Developing low-cost, reusable solar observation platforms to advance sustainable heliophysics research

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Abstract
The objective of this paper is to describe a methodology for cheaper solar observation, which would make it available to research institutions of all sizes. This is done through the use of low cost, reusable components, innovative manufacturing and by using high altitude balloons to transport the payload. The aims of the project are to produce clear, sharp images of the solar chromosphere. This proves that it is possible to produce research-grade images without the need for expensive alternatives such as adaptive optics on ground telescopes or satellites. As well as discussing the technical points of the project, the paper will discuss the technical hurdles encountered before this design iteration and how these have been overcome. The other aims of the project are to facilitate students introduction to the space industry and allow them to practice their skills in a practical manner. This is very different from the work done theoretically in the classroom and exposes students to the challenges of working in industrial teams.

Keywords
Heliophysics, Reusable, Low-Cost

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Acronyms/Abbreviations

CME	Coronal Mass Ejection
FEA	Finite Element Analysis
HASP	High Altitude Student Platform
ROS	Robot Operating System
RPi	Raspberry Pi
SBC	Single Board Computers
SSD	Solid State Disk
ZPB	Zero Pressure Balloons

1. Introduction

Solar observation is a important method of research in heliophysics, which allows for the observation and modelling of solar behaviour and how that impacts objects throughout the heliosphere [1]. The models developed from our sun allow us to make predictions about the behaviour of other stars and what might exist in their own solar system [2].

Since the earth is located within the heliosphere and is relatively close to the sun, earth is exposed to a variety of solar activity, which keeps our planet warm, whilst bombarding us with charged particles, known as solar wind. Though mostly harmless, as we are shielded by the earths magnetosphere and atmosphere, solar wind can become dangerous when emitted as a Coronal Mass Ejections (CME). Which upon contact with earth can induce large electric currents though magnetic coupling. Before the electrification of the planet this was not a significant issue and large storms have hit before [3]. Now though, a repeat CME strike could cause incalculable damage to modern communications and navigation systems [4].

Cheaper solar observation methodologies would lower the cost of failure and encourage innovation in the field, potentially increasing the number of novel observation methods proposed and modernising the equipment used through shorter development cycles. This would open up primary data collection to small and medium sized research institutions, or hobbyists, who would then be able to capture sharp and informative images of the solar chromosphere or corona for research purposes. The Solar observation platform discussed in this paper, SunbYte, is intended to act as a proof of concept for this approach to research. This is why SunbYte is capturing in Hα, a region of the solar spectrum visible though earths atmosphere, in order to compare high altitude observation with a ground based approach.

2. Requirements

In order to reach the reusable targets of the project, the various subsystems of SunbYte must be robust enough to survive multiple high altitude flights weathering harsh, variable, conditions whilst minimising the amount of repair work needed.

The environmental conditions at 35km, the highest point the Zero Pressure Balloon will reach, experience a pressure minimum of 5mb [5] and a temperature of $-40\ ^oC$ / $233\ K$. Because of the temperature inversion caused by ozone heating, the harshest temperature conditions are experienced when transiting though the atmosphere, with minimums of $-71\ ^oC$ / $221\ K$. These conditions were calculated for September launch, above $60\ ^oN$, and will vary by time of year and position [6]. The environment within the stratosphere has not changed significantly from 1980, with variation of up to $1\ K$ depending upon its height [7]. Changes of $1\ K$, are not significant enough to impact on the platforms design, permitting the values to be used as reference. At $35\ km$, SunbYte would rest above the majority of the atmosphere and ozone layer [8], allowing for clear astronomical observation, free of large atmospheric distortion or absorbance. This position exposes the external surfaces of SunbYte to unobstructed Infrared and UV light, leading to heating on metallic surfaces and potential damage to optics not shielded with UV blocks.

Unlike a balloon launch, a rocket subjects payloads to large axial and lateral accelerations exceeding 7.5 and $2\ g$ respectively as well as high frequency shock, vibrations and acoustic profiles [9]. The noise alone can be loud enough to cause damage to poorly designed or unlucky payloads. This means that the threshold for a successful design and launch is significantly higher, pushing costs up even before the launch itself. The physical requirements for a balloon flight are lower, as the largest acceleration shocks occur when the parachute deploys and when the gondola, the part under the balloon where experiments are typically attached, hits the ground. The deceleration experienced on impact can be up to $35\ g$. This means that balloon flights, while still technically challenging to design and build for, have fewer challenges that those designing rocket lifted payloads. Fewer challenges can encourage smaller teams to produce novel or sensitive designs, producing more affordable solar observation. Though balloons are more environmentally friendly than rockets producing fewer emissions, they may not be more sustainable. ZPB's use helium for lift, an expensive non-renewable natural resource [10], and the balloon envelopes are not reused between flights. Meaning though an experiment may be reusable, part of the process of capturing data might is not.

3. Structural and Thermal

In order to withstand the instantaneous impact forces and velocity changes during ascent and decent, the mounting and base plates were constructed out of steel. Plate thickness was determined though Finite Element Analysis (FEA), instantaneous forces were applied to the mounting points to test fracture and torsional resistance. Based on these results and a factor of safety of 2, a plate thickness of 3 mm was chosen.

Due to the loading mechanisms experienced by SunbYte, which are predominantly axial, the primary failure mode is buckling. Due to the bracing provided by the battery box, the thickness and material of the side planes can be reduced to 3 mm aluminium. The telescope is placed between the plates, mounted on a machined steel crossbar to prevent bucking that would damage the telescope pivot, and provide extra support between the plates.

The other, non structural elements of SunbYte are comprised of bent and mounted aluminium plates which act as an environmental shield. These structures should not be airtight, to avoid becoming pressurised containers, and consequently expose internal components to external atmospheric conditions. This could potentially reduce the temperature of critical electronic components below their operating limits, preventing them from working as expected. In order to prevent this from happening, heaters will be added to keep the critical electronics and batteries warm. Due to the high surface temperatures of these heaters when turned on, they cannot be placed directly onto the electronics and will instead be coupled indirectly to heatsinks. Lastly coupling the thermal mass of the electronics together captures wasted heat, allowing operating electronics to help maintain a steady temperature.

Due to the low external pressure environment, convective heat transfer is significantly reduced internally and externally. This presents problems when considering cooling electronics and batteries. One solution would be to connect the internal thermal mass to an external radiator, placed at the back to prevent contact with direct sunlight. This method would require heaters to function continuously in order to prevent external exposure from damaging the electronics. To limit the complexity of the thermal system, a smaller external radiator was chosen to provide the internals with adequate cooling if required. This reduces the power and heaters required to maintain an internal temperature allowing for greater thermal control. For this method to work effectively, the internal components of SunbYte will be insulated from its external walls through the use of air gaps and thermoplastics. This helps isolate from both extreme cold, but also heat, as in operation certain parts of SunbYte are permanently aligned with the sun. The affects of this external heating could be reduced by painting the external surfaces with white on the front, to prevent absorption and black on the back to promote emission.

4. Electrical

In order to reduce the cost and development time of SunbYte, the decision was made to use off the shelf components including Single Board Computers (SBC), like the Raspberry Pi (RPi), and DC converters. These components often require previous expertise to design and can be costly to manufacture in small quantities; by using this method SunbYte can benefit from external design experience and the economies of scale felt by those manufacturers. In future flights, without a preestablished communications link or though novel design, where it is necessary to have radio transceivers onboard, the use of premade and certified modules would be the most cost effective method of gaining regulatory and flight approval.

The electronics subsystem is further divided into separate boards stacked on top of each other to reduce heating requirements. Each board contains a separable subsystem, power supply and management, thermal control, motor control and processing. The processing capacities are maintained throughout the flight using a separate, smaller, reserve $LiFePO_4$ battery. This allows communications and remote activation of the payload to commence during the flight to conserve power. The primary $LiFePO_4$ battery can therefore be connected and disconnected remotely, and once connected provides power to all electronics sub-systems and charges the reserve battery. Switching can occur at any time during the flight, and will likely be needed before tracking operations commence to maintain a stable internal temperature.

The RPis do not switch high current loads directly, instead charging and discharging MOSFETTs though gate drivers to avoid potentially damaging current spikes. The same is true for the stepper motors, which use dual H bridges to control and record motor positions, whilst coupled to encoders to ensure there is no slippage.

5. Software

In order to reduce development time, SunbYte will use open source software within it's codebase. This drastically reduces development time and allows the project to benefit from software expertise that it would be unable to find otherwise. The solar tracking and observation system is developed on top of OpenCV. Using a low resolution primary camera to align the main telescope with the solar plane, before capturing and saving high resolution images onto a Solid State Disk (SSD). Real time operations are important prompting the use of either, Robot Operating System (ROS) or Real time Scheduling on Linux.

In order to take advantage of HEMERA's existing communications stack, which is RF, Ethernet, IP between the gondola and ground station, TCP packets were chosen to ensure delivery. Due to the bandwidth limits imposed, down linking high resolution images would be difficult requiring them to be stored locally for collection. Since communications between SunbYte and the ground is limited, operations should be semi-autonomous once main power is connected. Though in order to assess payload health, all sensor data should be down linked, and the option of manual operator control should be available.

The computers on board SunbYte the RPi are not incredibly powerful devices, so in order to perform all the necessary operations, they will be run in parallel. In the same way the electronics onboard is divided by subsystem, so are the RPis. With each one devoted to a series of tasks, depending on the computing power required. Communications will be performed over I2C links, with each task specific communicating with a coordinator which reports to ground.

A modular software design reduces future redesign time, if the mission changes scope and increases code reusablity by reducing the size of each tasks code base. This design methodology would benefit the separation of tasks, as each RPi would be only running necessary operations; reducing the chance of software crashes or bugs. This would be achieved though a kernel like approach, where core operations are always running, but specific modules for large tasks can be loaded, or compiled in.

6. Optical

The telescope that was chosen for this project is William Optics Zenithstar 61 II APO Refractor OTA. It is a refractor telescope, meaning the front lens is used to form an image of an observed object. The perfect refractors for solar observing range in size between 60-80 mm, with this aperture being 71 mm. In order to reduce the chance of oversaturating or overexposing images and obtaining scientifically unusable data, a telescope with a short focal length 420 mm was chosen.

The refractor telescope is fast, having a low focal ratio of f/5.9. This allows lots of light into the telescope, allowing for faster shutter speeds. Faster shutter speeds mean that CMOS sensors with line scanning shutters can be used. The small aperture helps to reduce telescope weight, with it weighting in at 3 kg, 10% of the projects weight budget.

A monochrome, ZWO ASI183MM USB 3.0 Mono 4/3" CMOS Deep Sky Imaging camera was chosen as the primary scientific instrument. Its' very high quantum efficiency of 84%, alongside the low read noise of 1.6 e$^-$ and high resolution will allow us to image the Sun in detail. Most importantly the fast, high quality CMOS sensor complements the refractor telescope design, producing short exposure images of high quality. The camera is also very compact and lightweight (0.80 kg), further minimising weight.

Lastly, to allow for ground testing and calibration SunbYte will be imaging in the $H-\alpha$ part of the spectrum (656.3 nm). At this wavelength it is possible to observe a lot of solar activity and this emission line allows for observation of different features such as granulation of the chromosphere, prominences and flares. The chosen eyepiece is a Daystar QUARK Hydrogen Alpha Solar Eyepiece with an integrated filter to simplify the build process.

7. Costs

There are various levels of costs to projects such as SunbYte, there is material cost, cost of equipment used in design and manufacture and cost of labour. Since SunbYte is being manufactured with volunteer student help, and with existing tools within university labs, the initial costing will be one of materials only.

Table 1: A summary of the various materials costs, per sub-team, over SunbYte 4.

Year Ending	2020	2021	2022	Total
Structures	£800	£1000	£300	£2000
Optical	£0	£0	£1644	£1644
Electronics	£600	£430	£130	£1180
Software	£0	£0	£0	£0
Total	£1400	£1430	£1994	£4824

It should be noted that though no software was purchase by us, it was provided for free though the university. Due to the closed nature of the licensing it would be difficult to cost, but discounts are available to research institutions and hobbyists. Table 1 places the cost of replicating SunbYte at £4824 from parts at their time of purchase. Had all these parts been purchased at once, rather than over 3 years, then accounting for inflation, the figure would be slightly higher. At the time of writing, the current highest estimate of parts costs is £$5,500$, within the budget of many hobbyists. Unlike hobbyist groups, or university students who are volunteering, staff at research institutions are paid workers, and thus the total project budget would be significantly higher. To date, over the last three years, students have recorded the approximate number of hours spent working on the project. Their reported working times are summarised below, broken down by year and position.

Year Ending	2020	2021	2022	Total
Leaders	112	173	220	505
Members	47	56	101	204

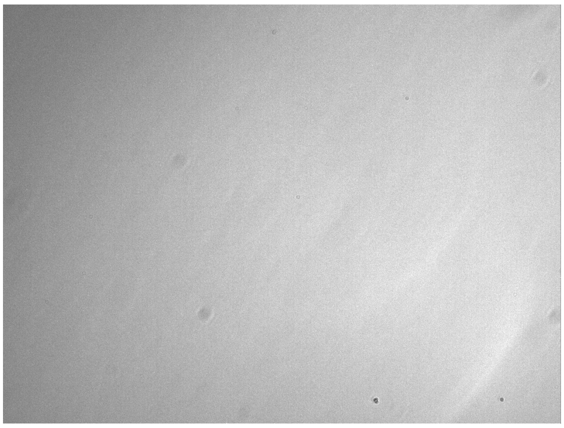
Table 2: The approximate number of working hours, per student, over the year broken down by position in the project.

The values for 2022 are still projections based on the number of working hours to date, extrapolated to the end of the academic year. They may increase as deadlines approach. Using the data provided in Table 2, and using the average team size over all 3 years, produces around 5080 labour hours. At national living wage produces a total cost of £$48,260$ for labour and a total project cost of £$53,760$, well within the three year budget of a small research institution.

8. Discussion

This iteration of the payload is the fourth, there have been many designs and challenges throughout the process. The previous three iterations have failed to capture viable images of the solar plane. The best image captured so far, on Sunbyte 3, is in Figure 1. Each failure has been different, and all have been small oversights in design or preparation. The first prototype of the experiment was supported by the REXUS/BEXUS programme and was launched from the Esrange Space Center in 2017. Subsequent re-flights were made in 2018 and 2019 with NASA, as part of the High Altitude Student Platform (HASP) program. The design has been significantly altered throughout the redesign process over the last three years, in the hope that any oversights have been fixed. SunbYte IV is set to launch in September 2022, from the Esrange Space Center in Sweden.

Figure 1: Image of the solar surface, captured by SunbYte 3.



The next big challenge after the successful capture of imagery, aside from expanding the scope of the project to capture alternative wavelengths, is to the limited number of open balloon launches each year. It is certainly possible, with the correct level of funding to buy and perform your own launches, especially as an institution with other payloads being flown. This would allow for optimised flight plans and altitudes for solar observation and would mean that observation experiments, especially novel designs, would not have to compete for space on the more general scientific flights performed by NASA or ESA. Using dedicated launches would allow for further reusable balloon development or research into recycling used helium.

SunbYte's other purpose is to introduce passionate students to the space industry and give them an experience of what higher-calibre space missions feel like. Our team is composed of mainly undergraduate students from the departments of Engineering, and Physics and Astronomy and is a sister project to a variety of other experiments such as SunRide and SunSat, who are developing rockets and cubesats.

9. Conclusions

Due to advancements made in manufacturing, low cost electronic components and open source software, it is certainly possible to manufacture a high altitude solar telescope. Though careful budgeting, manufacturing one is even within the grasp of hobbyists and small research institutions. These groups would likely have to launch with the help of a space agency, a private launch would only be within the reach of well funded groups. The next step, once solar images have been captured and their quality established, is to introduce a filter wheel into the design. This would allow for multi wavelength viewing of the Sun, further increasing the versatility of the system and allowing it to capture bandwidths which are not visible though the atmosphere.

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