoring phase some sort of fault occurs. The diagnostic functionality can be split in two stages:

- during the prototype phase and pre-flight when extensive measurements are conducted (for example energy usage scenarios are tested to determine compliance with the available battery capacity)
- during the flight itself when only a very useful handful of diagnostics are collected

The possible actions available to the ground station operator are going to be taking control (manual mode) of the telescope positioning and focusing, restarting the on-board computers, etc.

4.3.3 Redundancy of hardware and software

Single focal point telescope accepts only one camera, due to constraints of telescope design, weight and power consumption, redundancy cannot be fully implemented for these two components. However, extra care is taken for auxiliary systems such as sensing and tracking. The sensing signal are stored in the SD card of the sensing arduino and send a copy to the Raspberry Pi as well as the ground station. Therefore, there are 3 copies of the data.

The tracking system is implemented via the use of a ‘tracking camera’, Logitech C920, to get the current position of the telescope, and a pair of 24VDC stepper motors. Once the system is powered, it will rotate automatically searching for the brightest spot, in this case, the sun. The freedom of movement for the gimbal will be restricted by the use of 4 limit switches: 2 switches controlling the pitch angle, and 2 switches for the yaw angle. This will be further explained in the coming sections.

In addition, there are a manual vertical control and horizontal controllisted in Uplink Command Format. This functionality will not activated except from a very unlikely event, when all the automatic software lost its functionality. The telescope will be manually positioned in a particular allocation in each hour which then taken image from that position, when the uplink is limited by once per hour.

4.3.4 Data storage system

Images and data recorded by the telescope imager will be stored onto a SD micro card in the science acquisition Raspberry Pi. This will be downloaded after retrieval for analysis. All systems will be tested for low temperatures, outgassing and other space hazards such as atomic oxygen.

4.3.5 Selection of the tracking camera and filter

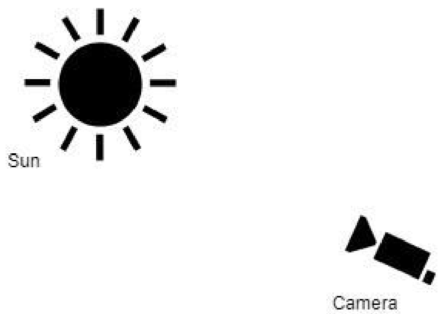
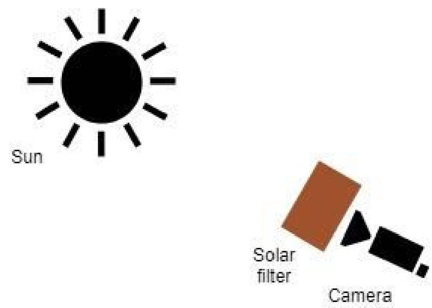
	
(a)Experiment 1: testing camera	(b)Experiment 2: testing camera with a filter

Figure 4.3.5.1 – Testing configurations

Tracking camera

Series of tests were conducted in order to develop the Sun tracking algorithm. Three sets of camera setting were tested, including a 360 degree Linux camera, C920 Web camera with a 360 degree plastic lens attached and a C920 webcam without 360 degree plastic lens. The experiment configuration is demonstrated in Figure 4.3.5.1(a). During the Experiment 1, each of the cameras was pointing at the Sun and taking ten sets of sample pictures.

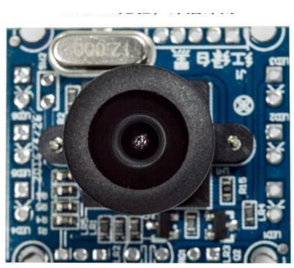
		
(a) 360 degree Linux Camera	(b) 360 degree lens	(c) C920 webcam

Figure 4.3.5.2 – Tested cameras

Figure 4.3.5.3 below shows the test images of 360 degree Linux camera, which showed the Sun as a black dot. Unfortunately, the lens was curved, making it nearly impossible to add solar filter on top of it. Therefore the decision was made not to use it.

Figure 4.3.5.3 – Linux camera sample picture

Figure 4.3.5.4 indicates the test images of 360 degree lens used with C920 Web camera. Figure (a) shows the expected performance of the image. The black area is the covered area of the lens, blue area is the surroundings. The white dot represents the brightest point in the image, which should be the Sun. Figures (b-e) show the actual performance of the 360 degree lens, with different times of the day and reflections from different light sources. Figure (b) shows the most ideal case of the lens, where the surrounding environment and the Sun is in a sharp contrast. Figure (c) shows the third worst-case scenario where the lens itself has shifted and the Sun occupies half of the image. Figures (d) and (e) show the worst-case scenario where it is obvious that the Sun is within the scope but the angle of the Sun has caused glares. This made it very difficult to distinguish the light direction correctly. Based on the results of these tests, it was decided that this 360 degree lens would not be suitable for the project. C920 Web camera without a 360 degree lens was chosen.

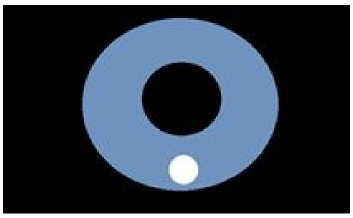
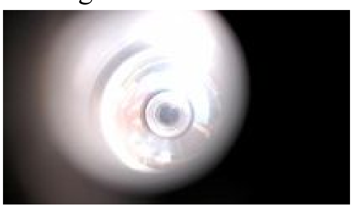
(a) Ideal image of the 360 degree lens 	(b)Solar image with 360 degree lens 1 in low light 	(c)Solar image with 360 degree lens in low Sunlight where the 360 degree lens is 0.1mm off the camera centre 
(d) Solar image at noon with 360 degree lens 	(e) Solar image 2pm with 360 degree lens 	

Figure 4.3.5.4: C920 Web camera with 360 degree lens solar image

Solar filter

Experiment 2 was conducted in order to see which solar filter would suit the needs of the projects the best. The filters that were tested included a wavelength selection filter, solar filter and badder filter. These were installed on the tracking cameras in the configuration seen in Figure 4.3.5.1(b).

After the first experiment, three types of filters were tested with the C920 web camera in the Experiment 2 in order to select the most suitable filter. These filters are represented in Figure 4.3.5.5(a-c) and images taken with them are shown in Figure 9.1.6.

(a) Wavelength selection filters

(b) Solar filter

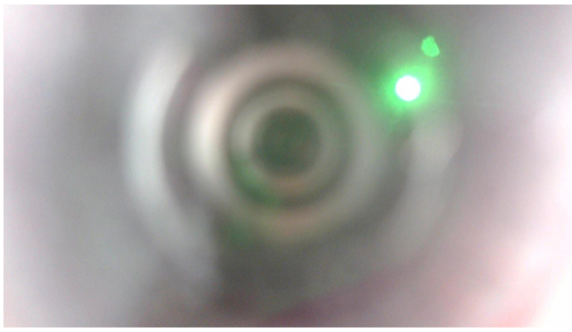
© Baader filter

Figure 4.3.5.5 - Tested filters

First of all, the wavelength selection filters were tested, Figure 4.3.6.6 (b). It turned out that some of the sunlight was scattered, there was a dot of reflected glare on the surrounding of the brightest dot (the Sun), thus making the wavelength selection filter option unsuitable for our payload. Then, a solar filter was tested, Figure (c), and it was found that solar film did not block enough sunlight. Finally, the traditional Baader filter, shown in Figure (d), was tested and it turned out that it blocked almost all the incoming sunlight. Moreover, there was significantly less glare from the Sun on the image, compared to when other filters were used. Thus, a Baader filter was chosen.

(a) Control image without a filter

(b) Wavelength selection filter test image



(c) Solar filter test image

(d) Baader filter test image

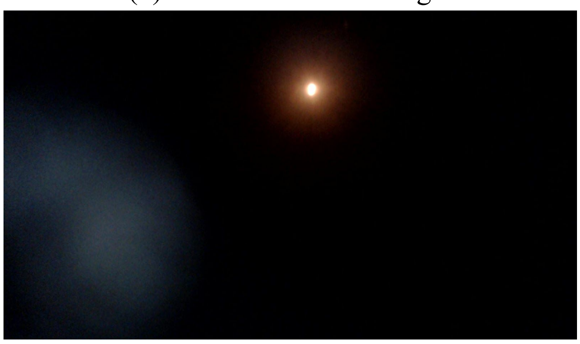


Figure 4.3.5.6 - Images of the Sun with a tracking camera and various filters

4.3.6 Control

4.3.6.1 Command line

Arduino

The arduino processor takes the input data and assesses the status of the limiting switches. Only if none of the switches are activated, will the arduino execute the command. If any of the switches are found to be activated when the command from the raspberry pi is received, the arduino will ignore this command and instead proceed to reversing the movement until it detects that the switches are no longer engaged. It will then await the next command from the RPi.

If during the execution of the command from the raspberry pi, a yaw switch is activated, the arduino will halt the movement of the yaw switch and reverse the direction, rotating the gimbal all the way around until the opposing yaw switch is activated. This is because if the raspberry pi requests the gimbal to move beyond a yaw switch, the closest physical location to meeting the request is to rotate to the other side of that switch (which is adjacent to to the opposing yaw switch). Simultaneously, the pitch movement is completely unaffected.

If during the execution of the command from the raspberry pi, a pitch switch is activated, the arduino will halt the movement of the pitch switch and reverse the direction, pitching up by 40 degrees. This is because if the raspberry pi requests the gimbal to move beyond a pitch switch, the closest physical location to meeting the request is as close to the same pitch switch as possible. However, in order to assist tracking, a compromise was made to ensure that the tracking camera was able to scan the upper part of the sky. Simultaneously, the yaw movement is completely unaffected.

If during the switching activation and reversal of one axis, the other axis also hits a switch, that axis will respond according to the same principles explained above. Naturally, if the steps required to turn on one axis are completed during the reversal of another axis, the completed axis will cease to rotate whilst the reversal will continue until it has reached the states described above (opposing yaw switch activated for a yaw reversal, or original pitch switch deactivated on a pitch reversal).

In order to execute the command, the arduino generates produces 3 main signals for the motor driver. These are high and low pulse signals, direction signal and the step size.

Motor driver

The high and low pulse signals represent the step changes of the motor so the frequency of these pulses are directly correlated to the speed of the motor. The direction signal indicates to the driver if it should turn clockwise or anti-clockwise and the step size signal enables or disables microstepping. If microstepping is enabled, the dial on the driver is activated and the step size is set according to the physical setting on the motor driver.

The motor driver receives the signals from the Arduino and amplifies the high and low pulse signals with a stronger current necessary to actually drive the motors. Other features which are available but not used on the driver include an emergency stop signal.

4.3.6.2 Force transmission line

Stepper motor

Based on the signal from the driver, the stepper motor turns the required number of steps and rotates the shaft accordingly. The stepper motor's shaft has been fitted with an SLM 3D printed titanium adapter which transmits the torque from the motor to the harmonic drive.

Harmonic Drives

In order to produce enough torque to move the telescope and in an accurate manner, some kind of torque amplification was needed. Naturally, gears were investigated, however due to backlash in traditional gears such as spur or helical gears, effort was made to minimise the use of gearing systems. In order to meet the accuracy and torque requirements without losing locational precision through gear backlash, a high gear ratio 160:1 Harmonic Drive was used. A Harmonic Drive is a special gearbox which uses the oscillation of a flexible ring to transfer movement thus eliminating backlash and maintaining high accuracy. The only issue that arose was the potential for the silicone lubricant to freeze or outgas in the low temperature, low pressure environment but this was shown not to be a problem due to the insulation and the adjacent motor providing some heating. The high torque of a 160:1 ensured the motor would constantly be running at full speed, generating heat and avoiding seizing. The harmonic drive acted as a suitable mounting point for the axis and provided good radial support with many mounting holes in sturdy flanges for both the drive itself and the motor - leading to a well designed motor bracket.The high gear ratio meant the magnification of the holding torque of the motor was sufficient to hold the telescope in place under shock. For future iterations it may be more advantageous to use a lower ratio as this would increase tracking speed for a trade off in holding torque (depending on the torque exerted from the payload center of mass).

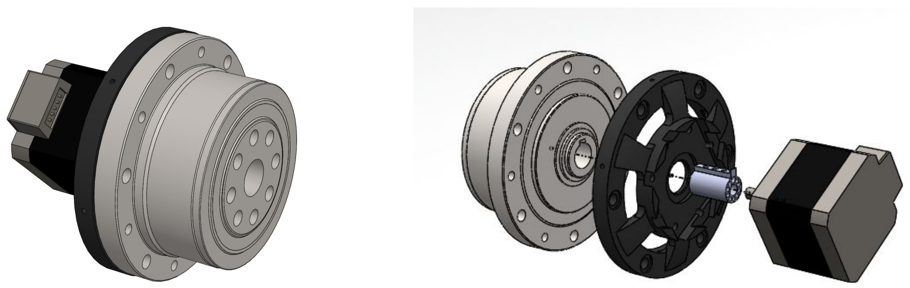


Figure 4.3.6.2.1 - Motor, Bracket, and Harmonic Drive Assembly. The Motor Bracket was manufactured by SLM which allowed for mass saving optimizations.

Adapter and Shaft

In order to transfer the torque from the harmonic drive to the shaft an adapter was designed. This aluminium adapter was circular with four holes used to attach it to the drive with bolts and a square hole in the middle that the shaft plugged into. The shaft had a complimentary square ending which meant that the shaft fitted in snuggly into the adapter but also allowed it to be removed quickly without the need to unscrew anything. The tight fit between these components was crucial as if there was any play in the system then this would be transferred to the telescope, potentially affecting the quality of the photos taken. In order to reduce this a computer controlled milling machine was used to manufacture both of these parts.

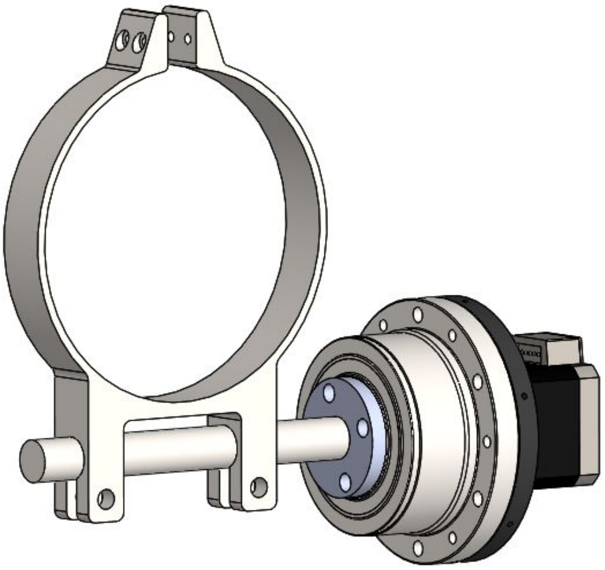


Figure 4.3.6.2.2 - Motor, Bracket, Harmonic Drive, Shaft and Clamp Assembly.

Clamp

Telescope clamp, shown on Figure 4.3.6.2.2 is used to transform the rotation of the pitch harmonic drive into the pitch deflections of the telescope. It was manufactured using the Electrical Discharge Machining (EDM) technique and can be seen on the Figure 4.3.6.2.3 (a). The clamp was manufactured very accurately so the fit between the shaft and the legs of the clamp was very snug. This meant that once the clamp was tightened it gripped the shaft strongly, eliminating the need for any extra screws to keep it from slipping.

As it was mentioned in the Section 4.1.3.2 of this report, telescope selection have changed throughout the project. The final telescope was smaller in diameter and thus a new clamp had to be manufactured, as shown on the Figure 4.3.6.2.3 (b). Because the EDM is a very expensive technique, a decision was made to cut the original clamp and accommodate it for a new telescope.

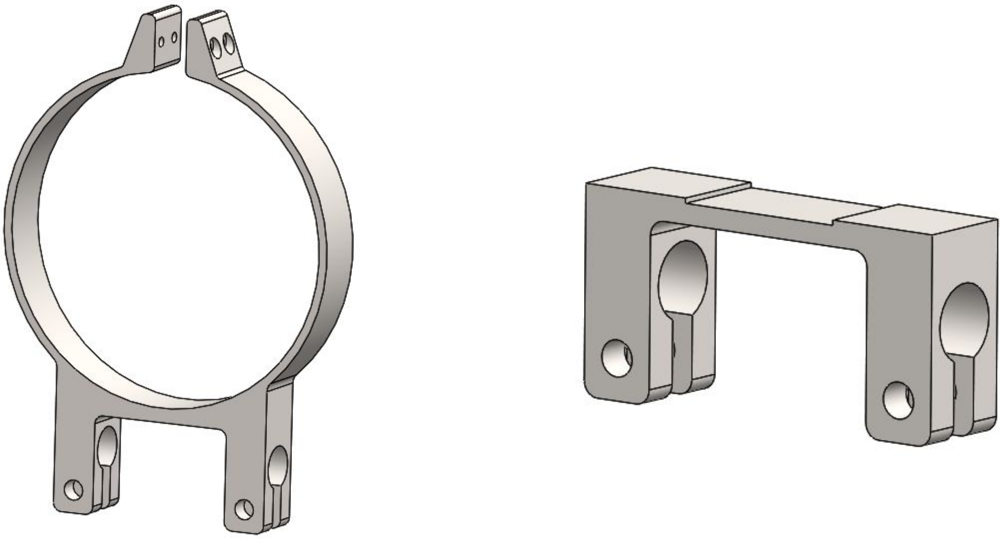


Figure 4.3.6.2.3 - (a) Original telescope clamp. (b) modified telescope clamp

Yaw and pitch mechanical switches

Yaw rotation of the gimbal was limited to prevent the HASP to SunbYte cable from tangling around the base. For this reason, limiting switches were installed at each end which caused the yaw sweep (Section 4.3.1.1) to change direction upon contact. Pitch rotation on the other hand was limited to prevent telescope from hitting the front e-box and from exceeding the vertical dimensional constraint. Likewise, limiting switches were implemented to restrict pitch movement.

Housings for pitch and yaw limiting switches were designed to secure the limiting switches to the structure. Wall thickness was 3mm and covered with reflective aluminium to provide insulation. Computer CAD models for the limiting switches were utilized in the design process to ensure perfect dimensional fit.

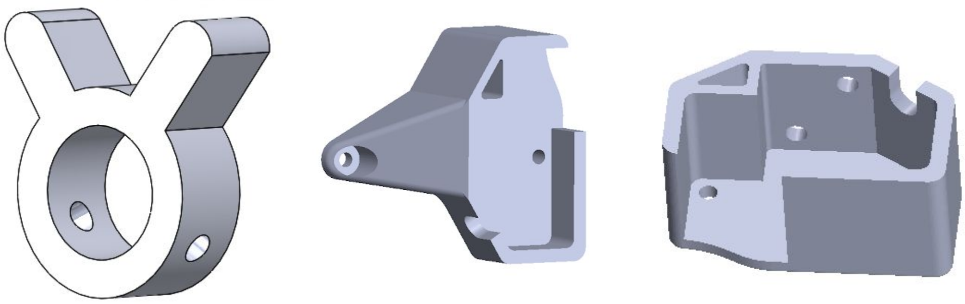


Figure 4.3.6.2.4 - (a) Switch ring, (b) pitch micro switch housing, (c) yaw micro switch housing

Housings for **pitch microswitches**: Two secured either side of the central shaft, with each holding one limiting switch (Figure 4.3.6.2.4 b). They are fastened to slots that enable them to be adjusted to the correct position. Also attached to the shaft is a 'switch ring' (Figure 4.3.6.2.4 a) which rotates to active the limiting switches.

Housing for **yaw microswitch**: One secured to the frame of the gimbal, holding two limiting switches (Figure 4.3.6.2.4 c). An activating switch was secured to the base plate, which activated the limiting switches when the gimbal rotates, as shown on Figure 4.3.6.2.5.

Both were prototyped using 3D printing and the final model laser sintered from nylon.

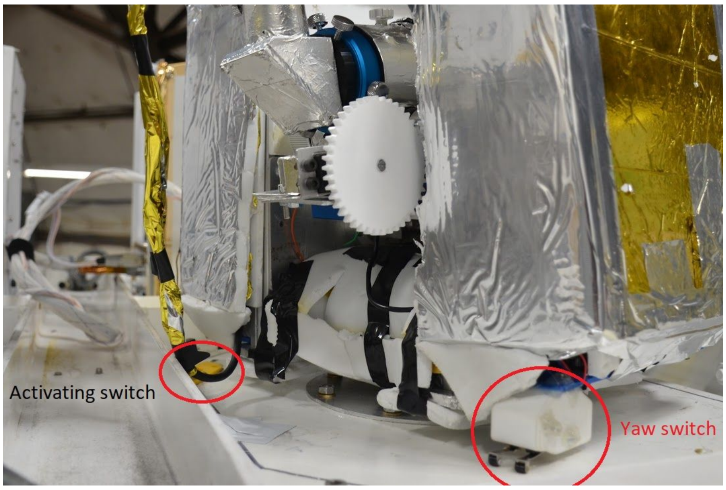


Figure 4.3.6.2.5 - An activating switch was secured to the base plate, which activated the limiting switches when the gimbal rotates

4.4 Structure

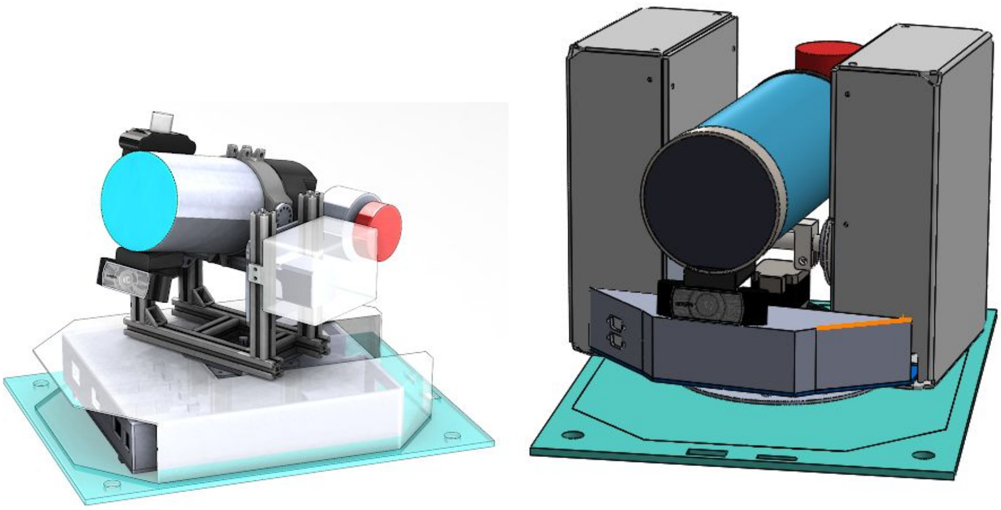


Figure 4.4.1 - (a) Initial gimbal design, (b) final gimbal design

The mechanical structure went through many different design iterations. Mainly in an effort to overcome the problem of constantly changing electronics. This lead to developing concepts in parallel until one concept appeared unfeasible or the other proved to be significantly better in many regards. One idea was to use a slip-ring to keep the electronics stationary, as in Figure 4.4.1 (a) while the telescope rotated about the yaw axis, however feedback from industry experts suggested that slip-rings were notoriously unreliable, expensive and did not offer enough channels to use the USB connection cables. This benefitted the design in many ways: the electronics stayed out of range of the telescouired by the camera. So the decision to mount the electronics in two “E-Boxes” on the side of the structure was made, see Figure 4.4.1 (b) and 4.4.2; there was no need to balance mass about the pitch axis, as required by mounting the electronics around the telescope; the electronics were kept in a compact, orderly manner; and keeping the electronics is as few boxes as possible meant dissipated heat would warm cooler circuit boards.

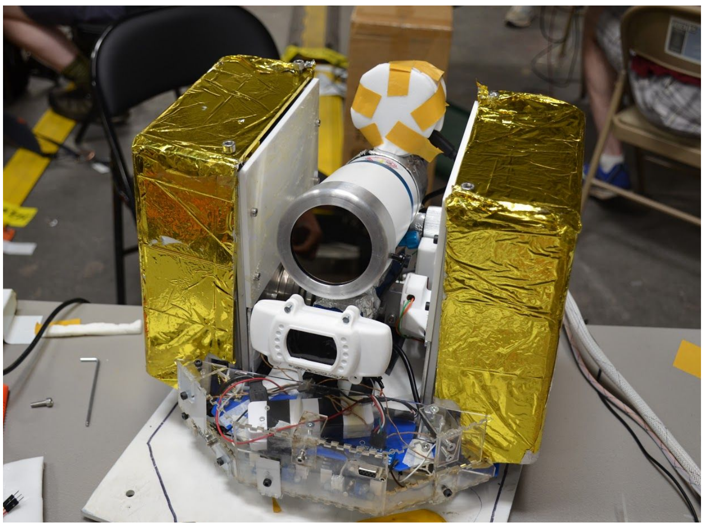


Figure 4.4.2. - Final gimbal design.

4.4.1 Gimbal Frame

A Bosch extrude frame was used for the struts while plates were used at interfaces. Bosch extrude has a high second moment of area across its cross section allowing for an incredibly stable structure even whilst being made of aluminium for mass reduction. The result was a space saving, stiff, light frame which easily supported the rest of the structure. The rail design of the Bosch extrude let us mount the electronics to the frame on shelves, allowing for vertical adjustment to make the most of the space we had..

(a) CAD model (b)Real frame

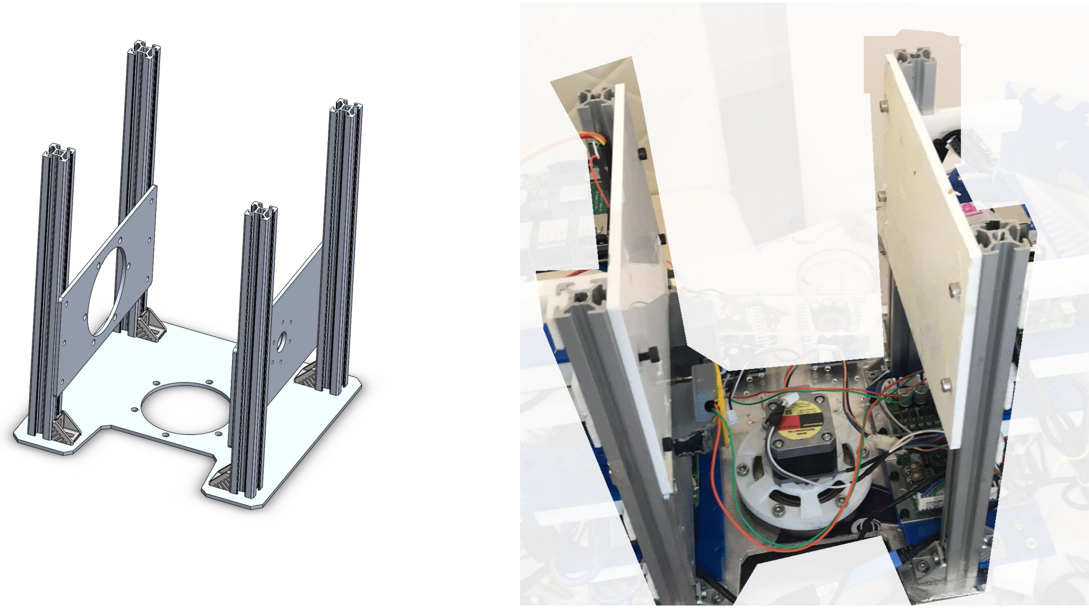


Figure 4.4.1.1 - Bosch Extrude frame with 3mm Aluminium 6010 plates.

The rails (Figure 4.4.1.2) were Selective Layer Manufactured (SLM) out of Nylon 6, the most thermally stable nylon. This was provided by AdAM, the University of Sheffield additive manufacturing research facility. This allowed for an intricate design that could meet the outline of the Bosch extrude which would be near impossible by any other means

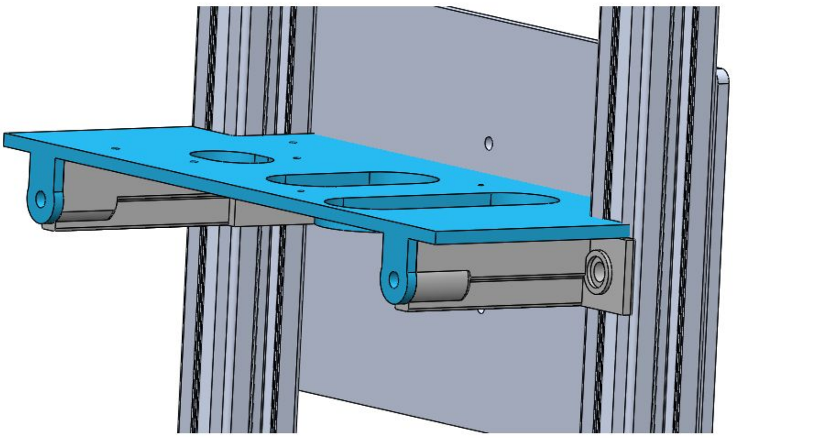


Figure 4.4.1.2 - SLM rails support acrylic trays to which electronics such as Arduinos were attached to directly via nylon standoff screws.

4.4.2 E-Box

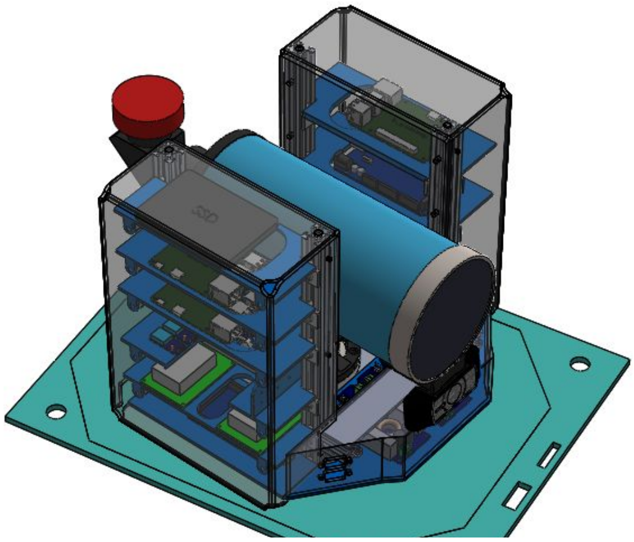


Figure 4.4.2.1 - E-Box

The new E-box was designed with modularity and flexibility in mind. Acrylic trays for the side E-box were designed to accommodate the numerous electrical circuitry of the system. It was designed to be a 'plug-and-play' module. All the wiring was neatly cable tied and labeled in order to avoid confusions in the future.

Front E-box was made from acrylic: parts of it were laser cut and then glued together. It was possible to remove a lid of the front E-box without dismounting the sides of the front E-box, to which the RS232 and Power supply D-subs were attached. Front E-box accommodated USB-hubs, DC-DC converters and sensors.

4.4.3 Mass Budget

The mass budget is listed in details in Table 4.4.3.1. The total mass budget is calculated by conducting researches online from the manufacturer data sheet and relevant engineering assumption. However the measured mass and uncertainty mass is unable to provide because majority of the component is under shipping. It will be updated as soon as all the components are arrived.

Table 4.4.3.1 – Mass of various components in kg

Mass (Kg)		
Actuators	**Data Sheet**	**Calculated**
Raspberry Pi 3	0.4	-
Arduino Mega	0.4	-
Arduino Mega USB cable	0.05	-
Electrical motor (x2)	2 x 0.5	-
Focusing motor	0.17	-
Driver hardware including heat sinks (x2)	2 x 0.15	-

Harmonic drive HFUC-20-2UH	0.98	-
DC-DC converters (x2)	2 x 0.2	-
DB15 socket (x6)	6 x 0.1	-
DB 15 wire 0.5m (x3)	3 x 0.2	-
Connection wires (5% of the mass)	0.2	-
Actuator Sub-Total:	**5.1kg**	
Datalogger	**Data sheet**	**Calculated**
Arduino Mega	0.4	-
Arduino Mega USB cable	0.01	-
Thermocouple Amplifier - MAX31850K (x3)	3 x 0.01	-
Switches (x2)	2 x 0.02	-
INA219 High Side DC Current Sensor	0.01	-
DHT11 humidity sensor	0.03	-
10-DOF Accel/Mag/Gyro+Temp Breakout Board	0.03	-
BMP180 Barometric Pressure Sensor	0.02	-
Sensors connection cables (10% of the mass)	0.02	-
Datalogger Sub-Total:	**1.61kg**	
Image Acquisition System	**Data Sheet**	**Calculated**
Raspberry Pi 3	0.4	-
Arduino Mega	0.4	-
Arduino Mega USB cable	0.05	-
Scientific camera (ZWO ASI120MM-S)	0.1	-
Camera cable	0.05	-
Connection wires (10% of the mass)	-	0.1
Acquisition Sub-Total:	**1.1kg**	
Optics	**Data Sheet**	**Calculated**
Telescope tube (Meada ETX 90)	*2.5*	-
Additional optics (etalon, ERF, focuser)	0.9	-
Tracking camera (HD PRO WEBCAM C920)	0.4	-

Tracking camera cable (x2)	2 x 0.05	-
Optics Sub-Total:	**3.9kg**	
Mechanical structure	**Data Sheet**	**Calculated**
Gimbal structure and electronic box (excluding hardware)	-	5.1
Focusing gear system	-	0.15
Nuts and bolts (assumed 5% of gimbal, E-box and focusing gear system)	-	0.2
Insulation (Polyethelene foam)	-	0.25
Mechanical structure Sub-total:	5.7kg	
Total	**17.41 kg**	

4.5 Datalogger

The data-logging subsystem consisted of multiple arduino sensors, including:

- Four temperature sensors: By connecting thermocouples to these sensors, it would be possible to measure the temperature at four critical locations: each motor, the outside, and the centre E-box. The sensor's E-box temperature was measured with other sensors that included local temperature but could not be extended via thermocouples.
- Two humidity sensors: These were to, not only measure humidity, but also local temperature (that of the Sensor´s E-box). The reason behind having two of these sensors is that it was expected that humidity and internal temperature could play a critical role in the functionality of the entire subsystem, but one sensor by itself would not give an accuracy that satisfies the given needs. Therefore, a second sensor was added so that an average could be calculated, giving more robust data, as well as a solution to the possibility of one of them failing in-flight, ensuring the acquisition of important data.
- One pressure sensor: Due to its difference in required input voltage (3V instead of the general 5V required by all other sensors), only one was introduced to the subsystem. Through basic calculations, it would be possible to estimate the altitude at which the system is, at any given time during the flight, and compare it with the altitude given. This sensor would also allow for comparative values of temperature to be analyzed, and even a calculate a better average.
- Two different types of compass sensors were included. They are referred to as MPU and Compass to avoid confusion. The "compass" is a 9DOF gyroscopic compass that would be located at the end of the telescope, together with the webcam. This would give the exact location of the telescope. On the other hand, the MPU is a 6DOF sensor that was located in the E-box, providing a second referential value for the location of the telescope's lens. The difference in degrees of freedom is given because the E-box can only rotate with respect to one axis, on contrast to the compass, allowing for a simpler sensor to me added in such a location. This decision also improved the simplicity of connectivity and data reading as well, since having two compass (9DOF) sensors would require a data-input divider, which would make the system much more complex.
- Four current sensors: two different kinds of current sensors would allow close analysis of the current drawn from motors and computational subsystems at any given point in the flight. By comparing these reading with the temperature, conclusions could be drawn relating the functionality and robustness of the system at different temperatures and altitudes. The two different kinds of sensors were included because two different voltages are drawn from the main powerline. These were 24V and 5V, and so it was necessary to include sensors that would read such a load without failing.
- One clock: finally, an RTC, was included so that a timestamp could be added to the data recorded without the need of internet connection, allowing for a more robust and independent subsystem.

All these sensors were connected through two PC Boards to an Arduino Mega, that would then send the data to the Scientific Raspberry Pi.

4.6 Thermal Design

Temperatures outside the gondola vary between -80 and 50 degrees celsius. The following requirement have been outlined:

- The temperature inside the SunbYte III structure shall be maintained at a temperature range between 5 and 25 degrees Celsius.

A combination of passive heating and insulation was implemented.

4.6.1 Insulation

Closed cell polyethylene EFP30 sheets of foam were used for insulation. Sheets with thickness of 1 cm were ordered and cut to size, then installed using double sided tape. Only 2 cm of insulation were used for the side E-boxes because of the constraints due to total width of the experiment. The front E-box and the yaw plate were also covered with insulation, however, with a thickness of 1 cm only, also due to constraints. The scientific camera was insulated as well with one layer of insulation.

4.6.2 Passive heating - heating mats

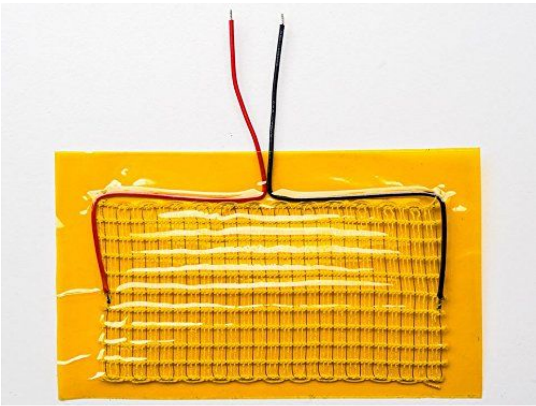


Figure 4.4.1 - Adafruit Electric Heating Pad

After the integration test when thermal vacuum testing discovered the need for heaters, a passive thermal system with no feedback control was tested. Several heaters (Figure 4.4.1) were connected in series to a 5V supply. In order to prevent overloading of the DC DC converter, a new converter and USB hub were installed in the fron E-box to distribute power more effectively. Unfortunately, testing found that on power on, the heaters caused the entire experiment voltage to drop from 30V to 5V at the power supply unit. Investigations yielded no conclusions except that when the voltage was slowly increased to 30V instead of being set to 30V immediately on power on, the experiment was able to maintain 30V at 2A. To prevent damage to the experiment, the heaters were not used and significant amounts of insulation were used to ensure that heat generated by the electronics were enough to keep the experiment operating.

4.7 Communication system

4.7.1 Analog and discrete channels design

The system is mostly autonomous so the analog and discrete channels are not in use.

4.7.2 Uplink using HASP Serial

The system should be able to run autonomously once switched on, automatically finding and tracking the sun with the ability to focus on the fly. However to improve the reliability and enable troubleshooting during flight, the serial of the tracking Raspberry Pi is accessible with a RS 232 terminal via the HASP serial interface [2].

The uplink command are used for manual adjustment of the system, it provide extra controllability in case of uncertain situation in flight. The first five bits are used for reducnary checksum, this provide a security for the command uplink, ensure the system are not answering other student payload comment in case of error. The command only executed when the return of checksum are matched. The command table below shows the possibility to turn on the Pan mode for both axis, it is a backup tracking method only used when automatic graphical tracking system is not functioning properly.

4.7.3 Downlink via HASP Serial

Downlink is mainly used for downloading images from all the cameras, so we know how the camera is moving and if it is detecting the Sun or other light sources. The data of other sensors also returned. Location, temp, humidity, attitude, pressure, the direction of the telescope and feedback of the motor are known. The data are stored in SD cards and every 1 mins it sends the most up to date version of file to the ground station. A small number of highly compressed and cropped images can also be downloaded to the Ground segment during flight, to give us an idea of the performance of tracking and focusing. The data format are shown below, datas types are identified by a characters at the front. Requested GPS Time and Position Data helps to identify the movement of the gondola with respect to the telescope, it act as a reference information for the ground segment to determine if the telescope is tracking the sun in a correct operation mode. There are 5 types of Downlink possible, depends on the available information.

Table 4.7.3.1 – Uplink Command Format

Command	Byte	Notes
CRC redundancy check sum	0x3E 0x00-0x00 0x00	First five bits reserved for CRC check
Ping	0x000x00	Ping the Raspberry Pi
Vertical Pan mode on (default off)	0x00 0x02	
Vertical Pan mode off	0x00 0x03	
Horizontal Pan mode on (default off)	0x00 0x04	
Horizontal Pan mode off	0x00 0x05	
Vertical control	0x00 0x06- 0x01 0x1E	Vertical position of gimble(0 to 70 deg) 0.25 deg steps
Horizontal control	0x01 0x1F- 0x02 0x7D	Horizontal position of gimble (+/-175 deg) 1 deg steps

Night Mode on (default off)	0x02 0x7E	
Night Mode off	0x02 0x7F	
Science Cam On	0x02 0x080	
Science Cam off	0x02 0x81	
Tracking camera Threshold removal	0x02 0x8 - 0x03 0x4A	Threshold to determine the black and white area
Tracking camera Gaussian blurred	0x03 0x04 - 0x03 0x54	9 value of Gaussian blur selections
Tracking camera erode filter	0x03 0x55 - 0x03 0x5F	9 value of erode filter
Tracking camera dilate filter	0x03 0x60 -0x03 0x6A	9 value of dilate filter
Tracking camera Filter selection	0x03 0x7C- 0x03 0x7B	Determine the filters (4x4 combinations)
Focus increment	0x03 0x7C - 0x03 0x87	Moving Focuser forward in (0.5mm per step)
Focus decrement	0x03 0x88 - 0x03 0x93	Moving Focuser forward in (0.5mm per step)
360 camera Threshold	0x03 0x94 - 0x04 0x5C	Threshold to determine the black and white area
360 camera Gaussian blurred region	0x04 0x5D - 0x04 0x66	9 value of Gaussian blur selections
360 camera erode filter	0x04 0x67 - 0x04 0x71	9 value of erode filter
360 camera dilate filter	0x04 0x72 - 0x04 0x7C	9 value of dilate filter
360 camera Filter selection	0x04 0x7D - 0x04 0x8D	Determine the filters (4x4 combinations)

Table 4.7.3.2 – The communication protocol of downlink

Record Type 1: full data received				
Sources	Info	Byte	Format	Description
Housekeeping	**Housekeeping**	2 Byte	SR	Start
		8 Byte	CRCXXXXX	CRC
		3 Byte	TXXXXXXX.XXX	Timestamp
		2 Byte	RSXX	Record Size
HASP GPS	Time and Position Data	125 Byte	GPS String	Requested GPS Time and Position Data
Arduino data	Power Data	5 Byte	AXX.XX	Total power
		5 Byte	B XX.XX	Main Pi power
		5 Byte	C XX.XX	Sci Pi Power
	Pitch Data	5 Byte	D XX.XX	Pitch Motor Temp
	Yaw Data	5 Byte	E XXX.XX	Yaw Motor Temp

		5 Byte	FXXX.XX	Ebox temp
		5 Byte	G XXX.XX	Pressure
	Sensors details	5 Byte	HXXX.XX	Temperature
		5 Byte	IXXXXX	Altitude
		5 Byte	JXXX	Humidity
		108 Byte	K1XXXX - K18XXXX	Compass
Raspberry Pi data		String	Z2: String	Compressed Tracking camera image
		4 Byte	E:XX	Erode filter: 2-5
		4 Byte	D:XX	Dilate filter: 2-5
		8 Byte	Mx:XXXX	Pitch Motor steps
		8 Byte	My:XXXX	Yaw Motor steps
		8 Byte	FPS:XXXXXXXX	Frame rate per second
Sci Pi		String	Z3: String	Compressed Sci camera image
		8 Byte	FPS:XXXXXXXX	Fram rate per second
		4 Byte	G:XXX	Gain
		4 Byte	E:XXX	Exposture
	End	3 Byte	:END	End of file

Record Type 2: Sci data received				
Sources	Info	Byte	Format	Description
Housekeeping	**Housekeeping**	2 Byte	SR	Start
		8 Byte	CRCXXXXX	CRC
		3 Byte	TXXXXXXX.XXX	Timestamp
		2 Byte	RSXX	Record Size
HASP GPS	Time and Position Data	125 Byte	GPS String	Requested GPS Time and Position Data
Arduino data	Power Data	5 Byte	AXX.XX	Total power
		5 Byte	B XX.XX	Main Pi power
		5 Byte	C XX.XX	Sci Pi Power
	Pitch Data	5 Byte	D XX.XX	Pitch Motor Temp
	Yaw Data	5 Byte	E XXX.XX	Yaw Motor Temp
		5 Byte	FXXX.XX	Ebox temp
		5 Byte	G XXX.XX	Pressure
	Sensors details	5 Byte	HXXX.XX	Temperature
		5 Byte	IXXXXX	Altitude
		5 Byte	JXXX	Humidity
		108 Byte	K1XXXX - K18XXXX	Compass
Sci Pi		String	Z3: String	Compressed Sci camera image
		8 Byte	FPS:XXXXXXXX	Fram rate per second
		4 Byte	G:XXX	Gain
		4 Byte	E:XXX	Exposture

	End	3 Byte	:END	End of file

Record Type 4: Tracking data received				
Sources	Info	Byte	Format	Description
Housekeeping	**Housekeeping**	2 Byte	SR	Start
		8 Byte	CRCXXXXX	CRC
		3 Byte	TXXXXXXX.XXX	Timestamp
		2 Byte	RSXX	Record Size
HASP GPS	Time and Position Data	125 Byte	GPS String	Requested GPS Time and Position Data
Arduino data	Power Data	5 Byte	AXX.XX	Total power
		5 Byte	B XX.XX	Main Pi power
		5 Byte	C XX.XX	Sci Pi Power
	Pitch Data	5 Byte	D XX.XX	Pitch Motor Temp
	Yaw Data	5 Byte	E XXX.XX	Yaw Motor Temp
		5 Byte	FXXX.XX	Ebox temp
		5 Byte	G XXX.XX	Pressure
	Sensors details	5 Byte	HXXX.XX	Temperature
		5 Byte	IXXXXX	Altitude
		5 Byte	JXXX	Humidity
		108 Byte	K1XXXX - K18XXXX	Compass
Raspberry Pi data		String	Z2: String	Compressed Tracking camera image
		4 Byte	E:XX	Erode filter: 2-5
		4 Byte	D:XX	Dilate filter: 2-5
		8 Byte	Mx:XXXX	Pitch Motor steps
		8 Byte	My:XXXX	Yaw Motor steps
		8 Byte	FPS:XXXXXXXX	Frame rate per second
	End	3 Byte	:END	End of file

Record Type 5: Datalogger data received				
Sources	Info	Byte	Format	Description
Housekeeping	**Housekeeping**	2 Byte	SR	Start
		8 Byte	CRCXXXXX	CRC
		3 Byte	TXXXXXXX.XXX	Timestamp
		2 Byte	RSXX	Record Size
HASP GPS	Time and Position Data	125 Byte	GPS String	Requested GPS Time and Position Data
Arduino data	Power Data	5 Byte	AXX.XX	Total power
		5 Byte	B XX.XX	Main Pi power

		5 Byte	C XX.XX	Sci Pi Power
	Pitch Data	5 Byte	D XX.XX	Pitch Motor Temp
		5 Byte	E XXX.XX	Yaw Motor Temp
		5 Byte	FXXX.XX	Ebox temp
	Yaw Data	5 Byte	G XXX.XX	Pressure
		5 Byte	HXXX.XX	Temperature
		5 Byte	IXXXXX	Altitude
		5 Byte	JXXX	Humidity
	Sensors details	108 Byte	K1XXXX - K18XXXX	Compass
	End	3 Byte	:END	End of file

Record Type 6: Functional data received				
Sources	Info	Byte	Format	Description
		2 Byte	SR	Start
		8 Byte	CRCXXXXX	CRC
		3 Byte	TXXXXXXX.XXX	Timestamp
Housekeeping	**Housekeeping**	2 Byte	RSXX	Record Size
HASP GPS	Time and Position Data	125 Byte	GPS String	Requested GPS Time and Position Data
	End	3 Byte	:END	End of file

4.7.4 Cyclic Redundancy Check (CRC) Checksum

CRC is a check scheme that used to detect accidental changes to raw data. The CRC checksum has been selected because due to its robustness and reliability.

A predetermined number is entered and stored in both the receiver and transmitter. For a n-bit of transmission data, the first k bit is the useful message, the reminded (n-k) bit is the frame check sequence (FCS). The transmitter generates the FCS by dividing the data by a predetermined pattern and attaching it to the end of the frame.

The receiver performs the identical division using the incoming frame and predetermined pattern. Once the receiver calculates the reminder, if it is identical to the received FCK, the message is shown to be correct, else it is incorrect.

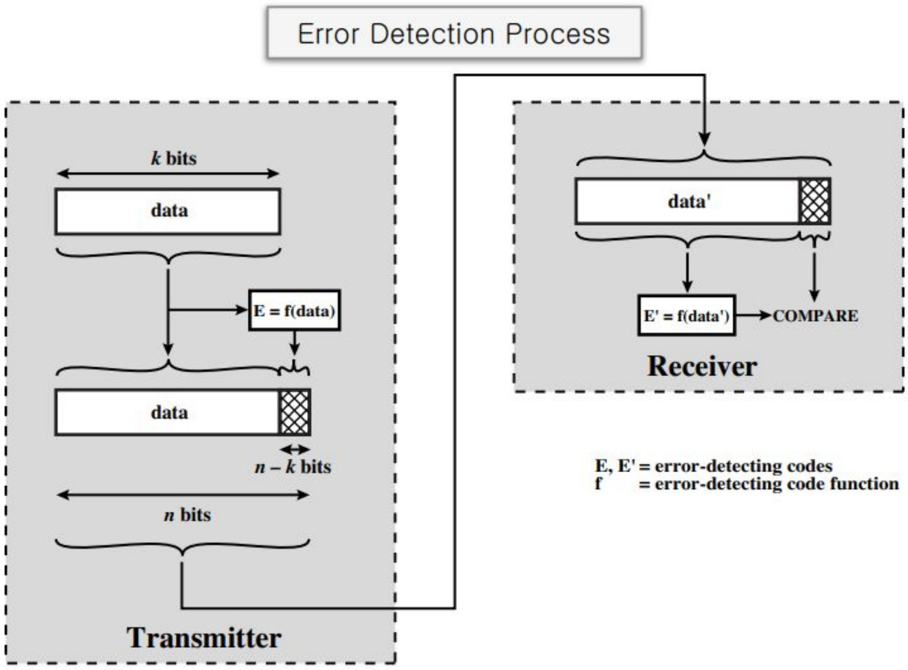


Figure 4.7.4.1 – Demonstration of CRC [3]

4.7.5 Ground segment design

The ground station system required the manual downloading of the files containing the necessary data from our payload from the HASP website. Once the files were downloaded they were manually sorted to ensure that only the un corrupted data was fed into a python script that sorts the data coming in. The data being received looked like what the Table 4.7.3.2 portrays. The python script separated the data for each type of data as the downlink string was just one string that contained a series of letters and numbers, this was split in order to save the data points to a .txt file as shown in Figure 4.7.5.1. For example the temperature for the Yaw Motor was saved in its own .txt file and the Altitude was saved in its own file. Therefore every different type of data was stored separately.

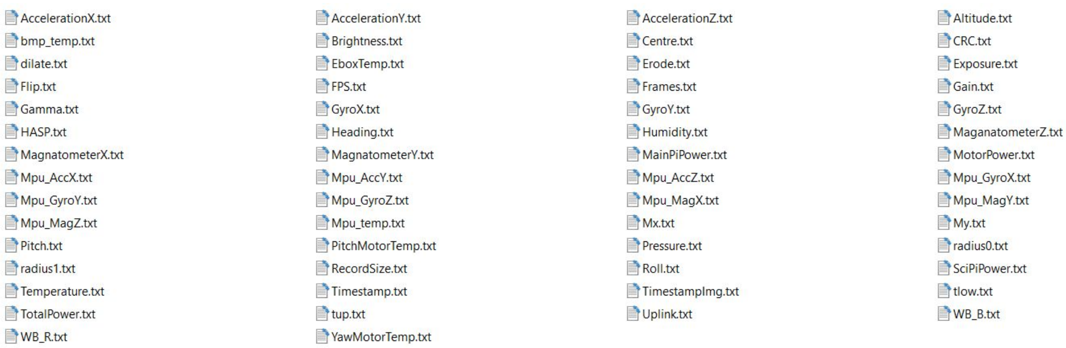


Figure 4.7.5.1 – The Saved Data

The next step was to graphically represent the data in the format displayed in Figure 4.7.5.2. This was done using MATLAB, one MATLAB script loaded in all the saved files and used a series of functions which plotted the separate graphs and added the axis labels, keys and graph titles.

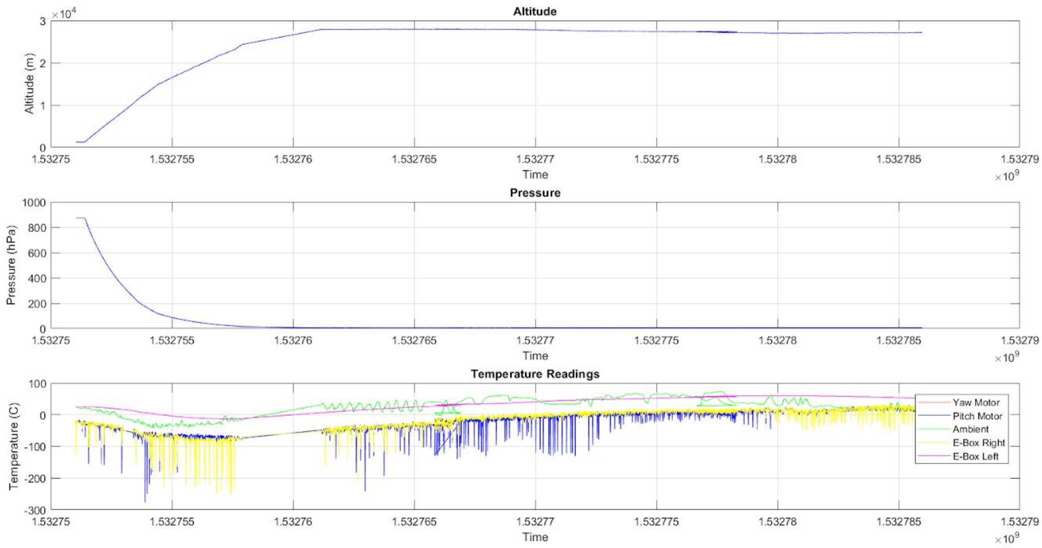


Figure 4.7.5.2 – The interface

5. Planned Post-Flight Activities

After the flight, the collected data was planned to be downloaded for processing. However, since SunbYte aim to obtain scientific information from the time series of data, we intended to go beyond standard image processing, e.g., correcting intensity. For proper analysis of the plasma dynamics of the lower solar atmosphere we would have had to remove the effects of e.g., solar rotation, spacecraft jitter and cosmic ray spikes, from the time series.

Although the first mission was planned for testing the proposed light-weight equipment, the obtained data was thought to potentially have scientific value since the images contain information on large-scale solar chromospheric activity, flows and oscillations measured with a very high time cadence. This information is much sought after in both the solar and stellar physics international communities. High-cadence full-disk, or Sun-as-a-star H-alpha observations could provide a connection between the integrated chromospheric intensity and the chromospheric activity, with potential applications to measurements of chromospheric activity of other stars. Furthermore, if a very high energy event takes place during the flight, e.g., a flare or coronal mass ejection, this could add even more scientific value to the obtained experimental data.

Additionally, we planned to compare data collected with data obtained by solar telescopes on the ground. For example, superpositioning would enable us to determine the exact advantages of a balloon telescope system.

The high resolution solar images was also planned to be used for outreach activities to promote Science and Engineering. From a more technical point of view, the proposed project would enable us to test the proposed stabilisation and observation system for using in the future missions. We anticipated that subsequent SunbYte telescopes shall become important and economically sustainable instruments of a high atmosphere-borne solar observatory. In the Figure 5.1 we have shown an example of images we expected to capture during SunbYte mission:

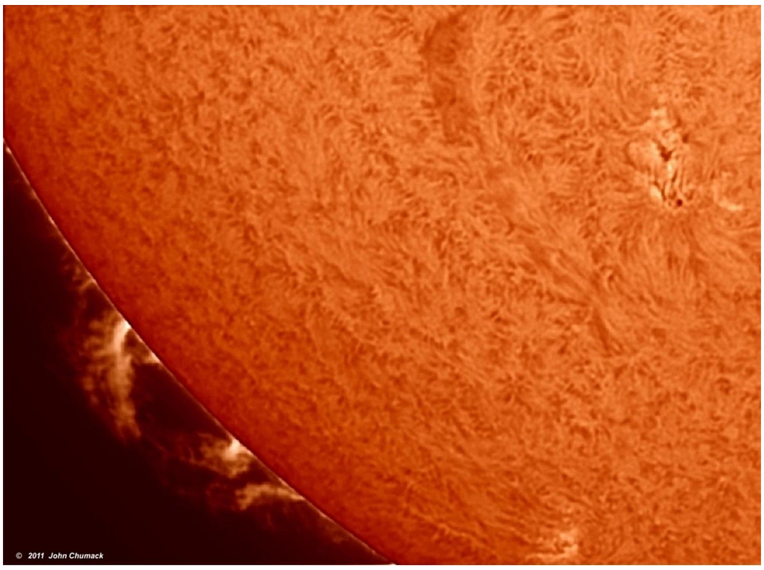


Figure 5.1 – Image of the Sun with an H-alpha filter, courtesy of John Chumack

6. Integration

6.1 Electronic Issues Encountered

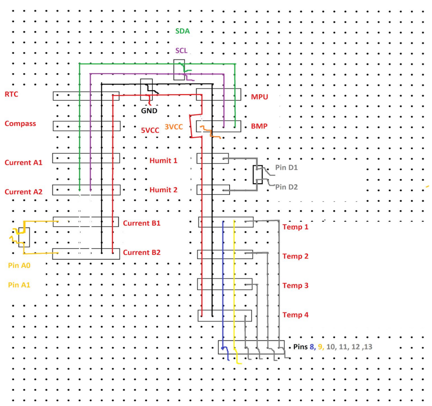
6.1.1 General Hardware Issue

From interacting with the different teams participating in HASP, our team members discovered that other groups were better organised. Our team could not bring all the tools from the UK, as we our luggage was limited to weight. This reminded SunbYte that more consideration needed to be put into tool organisation before travelling as a lot of time was wasted searching for tools in the US. Most of the US teams also used more expensive tools, such as a special crimping tool. Other teams also prepared better in a way that they considered current rating of every cable, while we did not. This should be considered in future for the next SunbYte project.

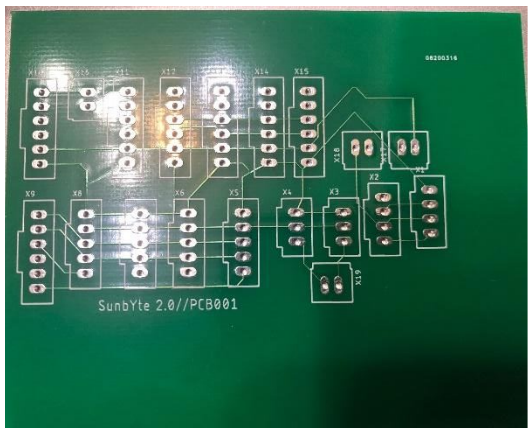
6.1.2 Datalogger

The datalogger-sensor system had been partially working in prototype tests but after the entire system was tested, it was discovered that the ‘Gyroscope, Accelerometer and Temperature Sensor Module’ (MPU) was not working together with the rest of the sensors. After trying to find and solve the problem by component-by-component systematic inspection and testing, it was concluded that the best solution would be to replace the boards with the new ones. Later, our hardware engineer manufactured new boards with design improvements and better quality components, such as core wire and high quality PCBs. Unfortunately, and for unknown reasons, the boards produced short circuit that did not allow the system to work as desired. Moreover, due to the lack of time because of the impending integration, a decision was made not to use any boards and only connect the most critical sensors to the Arduino. These included a pressure sensor, one humidity sensor instead of two, four temperature sensors and a real time clock. With this configuration, and more rudimental wire splits that replaced the PCBs, the system worked as desired.

A new board was designed after integration that was planned to be used at the launch, replacing two PCBs for one. It’s design is shown on Figure 6.1.1 (a-b)



(a)Wiring allocation of the sensor board



(b)PCB allocation of the sensor board

Figure 6.1.2.1 - data logger design circuit

6.1.3 Software problem

There were many software issues encountered, mainly, the auto-start configuration and the serial communication failures. The motivation behind using the auto-start was to ensure that when the system is powered on, the software should automatically start working. At first, a certain setting was applied to a configuration file in the RaspberryPi that enabled it to start whenever the user logged on. However, this was not what was required by the specifications and it was only realized during the integration. A different method was used in order to add the auto-start functionality in the system: a separate service. The software would become a unique ‘service’ that would run automatically once the system was powered on. A simple command was used to check the status of the service. The software became easier to debug as the user can easily access the latest logs and spot the errors.

There were also many serial communication failures. In order to illustrate this issue in greater detail, the design of the communication system will be restated. In order to monitor and control the system, there is an UPLINK, data that is transmitted to the system, and downlink, data that is sent back to the ground station (NASA computers). Three computers were used: Science Pi, Tracking Pi, and Network Pi in the system. Both the Science and Tracking Pis were required to send a unique string to the Network Pi, which would then send the final string to ground (NASA computers). There were many instances where the Science and/or the Tracking Pi failed to send a string to the Network Pi. After much testing, it was figured that the reason was faulty serial cables. In order to avoid this, high-quality cables were procured and installed. Following this, a systems test was conducted and a complete string was sent to ground.

In order for the computers to be recognizable, a unique background was used to identify each computer i.e. a background with writing ‘SCIENCE’ was used to identify the Science Pi and so on and so forth. To ensure no chance of mishaps, the microSD cards were cloned and backed up continuously.

6.2 Mechanical Issue Encountered

When the gimbal was placed onto the gondola for the first time it was discovered that there was a small lip that we hadn’t anticipated that caused the bottom of the E-boxes to catch, severely restricting movement. This was disappointing for the mechanical team as it signified a major design floor in the system but the fix turned out to be relatively simple. The bottoms of the e-boxes were cut out off and the resulting gap was sealed with foam insulation and mylar to keep the electronics from freezing. Although this was a change from our original design we were happy that the E-box was now optimised and that the issue had actually saved weight overall.

6.3 Integration Results

During the thermal vacuum test it was noted that whilst the temperature was above 0 degrees celsius the gimbal was operating perfectly from a mechanical standpoint. However as the temperature dropped the yaw stopped moving completely and the pitch had limited motion.

It was the fact that the pitch kept moving that told us that the issue was due to temperature rather than pressure as both gearing systems would have been at the same pressure but the pitch system would have been at a slightly higher temperature due to the insulation offered by the E-box. After some discussion the team decided that it must have been the motors that were seizing as our harmonic drives are a similar design to the ones used on the hubble space telescope and were lubricated using grease that was rated down to negative 60 celsius.

The solution to this was to have electronic heaters placed near the motors in order to keep them warm. These were installed during the phase between the integration and the launch but unfortunately weren't used during the flight due to an issue with the current they drew being too much.

The initial plan was to have more sensors, such as the humidity sensors, accelerometers and gyroscope. However, due issues with them all working and the unreliability of the system simplifications were made to ensure the datalogger produced the basic data we needed to validate our experiment was working nominally. Relating to the wire diagram above, the only sensors that were used were BMP, Temp1, Temp2, Temp3 and Temp4.

6.4 Summary

Ultimately the integration proved to be a difficult but rewarding time for the mechanical team as several issues were encountered but through working together all of the issues were solved in time for the flight.

7. Launch

7.1 Electrical and Software systems

7.1.1 Yaw limiting switches reallocation

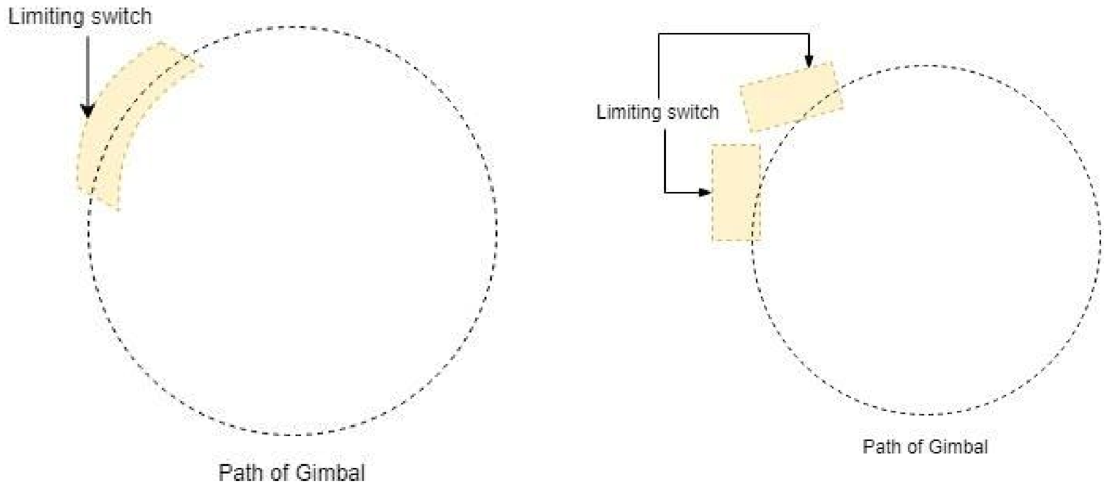


Figure 7.1.1.1 - Gimbal path and switch allocation: (a) old and (b) new location.

As it was mentioned in the Section 4.3.2.2, the limiting switches were designed to prevent cables from tangling around the base and from exceeding the vertical constraints. Originally, it was decided to install one ‘bump’ on the mounting plate, as shown in Figure 7.1.1.1 (a). However, during the integration of our payload on gondola prior to launch we found out that the mounting plate was not positioned in the center of the slot provided to us. We did not account for it and the e-box was hitting the small lip on a side of the gondola, preventing the gimbal from rotating until the bump. The bump was cut into two pieces and mounted as shown in Figure 7.1.1.1 (b), creating a forbidden zone. As the activating bump was not designed to be cut into two, they yaw switch did not work perfectly. It took a lot of time and effort to place the bumps in the correct position to allow the gimbal making almost a full rotation without hitting anything.

7.1.2 Sun Calibration

As it can be seen in Figure 9.2.1, the tracking camera is positioned slightly below the telescope. Certain steps, in order to calibrate the difference between these, had to be taken. First of all, the telescope had to be positioned to be pointing at the Sun. Then, a picture was taken from the tracking camera. A gap between the center of the image to the center of the Sun was calculated. On the Figure below such a gap is (351, 289). This was then fed into the tracking code in order to calibrate the tracking camera.

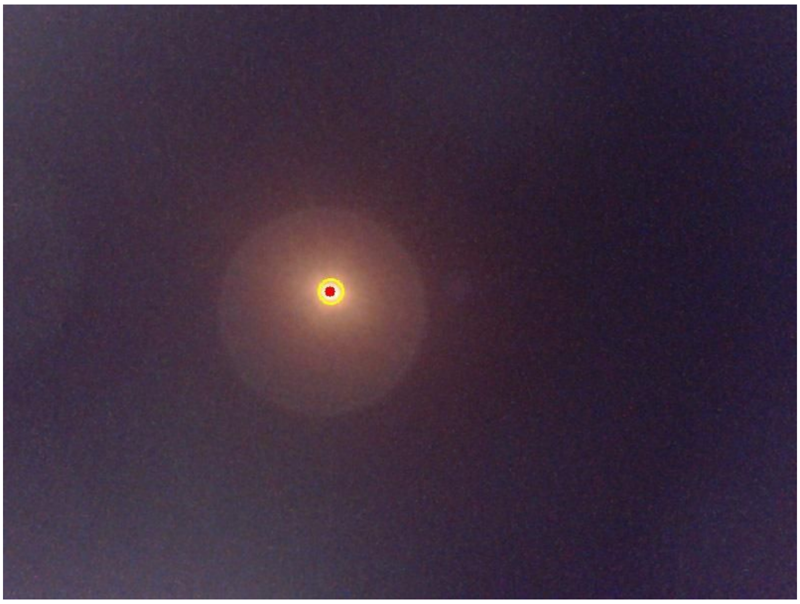


Figure 11.2.2 - Calibrated image of tracking.

7.1.3 Problem with auto start

Prior to the hang test, the auto start was not functioning as soon as the system was powered on. So the team spent 2 hours to tackle this issue, one possible explanation was that there were some data corruption on the sd card. Program file was deleted and copied in the same location. The problem was then fixed.

7.1.4 Updating software before launch

Early in the morning before the launch, it was discovered that the code uploaded on Arduino would allow swapping of the pitch to be from 0 degrees of elevation to only about 15 degrees of elevation. Thus, tracking would not work at the Sun elevation larger than 15 degrees, which is during most of the flight time. The decision to open the lids of the ebox and upload the corrected code was made just hours prior to the launch. This allowed us to extend the time during which the Sun would be in the field of view of the telescope when it was in the tracking mode.

7.1.5 Removal of Heating system

As it was mentioned in the Section XX, as a result of the thermal test, it was concluded that a heating system was required to heat the sensitive to cold electrical components. Heating system was designed by the electrical team upon returning home after integration, however, it was not implemented to the system and tested until the launch campaign. When the heating mats were installed, current was always dropping dramatically and the system could not not be powered. One of the explanation the team came up to was that the heating mat consumed more power than the power supply could handle. As the team did not have enough time to identify the problem, the heating mats were not installed.

7.2 Mechanical Preparation and Challenges

The mechanical preparation for the flight was fairly simple, assemble the gimbal, install insulation and then work with the E-team to calibrate the pitch and yaw limit switches.

The mylar insulation was cut to size using scissors and then installed using spray-on adhesive. This method proved to be quick and allowed the mylar to be pressed flat onto whatever surface it was being fixed upon. In some cases double sided tape was used when it wouldn't have been appropriate to spray glue onto an area i.e. where electronics were exposed.

Once the launch came around the gimbal had been taken apart and reassembled many times by the mechanical team so the steps required to do so were well known and almost second nature by this point. The main challenge was that once all of the electronics and insulation had been installed there was much less space than before and everything had to be done much more gently so as to avoid disturbing the electronics. This meant that the final assembly before launch took much longer than anticipated.

This caused frustration and friction within the team when the E-team requested access to the electronics shortly before launch. There was a fear that opening up the electronics boxes to fix one problem might inadvertently cause another. Thankfully although this didn't go completely smoothly there were no mechanical issues caused and the decision to modify the electronics proved to be the right one.

Calibrating the pitch switch was a simple matter of tipping the telescope down to the lowest pitch it would need during the flight and then fixing the limit switch cam collar in place with a grub screw. The telescope was then tilted back to make sure that the cam on the other side of the collar hit the maximum pitch switch before the telescope hit the gimbal base plate.

The yaw switches proved to be much more trouble than expected as it was discovered that our board was mounted asymmetrically within it's slot on the HASP gondola. This meant that whilst the yaw limit switch enclosure passed fine on one side it hit the wall of our tray on the other side meaning that full rotation was impossible The cams for the switches had been designed to provide roughly 357 degrees of rotation in order to maximise the time the telescope could see the sun for. We decided that a quick fix would be the best fix as we were needed to get the payload integrated before the gondola launched. For this reason a physical fix was considered rather than a software fix as this might have caused unexpected bugs in the rest of the code. Arthur proposed cutting the cam plate in half and and placing each half either side of the portion that our switches could not enter. This was agreed upon by the team as the system would still work in the way it was designed, however roughly 30 degrees field of view was sacrificed in order to achieve this.

7.3 Summary

From a mechanical standpoint the launch was a lot smoother than the integration as there was only one major issue encountered with the limiting switches. During the flight both motors worked well for the early part of the flight. As the temperature dropped however they froze up again as they had during the integration. The team expected this to happen however so there was not too much concern, once the system had heated up again in the sun the motors started working again. From the video stream provided by NASA the team was able to confirm that the gimbal operated correctly for the rest of the flight.

8. Post-Flight Recovery

After landing, the experiment mostly remained intact. Figure 8.1 shows the gondola after landing. Neither the gimal, front and side e-boxes or optics setup damaged. The pitch limiting switch remained in place, however, the acrylic yaw plate cracked and the yaw limiting switch housing did not remain attached to the gimbal, as it can be seen in Figure 8.2(c). Hence, the switch responsible for horizontal rotation of the gimbal stopped functioning after some time during the flight. The cables remained in place, as seen in Figure 8.2(d) and (f). The scientific camera that was used during the flight was tested on once recovered. Upon testing the camera worked as desired. However, the in flight SD card was damaged: the Network Pi OS SD card was not functioning after three reboots. Fortunately, SunbYte had downlink information to keep tracking on the flight performance.

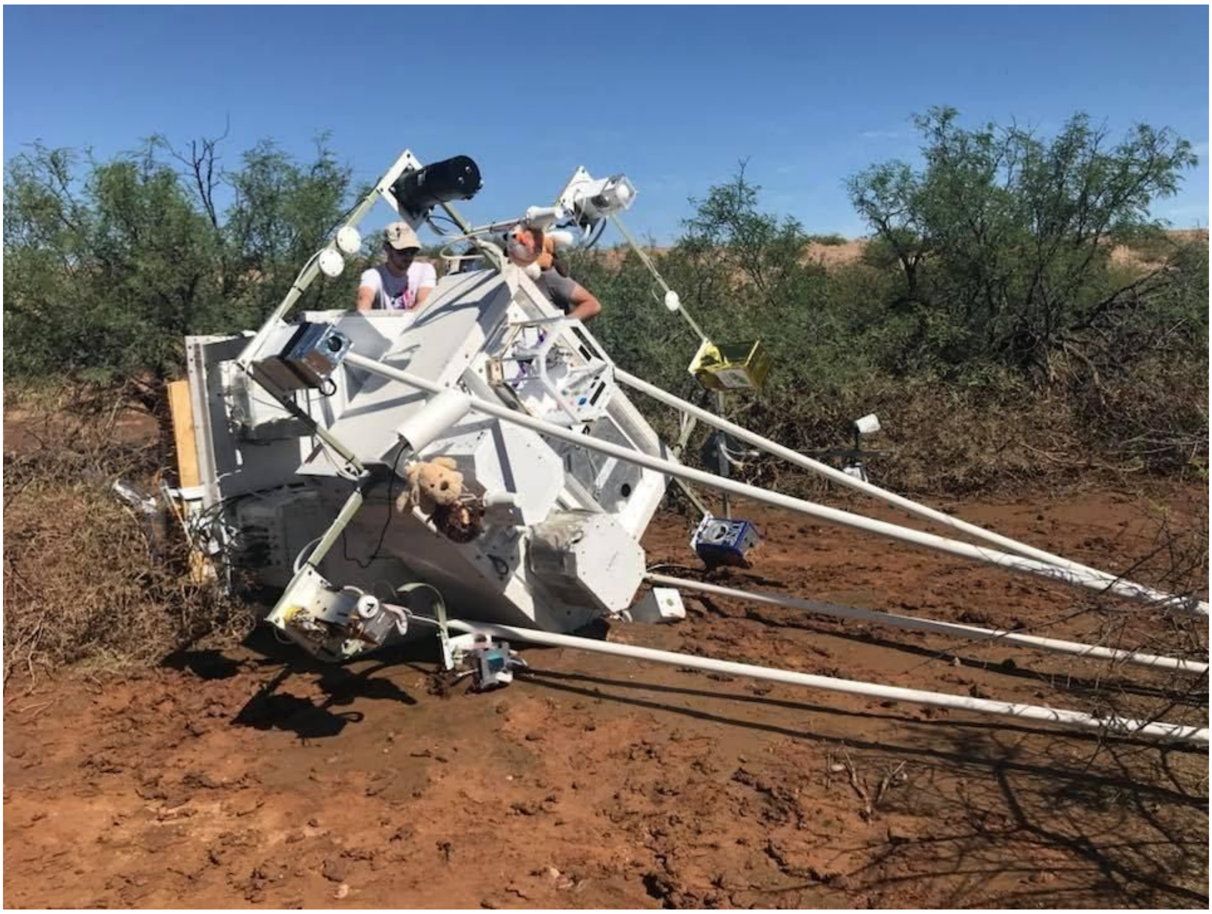
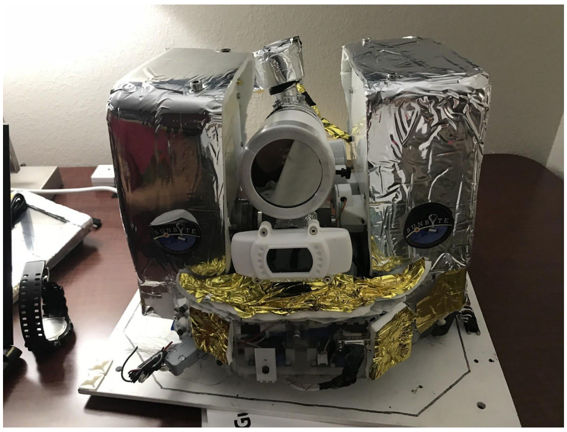
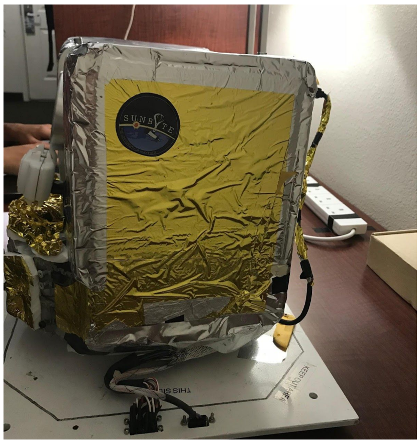


Figure 8.1 - Recovery

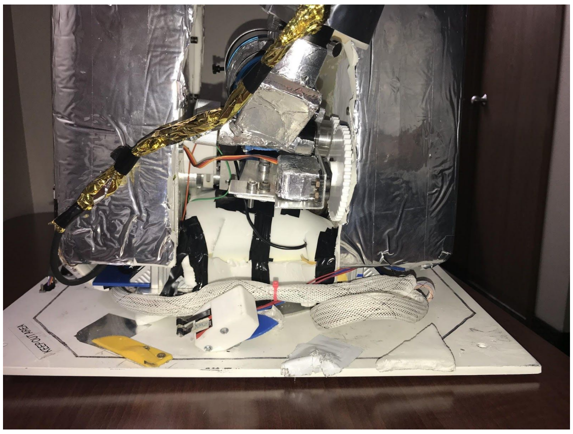
(a) Front view



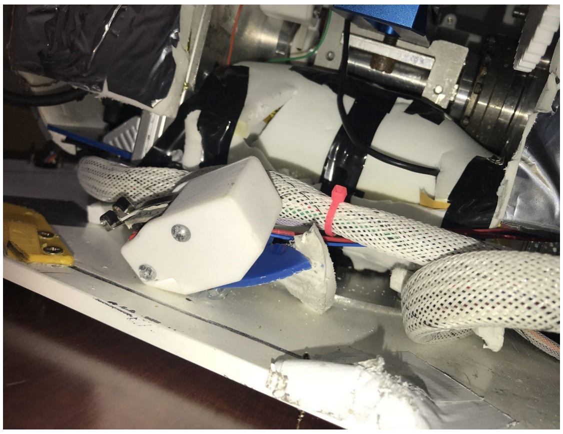
(b) Side view



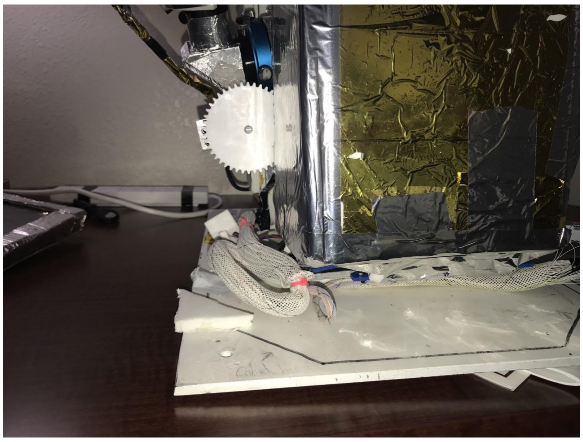
(c) Back view



(e) Yaw limiting switch



(d) Cables



(f) Cables

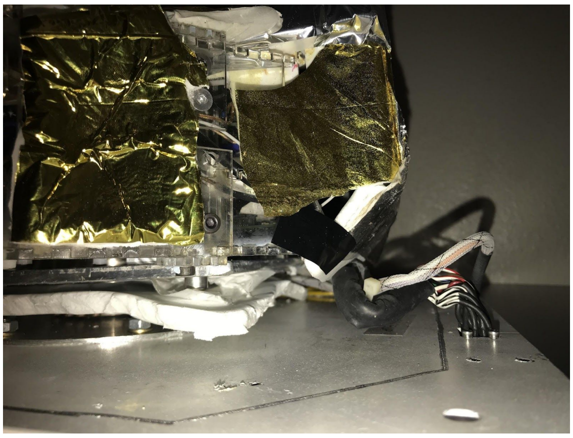


Figure 8.2 - Postflight condition of the experiment

9. Scientific Result

9.1 Scientific Images

No images from the science camera or the tracking camera were receive due to a human mistake. During the late access, a decision to erase stored testing images from the scientific camera was made and a folder where the images are stored was accidentally deleted. After that the program was unable to access the storage system.

This truly made it difficult to see whether the the payload was functioning nominally during flight. Without this data it was impossible to adjust the camera settings to ensure the Sun is in focus or manually control the attitude of the telescope to make sure it points to the Sun.

9.2 Tracking Images

However, the tracking program performed perfectly according to the design. A total of 33436 pictures were taken and saved on the SD card; on 3358 pictures the Sun can be seen - it is more than one tenth of the total number of images. There were 874 successful images when the telescope was correctly pointing at the Sun (marked with a red dot in Figure 9.2.2).

There are 6 distinct Sun tracking path in the graph moving towards the centre point. These path can be described as the tracking is slowly moving the gimbal and attempted to centre the Sun. As the HASP gondola is constantly rotating, it takes a while to centre the image. Some of the paths show that the harmonic drives were not rotating fast enough to capture the Sun movement. Further investigations need to be done in order to understand the speed of the motors used in the vacuum and low temperature environment.

Where the current tracking algorithm is taking the derivative between the centre point of the camera to the current position to the Sun.

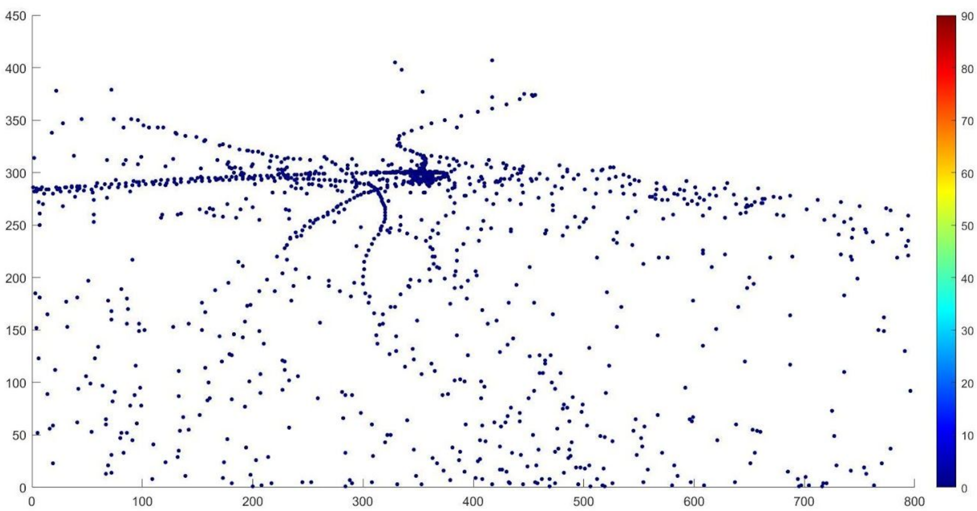


Figure 9.2.1 - Sun concentration location

The second graph indicates the concentracion location of the received tracking images. As it was mentioned above, 874 images were taken with the Sun in the centre. More than 500 images were just one pixel below the centre, as it is shown in Figure 9.2.2. Figure 9.2.2 indicates the centre point of graph 1, red pot is the centre of the tracking system with the coordinates (354,298). An example of the tracking image is shown on the Figure 9.2.3.

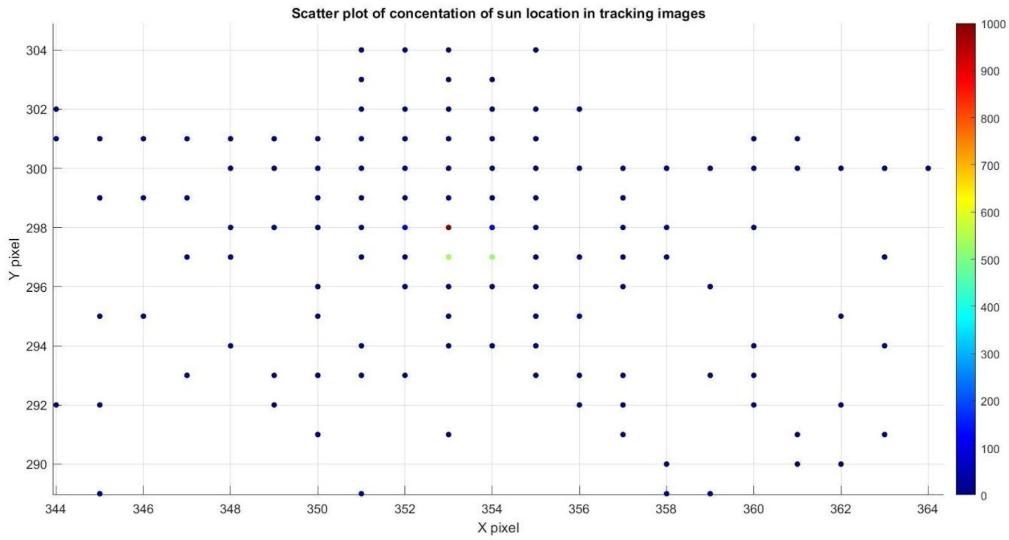


Figure 9.2.2 - Sun concentration location (zoomed in)

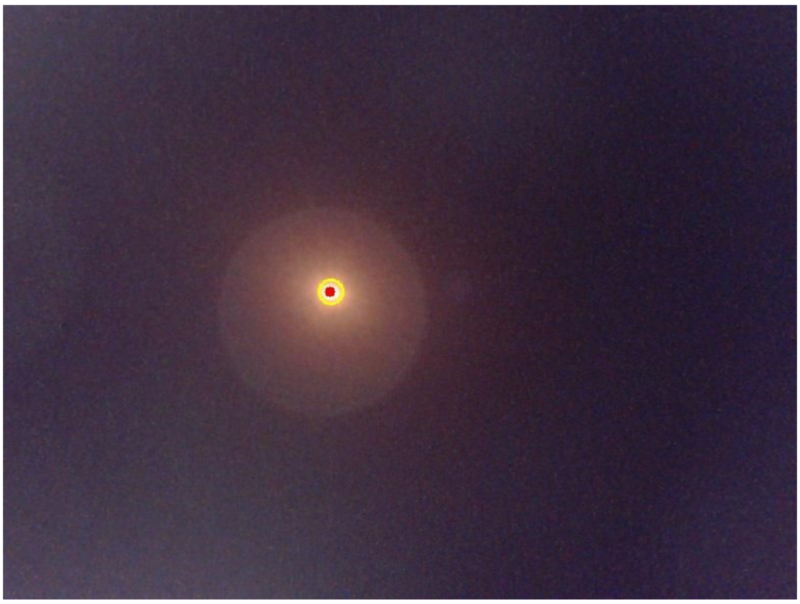


Figure 9.2.3 - Image from tracking camera

An animation (in the .avi format) of how tracking worked during the flight is available through this link: https://drive.google.com/open?id=1icpN6EQQ2vG6-bM3stdVOm0qbbPIFMSH

9.3 Surrounding Data

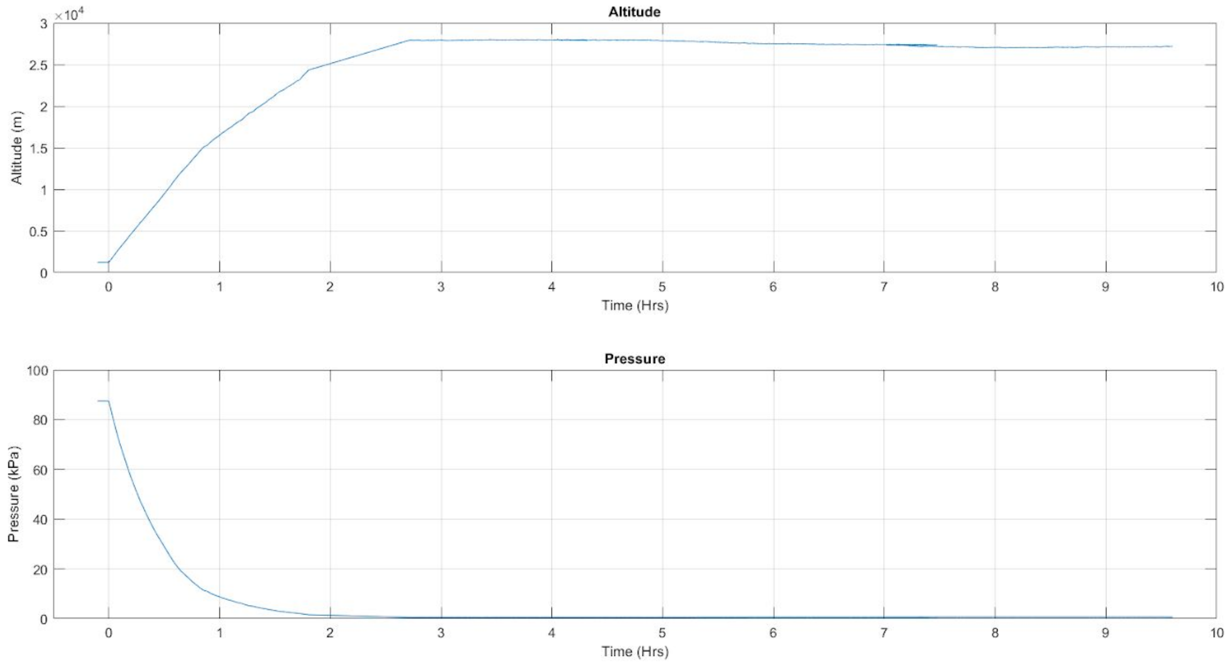


Figure 9.3.1- Altitude/Pressure Data from Downlink

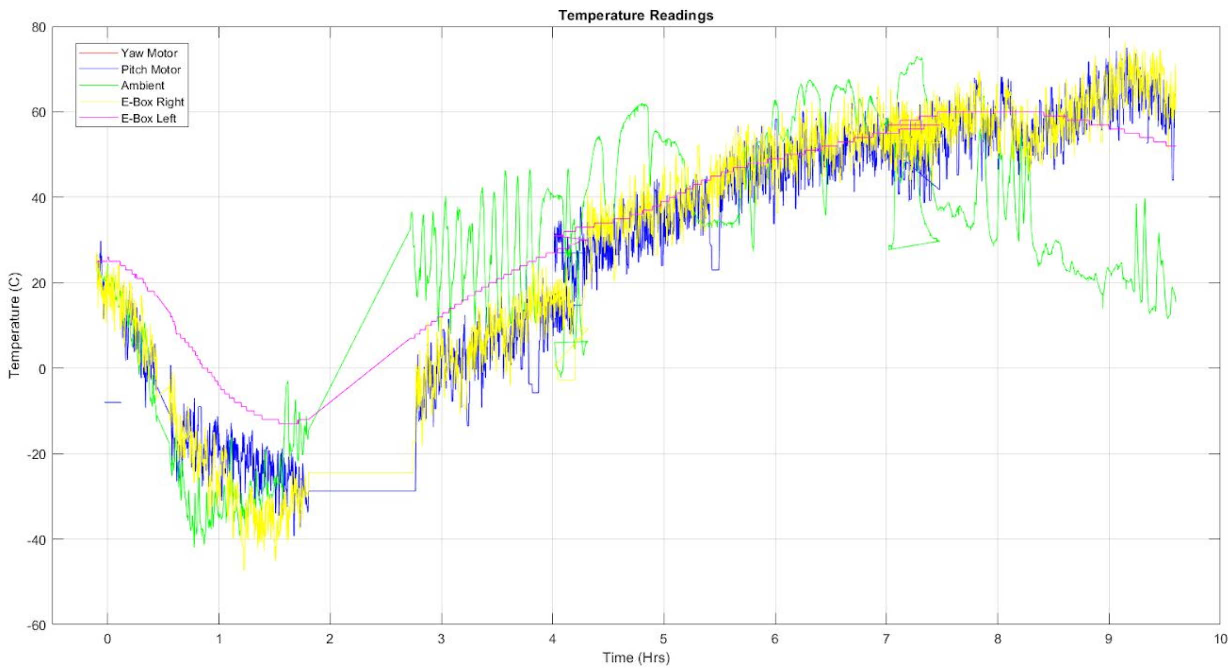


Figure 9.3.2- Temperature Data from Downlink

Figures 9.3.1 and 9.3.2 graphically represent the data received via the downlink from the payload. As expected as the altitude increased the air pressure decreased at the same rate. According to the pressure sensor the altitude at which our payload peaked to was approximately 27 km, however when comparing to the HASP GPS data (laspace.lsu.edu/hasp/xml/data_gps_positions.php?py=2018) the maximum altitude recorded was around 130000 ft (39 km). This suggests that the pressure sensor could not detect values smaller than about 1kPa.

Figure 9.3.2 is the data received from the 5 temperature sensors that were on board the payload, two of which were measuring the temperatures of the attitude control stepper motors, another two of which were measuring the temperature inside the electronics boxes, and the final one was measuring the ambient temperature. The data represented has been processed, the alterations have mainly been made to the E-box right and Pitch Motor readings. The data for these were riddled with noise and they were both linearly offset. Therefore using MATLAB the data was linearly shifted to match the start temperature of the ambient temperature because before power on the temperature of all components will have been at steady state and so will have been identical. The process to clean the graphs was conducted by ensuring that the points of data adjacent to each other did not vary erratically as it was assumed that temperature would not vary by large amounts every time the data was recorded.

10.Conclusion and future development

SunbYte II partly achieved its primary objective of successfully tracking the Sun. However, it could not achieve the objective of capturing 'high-quality' images of the sun. This was due to human error at time of the launch.

Looking at it from a different perspective, a lot was learnt through this flight as the data from the data logger showed that the temperature increased when the payload flew higher than 20 km. Therefore, we discovered how our payload would not completely seize for the rest of the flight, hence lack of active heating was not as big of an issue as first anticipated. Active heating will be needed in the future flight in order to get maximum time to gain scientific images to maximise mission return.

There is a great room for improvements in the future. We will focus on the following key aspects: team structure, electronic hardware, and software improvement and testing.

Team structure plays a major role in the development and fruition of the project. Dividing people based on their disciplines was not the most effective method in executing the project. The flaw in this structure is the communication gap that can develop. With SunbYte II being a complex system, a change in the mechanical end can affect the software and electronics end as well. In other words, there is a need for a greater coordination between these two team. This can only be achieved by splitting the team into based on the various ‘subsystems’ of a larger system.

Another area of further development is on the electronics end. From previous experience, circuit boards, such as strip board, tend to be unreliable and problematic for large circuits, given the increased possibility for incorrect wiring and poor connections. For the application environment of SunbYte II large quantities of solder connections can lead to outgassing, causing problems in the circuit. To mitigate these issues and reduce the overall size the electronics require, a printed circuit board (PCB) shall be used. The PCB shall developed after circuit prototyping is complete and a software simulation of the system has been completed using hardware-in-the-loop techniques. Utilising a PCB has many advantages, including robust integration of electronic components, reliable connections. This will result in a significant space saving and provide immunity to repeatability and wiring issues, particularly on launch day. In addition, molex connections, PICOBLADE 51021, should be used to connect from the PCB to off-board components. The PCB should be tested rigorously and reviewed by professionals before manufacture to mitigate design errors and reduce re-printing costs. A robust PCB circuit will save time in many stages of development alongside the significant reliability improvements.

The software can also be improved. Our previous software did not utilize the capability of the equipment to the fullest. For example, the Tracking Pi and Science Pi were two separate entities with no communication between them. This meant that, for example, when the system would receive power, the Science Pi would automatically start taking images, irrespective of whether it was completely black or was a picture of the sun. This would result in wastage of memory that can be better utilized into other things. To make our computer codes more robust and efficient, and utilize our equipment to its fullest, we should, in the future, aim to make our software ‘object-oriented’. This will make the computer codes ‘reusable’ and make the structure more ‘modular’. A main class can be created containing all other functionalities such as color conversion, filtering, and error calculations. This simplifies the addition of extra functionalities and reduces processor usage. By choosing to object-orient our software, we can further optimize one computer and eliminate the need for the remaining two computers.

Sunbyte III has taken these issues into consideration. To optimize its performance, SunbYte III has divided its engineering team into 6 teams, each responsible for a specific sub-system. It has also created a team that is solely concerned with outreach and financial management i.e. obtaining funds. With regards to the design and development, the team has begun designing a customized PCB which will integrate all the electronic components into one platform, thus, reducing wiring, and providing a space-saving. Furthermore, the team is restructuring the software by object-orienting it. This will allow SunbYte III to use one Raspberry Pi to its full potential, instead of using three Raspberry Pis.

11. Publications and outreach

11.1 Publications

https://www.sheffield.ac.uk/acse/news/the-launch-1.820189

In addition, we are planning to publish a scientific paper in "Astronomy and Geophysics". https://academic.oup.com/astrogeo

11.2 Outreach

A number of outreach events were conducted throughout the year in order to promote and increase space engineering studies across the country.

Date	Name of the event	Description	Location
16/5/18	Pint of science	Sharing our experience of work with ESA, NASA and IET to engage students to participate in space related projects.	Sheffield
13/4/18	British Conference of Undergraduate Research 2018	The largest undergraduate conference in the UK.	University of Sheffield
15/4/18	Get Up to Speed with STEM	This annual event is designed for young people, their families and teachers to see some of the UK's best innovations first hand.	Magna Science adventure Centre, Rotherham
17/10/18	Welcome Event for Late Engineering Students	Sharing our experience of work with ESA and NASA with new students.	University of Sheffield
20/10/18	Open Day	Sharing our experience of work with ESA and NASA with new students.	University of Sheffield
24.10.18	Student-Led-Activity event	Showcased a poster about the SunbYte II mission and its results.	University of Sheffield
25/10/18	Institute of Mechanical Engineering (IMechE) talk	Members of our team talked about the results of SunbYte II mission and the future of SunbYte.	Advanced Manufacturing Research Centre (AMRC)

12. References

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Appendix

A. Team demographics

Name	Start Date	End Date	Role	Student Status	Ethnicity	Race	Gender	Disabilit y
Iakov Bobrov	Nov 2017	Presen t	Overall Team Leader	Undergradu ate	Not Hispanic or Latino or Spanish Origin	White (Caucasian)	Male	No
Gianni Heung	Nov 2017	Presen t	Electronic Team Leader	Graduate	Not Hispanic or Latino or Spanish Origin	Asian	Female	No
George Robinson	Dec 2017	Presen t	Mechanical Team Leader	Undergradu ate	Not Hispanic or Latino or Spanish Origin	White (Caucasian)	Male	No
Alex Hamilton	Nov 2017	Presen t	Software Team Leader	Graduate	Not Hispanic or Latino or Spanish Origin	White (Caucasian)	Male	No
Arthur Cunningham	Feb 2018	Presen t	Mechanical Team member	Undergradu ate	Not Hispanic or Latino or Spanish Origin	White (Caucasian)	Male	No
Abdulla Omaruddin	Feb 2018	Presen t	Electrical Team member	Undergradu ate	Not Hispanic or Latino or Spanish Origin	Asian	Male	No
Federico Orrego Mendez	Feb 2018	Presen t	Mechanical Team member	Undergradu ate	Latino		Male	No
Tom Holford	Feb 2018	Presen t	Mechanical Team member	Undergradu ate	Not Hispanic or Latino or Spanish Origin)	White (Caucasian)	Male	No
Sagar Shah	May 2018	Presen t	Electrical Team member	Undergradu ate	Not Hispanic or Latino or Spanish Origin	Asian	Male	No

Theo Glashier	Feb 2018	Present	Mechanical Team member	Undergraduate	Not Hispanic or Latino or Spanish Origin	White (Caucasian)	Male	No
Yadav Dosieah	Feb 2018	Apr 2018	Electrical Team member	Undergraduate	Not Hispanic or Latino or Spanish Origin	Asian	Male	No
Alexander Menzies	Nov 2017	Feb 2018	Mechanical Team member	Undergraduate	Not Hispanic or Latino or Spanish Origin	White (Caucasian)	Male	No
Joycelyn Fontanilla	Nov 2017	Apr 2018	Mechanical Team member	Undergraduate	Not Hispanic or Latino or Spanish Origin	Asian	Female	No
James Hulse	May 2018	Apr 2018	Mechanical Team Member	Undergraduate	Not Hispanic or Latino or Spanish Origin	White (Caucasian)	Male	No
Brandon John O'Connell	Dec 2017	Apr 2018	Mechanical Team Member	Undergraduate	Not Hispanic or Latino or Spanish Origin	White (Caucasian)	Male	No
Andrew Baker	Apr 2018	Present	Mechanical Team Member	Undergraduate	Not Hispanic or Latino or Spanish Origin	White (Caucasian)	Male	No

B. Risk Analysis

1.1. Safety Risks

Risk	Key Characteristics	Mitigation
Sharp edges, machined Aluminium	Sheet and tubing, some sharp edges exist after machining.	Deburr edges where possible. Contain sharp edges in tough material. During transportation, use protective gloves when handling if sharp edges are still present.
Massive bulky structure	The mass of the assembly poses risk of trapped and damaged digits or feet being crushed.	Order of assembly should be well thought out and practiced. A safe number of people are present during assembly and that there is a dedicated space for assembly.
Motor speed > 10rev/s	During testing motors will be running at over 500 rpm.	Care should be taken to avoid hair getting caught around motor shaft. Long hair tied back.
Parts dropping from gondola	Parts are heavy enough to cause harm if they fall onto people	All parts sufficiently fastened. Testing conducted to ensure fastening is able to hold all parts in place in case of turbulence.

Table 1.1.1. – Experiment safety risks

Risk Register

Risk ID
TC - technical/implementation
MS - mission (operational performance)
SF - safety
VE - vehicle
PE - personnel
EN - environmental

Probability (P)
A. Minimum - Almost impossible to occur
B. Low - Small chance to occur
C. Medium - Reasonable chance to occur
D. High - Quite likely to occur
E. Maximum - Certain to occur, maybe more than once

Severity (S)

1. Negligible - Minimal or no impact
2. Significant - Leads to reduced experiment performance
3. Major - Leads to failure of subsystem or loss of flight data
4. Critical - Leads to experiment failure or creates minor health hazards
5. Catastrophic - Leads to termination of the HASP programme, damage to the vehicle or injury to personnel

Table 1.1.2 - Risk register

Risk	Risk and Consequences	Probability	Severity	PxS	Action
TC10	Sun not Found	A	4	Very low	Calibrate the telescope to find the Sun
TC20	Breakage of telescope	C	3	Low	Simulations done on the material to prevent it from breaking
MS10	Sun found but accurate pointing not achieved	B	2	Very low	The telescope calibrated under a light source so that it recognizes the intensity of the Sun
MS20	Telescope not focused	C	3	Low	Change the resolution and refocus
MS30	Motors overloaded	A	2	Very low	Multiple tests run before the launch to check the motor isn't overloaded
MS40	Control boards fail	B	4	Low	Multiple tests run before the launch to check the control boards work
MS50	Hard drives full	B	3	Low	Complete measures taken to ensure the hard drives are empty
MS60	Telemetry fails during focus	C	4	Medium	Recalibrate to refocus
MS70	Outgassing of the 3D printed parts	B	2	Very low	Specific care to be taken during the selection of appropriate materials

Table 1.1.3 - Risk register

Risk	Risk and Consequences	Probability	Severity	PxS	Action
MS80	Gears get jammed	C	2	Low	The gears must properly oiled before launch
MS90	Heavy winds might make it disbalanced	D	2	Low	A gyroscope will be used to get alerts for proper orientation
SF10	Parts of gondola fall off	A	5	Low	It is ensured that the all the parts are properly bolted in
EN10	Rays focused on someone due to damage to telescope camera	B	4	Low	Calibration of telescope set properly so that rays do not get misguided
EN20	Short circuiting of the system	B	3	Low	Implementation of a fuse or Mini circuit breaker to stop the system from burning down.
VE10	Side strut breaks	C	3	Low	Analysis of side struss done under excessive weight to make it strong
VE20	Collision of support structure with launching mechanism	B	4	Low	The angle of launching Mechanism calculated to prevent collision
PE10	Delay in achieving deadlines due to shortage of engineers	C	3	Medium	Recruitment of able engineers expediently by the management team.
PE20	Unprecedented cancellation of meetings	C	2	Medium	The management team must ensure the timings are appropriate and everyone abides by them

Table 1.1.4 - Risk register

Risk	Risk and Consequences	Probability	Severity	PxS	Action
PE30	Lack of skills for use of modelling and analysis softwares	B	2	Medium	Hiring across multiple disciplines using working groups rather than sole experts
PE40	Sudden resignation of members	C	1	Medium	Management team ensure morale remains high through a variety of techniques
PE50	Miscommunication of Information	D	2	Medium	The management team should be responsible for ensuring proper information is conveyed to all team members