University of Colorado
Department of Aerospace Engineering Sciences
Senior Projects - ASEN 4018
Conceptual Design Document
Spectropolarimeter Telescope Observatory for UV Transmissions

Project Customers

Phil Oakley 3090 Center Green Drive Boulder CO, 80301 Email: oakley@ucar.edu Phone: 303-497-1509	Scott Sewell 3090 Center Green Drive Boulder CO, 80301 Email: sewell@ucar.edu Phone: 303-497-1576

Team Members

Name: Zach Allen Email: zaal3595@colorado.edu Phone: 303-618-5952	Name: Andrew Arnold Email: andrew.arnold@colorado.edu Phone: 719-304-6587
Name: Caleb Beavers Email: cabe5588@colorado.edu Phone: 615-815-9869	Name: Darin Brock Email: dabr5969@colorado.edu Phone: 303-842-7833
Name: Joshua Bruski-Hyland Email: jobr1623@colorado.edu Phone: 303-478-7270	Name: Matt Funk Email: mafu4674@colorado.edu Phone: 719-338-8928
Name: Ian Geraghty Email: ian.geraghty@colorado.edu Phone: 970-946-6771	Name: Andrew Lux Email: anlu4044@colorado.edu Phone: 314-422-6814
Name: Ryan Lynch Email: ryly6375@colorado.edu Phone: 720-391-5496	Name: Matthew Normile Email: mano4559@colorado.edu Phone: 719-232-9655
Name: Dawson Stokley Email: charles.stokley@colorado.edu Phone: 513-404-3914	

Contents

Acronyms

ADS	=	Attitude Determination System
COCOM	=	COordinating COMmittee for multilateral export controls
CONOPS	=	Concept of Operations
DAQ	=	Data Acquisition System
DC	=	Direct Current
EMCS	=	Environmental Monitoring and Control System
EPS	=	Electrical Power System
FBD	=	Functional Block Diagram
FOS	=	Factor of Safety
FPGA	=	Field Programmable Gate Array
GPS	=	Global Positioning System
HDD	=	Hard Drive Disk
IC	=	Instruments and Instrument Control
ITLL	=	Integrated Teaching and Learning Laboratory
IMU	=	Inertial Measurement Unit
MIG	=	Metal Inert Gas
NASA	=	National Aeronautics and Space Administration
OEM	=	Original Equipment Manufacturer
PCB	=	Power Control Board
RADIANCE	=	Research at high Altitude on Distributed Irradiance Aboard an iNexpensive Cubesat Experiment
RAM	=	Random-Access Memory
SSD	=	Solid State Drive
STOUT	=	Spectropolarimeter Telescope Observatory for UV Transmissions
STR	=	Structures
TIG	=	Tungsten Inert Gas
UCAR	=	University Corporation for Atmospheric Research
USB	=	Universal Serial Bus
UV	=	Ultraviolet
VIPs	=	Vacuum Insulated Panels
WASP	=	Wallops Arc Second Pointer

List of Tables

List of Figures

1. Project Description

1.1. Project Objectives

In the past, solar storms have been observed to have extremely damaging impacts on Earth infrastructures. Ranging from spontaneous fires, to complete disruption and damage of radio communications, solar storms have the potential of causing trillions of dollars in damage. Consisting of flares and coronal mass ejections, these events are all instances of sudden releases of solar magnetic energy. Understanding these natural phenomenon are becoming of primary importance in our ever advancing technical world. This senior design project has the opportunity of taking some of the first steps into a deeper understanding of solar weather, which will be done through the high-altitude balloon CubeSat module "STOUT".

An add-on to the previous year's senior design project RADIANCE, STOUT will be integrated with last years module to record solar radiation in the UV spectrum. Most UV light is filtered out through Earth's atmosphere, and as such valuable UV data is sparse. To gain a better understanding of emissions in the UV spectrum and therefore gain a better understanding of solar storm behavior, STOUT will mount to a gondola flown on a NASA high altitude balloon at 40km allowing for a relatively unfiltered observations of UV light. A basic conceptual design of the gondola platform can be seen in figure 1. STOUT will need to be mounted on a forward point of the gondola to provide clear line-of-site to the sun during flight in order to make the desired data retrieval possible. Obtaining data in the UV spectrum allows us to gain a better understanding of an important layer of the Sun's atmosphere, and therefore analyze solar storm behavior on a deeper level. This layer is known as the solar transition region, and is only visible in the UV light spectrum from space, further highlighting the need to implement a system such as STOUT.

The main component of STOUT is a spectropolarimeter, which consists of a telescope lens, a rotating polarizer, and a spectrometer. The spectropolarimeter will also have pointing capability in order to more accurately observe specific UV solar regions. Furthermore, an adjustable pinhole will be implemented on the telescope lens, creating a robust UV solar mapping data system when used in conjunction with the pointing system. In terms of basic STOUT integration to RADIANCE, system computations will be done through RADIANCE's Raspberry Pi, UV data storage will be routed to RADIANCE's flash memory, and both modules will receive power through the provided gondola's power source. These applications and methods are further discussed in this document, where alternatives are considered through trade studies and specific materials/methods will be chosen for the overall mission. Details of STOUT project functions requirements are stated in Section 1.5 of this document, which includes sources and verification methods for each given requirement.

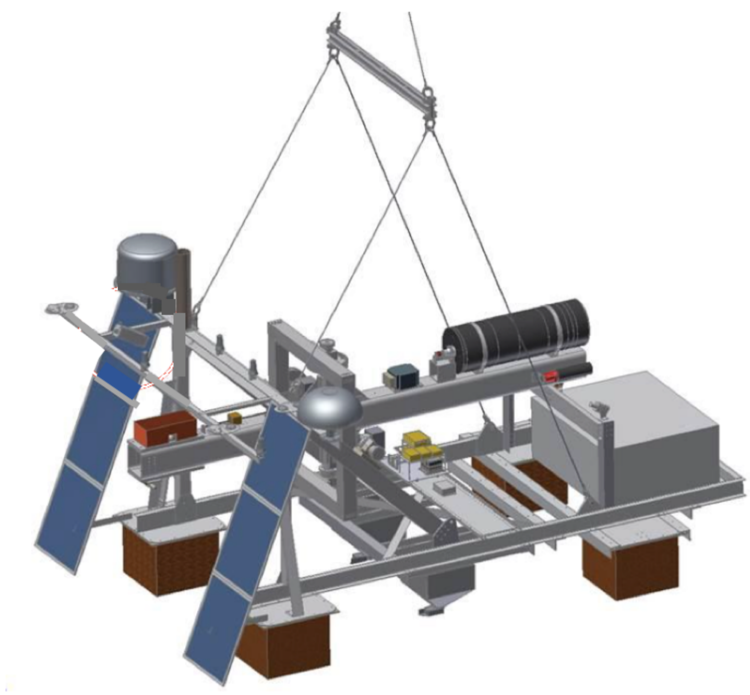

Figure 1: NASA Gondola

1.2. Project Deliverables

The main deliverables for this senior design project are as follows:

- A completed system (structure, hardware and software) which fulfills each of the requirements listed in Section 1.5
- Optical sensors capable of providing data within the specified 270-400 nm wavelength spectrum
- Attitude control capable of 2 degrees of freedom, with a range of $\pm$ 1 ° azimuth and $\pm$ 5 ° altitude
- Polarizer with a rotating mount capable of polarizing light at variable angles over a 360° rotation
- A comprehensive User's Manual which assists customers with the operation and preparation of the combined STOUT and RADIANCE system
- Monthly status reports to the customers in a given "Quad Chart" format
- All reports and review presentations as required by the 2017/18 ASEN 4018/4028 senior project program

1.3. Flight Conditions

STOUT will be mounted onto a NASA high altitude balloon and will fly at 40km in altitude for approximately two weeks. Thermal controls will need to be implemented in order to keep all instruments near thermal equilibrium during the volatile ascent and descent, and a stable environment will also need to be established during the cruise period. It should be noted that the specifics of flight-timeline, flightpath-type, and gondola models are non-specific at this time. The gondola will be the sole source of power during this mission, providing a continuous supply of no more than 30W to STOUT. Additionally, the instrument housing/structure will need to be built to withstand an overall impact of up to 5 g's, as required by NASA balloon operations support. Interestingly enough, at 40km the atmospheric pressure is well below 50 pascals which designates the environment as a medium-level vacuum. Because of this, all instrumentation will need to be capable of operating at near vacuum conditions, potentially creating drastic design changes and overall cost increases to the mission. As can be viewed in figure 2 the temperature conditions range from an average of sixty degrees Fahrenheit at sea level, to negative seventy degrees during the ascent. While at cruise, a more stable yet difficult design temperature of about zero degrees will be experienced. Turning towards figure 3, the pressure is seen to decrease exponentially with increase in altitude. As previously noted, the pressure is quite low at cruise altitude, in fact the vacuum conditions verge on the scope of "high vacuum" conditions.

To help clarify mission CONOPs and functional requirements of the overall mission, three main phases of flight must be understood and are described by the following:

1. Phase 1: Ascent. During this phase temperatures range from -70°F to 50°F. Pressure ranges from 100 kPa to 1 kPa. Humidity varies highly from 0% to 90%. Approximately 24 hour period.
2. Phase 2: Cruise. During cruise temperatures can hover near 0°F. Pressure ranges from 10 Pa to 1 kPa. Humidity varies from approximately 0% to 5%. Approximately 2 week period
3. Phase 3: Descent. During descent the STOUT will be exposed to similar ascent atmospheric conditions. Approximately 12 hour period.

1.4. Concept of Operations

For the project overall, there are two CONOPs diagrams. The reason for this is that the development of STOUT ends with the CubeSat delivery to the customer. However STOUT will go on to fly, and for a more specific overview of this portion of the project, a Mission CONOPs is shown. Shown below in Figures Figures 4 and 5 are the long term concept of operations for the Project Mission and the STOUT team concept of operations. The STOUT team CONOPs provides a path towards the customer's (UCAR) long term goals by providing a tested CubeSat unit capable of operating for extended periods at an altitude of 40 km.

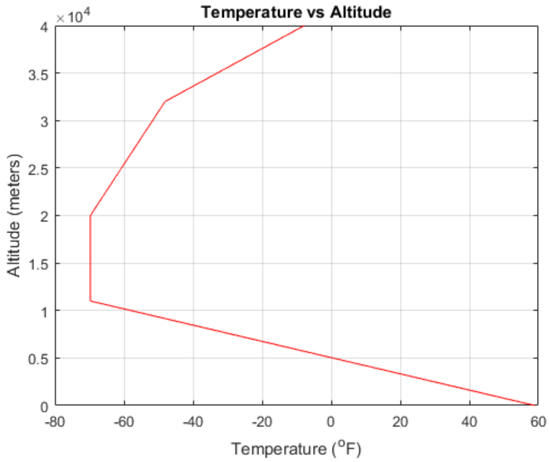

Figure 2: Temperature Flight Conditions

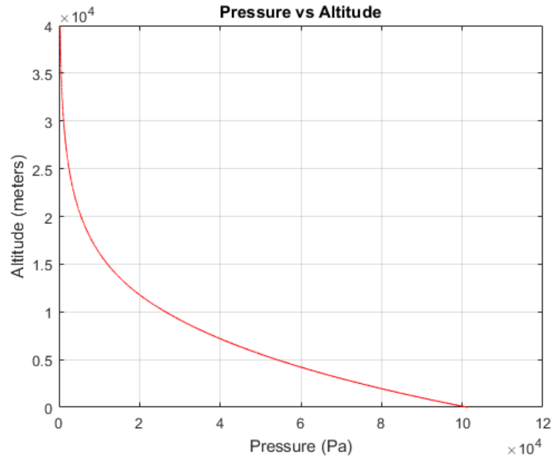

Figure 3: Pressure Flight Conditions

1.4.1. Mission CONOPS

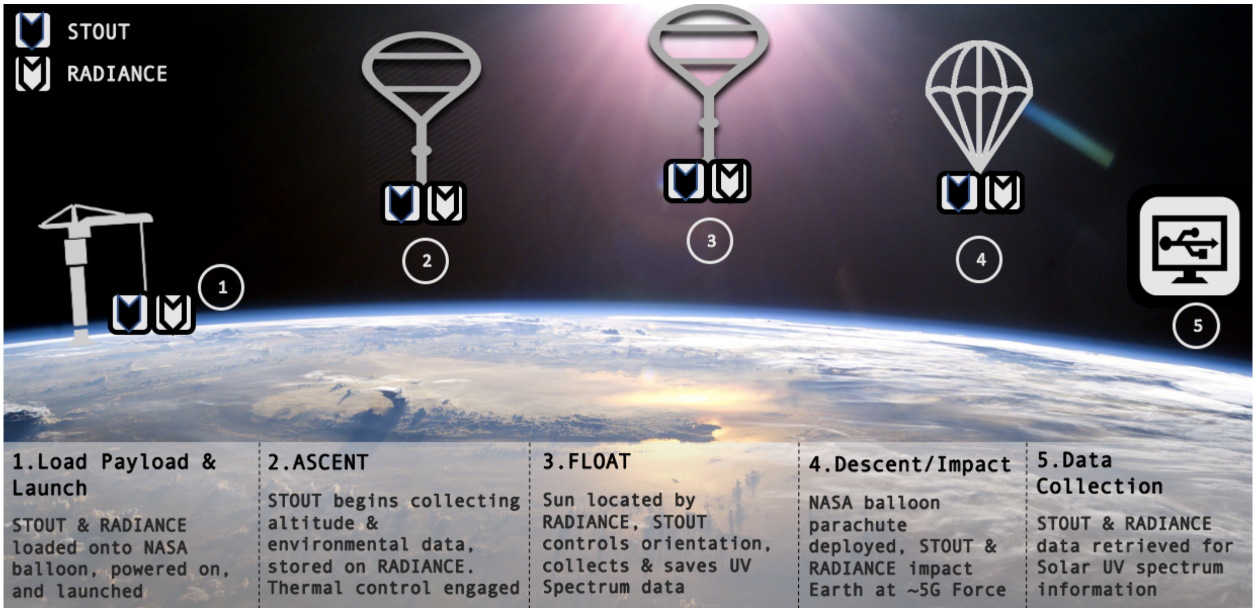

Figure 4: Mission CONOPS

As can be seen in Fig. 4, the long term CONOPs is broken into five stages, ranging from power on and ascent of the STOUT module, data collection, and finally the recovery of the STOUT module and data analysis.

1.4.2. STOUT CONOPS

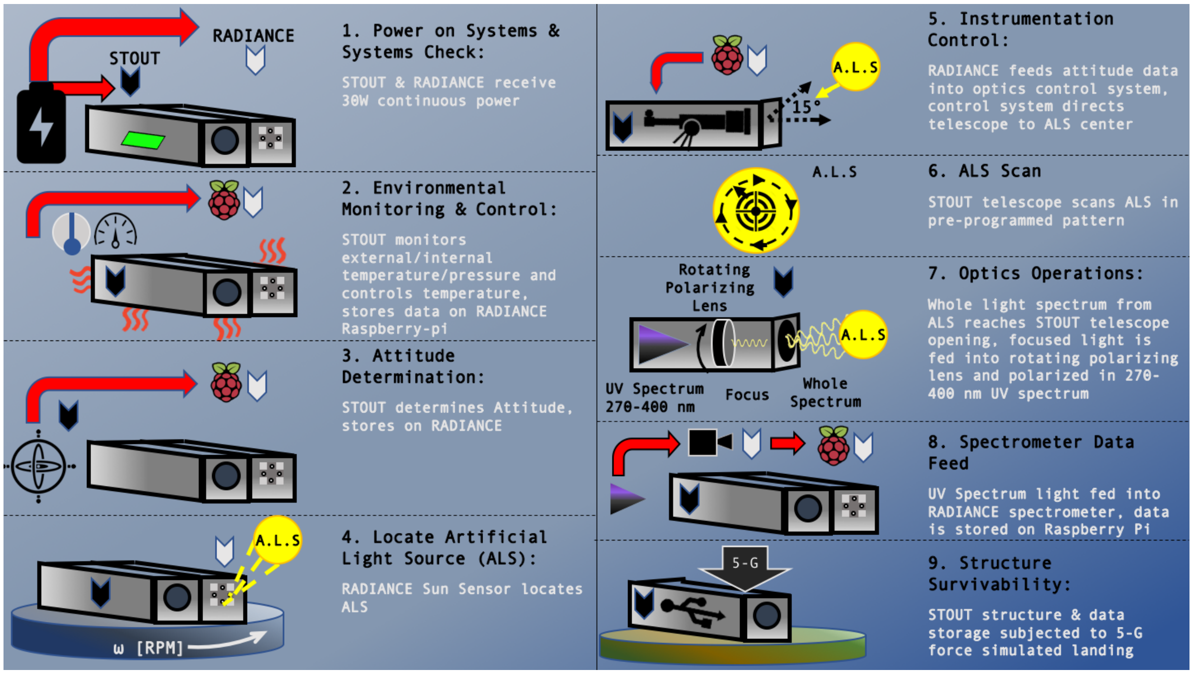

Figure 5: STOUT CONOPS

In Fig. 5, the STOUT team CONOPs at the time of delivery to the customer is shown. The data collection and operations are to be demonstrated through various testing protocols, such as pointing at an artificial sun source, which will prove the module's ability to function in UCAR's long term CONOPs.

1.5. Functional Block Diagram

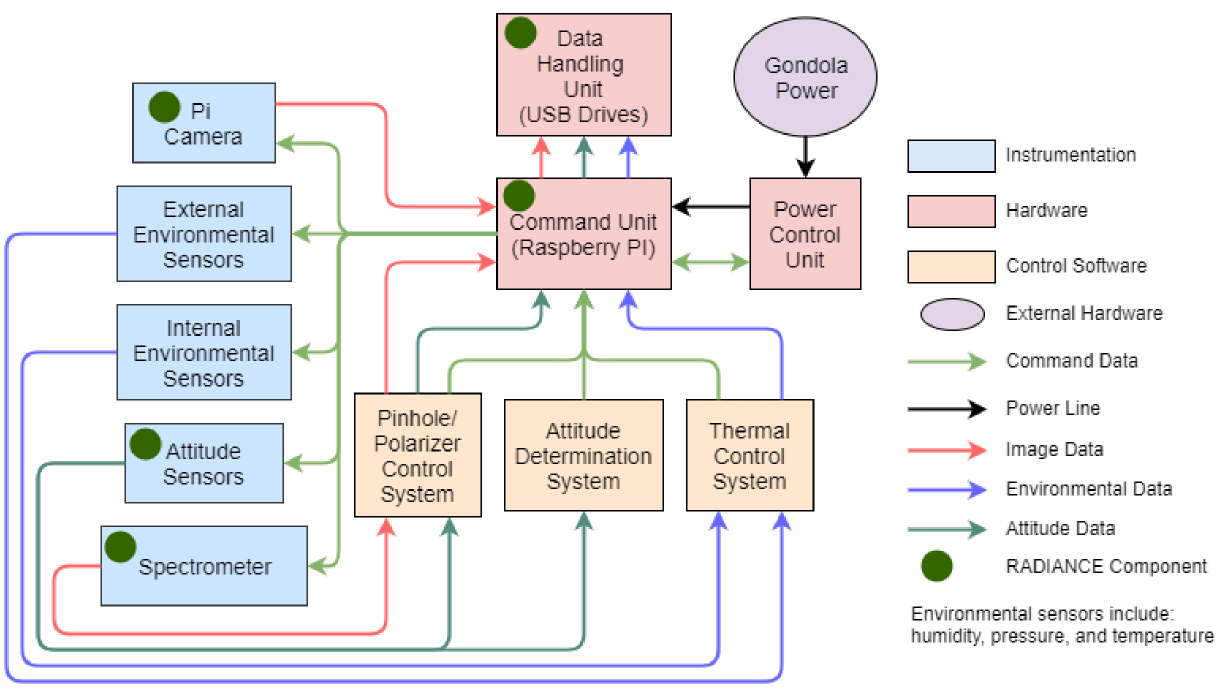

Figure 6: STOUT Functional Block Diagram

Figure 6 is a display of the overall system FBD. The FBD shows an overall system flow including integration with the RADIANCE module. A short summary of the system process is as follows: Beginning with the gondola, power is distributed and filtered through the control power unit and into the command unit. The command unit is the central piece to the system and initially sends commands to the attitude sensors as well as both the external and internal environmental sensors. The environmental sensors ensure that the system is within the specified thermal operating range and are also used to take useful mission environmental data. Simultaneously the attitude sensors begin to analyze STOUTS position relative to the sun (target). If STOUT is in the required range the spectropolarimeter (spectrometer,pinhole,polarizer,systems) begins to take the desired data, which is routed back to the command unit and stored properly. This loop repeats for the remainder of cruise. Within this system it can be noted that there are various modifications that can be made to attempt meeting higher level requirements. For example if achievable, the environmental sensors can sense night time conditions and feed this information to the command unit, where the entire system can go into a "sleep" mode, saving power, and preventing mass amounts of unhelpful data being retrieved and stored.

1.6. Functional Requirements

The following list is a short summary stating the STOUT projects overall functional requirements. Shown for reference, these requirements are expanded upon in Section 2, where source and validation methods for each requirement are briefly described.

1. The system shall interface with RADIANCE.
2. The system shall take polarized UV spectrum measurements.
3. The system shall determine its attitude.
4. The system shall take environmental measurements.
5. The system shall survive environmental conditions of a high altitude balloon flight.
6. The system shall record data.
7. The system shall interface with a NASA balloon gondola.
8. The system shall be delivered with a user's manual.

2. Functional and Design Requirements

The following section outlines the functional and design requirements for STOUT. Here each requirement broadly defines what STOUT will accomplish, the constraints of the system, and the specific needs of the project. Furthermore, the source and validation for each requirement is given.

1. The system shall be integrated with RADIANCE
   Source: Customer requirement

   1.1 STOUT shall interface with RADIANCE's Raspberry Pi
   Source: Customer requirement
   Validation: Analysis; recorded data will be evaluated to ensure the system is properly interfaced

   1.2 STOUT shall interface with RADIANCE ADS
   Source: Design need; STOUT requires photodiode sensors on RADIANCE to determine the location of the light source
   Validation: Demonstration; the integrated system will be tested with a simulated Sun

   1.3 STOUT shall use a modified version of RADIANCE's power board to supply power to its components
   Source: Design need
   Validation: Demonstration; verify that all of STOUT's components receive enough power to operate

   1.4 STOUT shall interface with RADIANCE's structure for a final body dimension of 10 cm x 20 cm x 30 cm
   Source: Customer requirement
   Validation: Design STOUT to be same size as RADIANCE

   1.5 STOUT shall interface with RADIANCE's spectrometer
   Source: Customer requirement; STOUT needs to use RADIANCE's spectrometer to take light spectrum measurements
   Validation: Characterization; measurements of light source with a known UV spectrum will be taken with the integrated optical system and verified

2. The system shall take polarized UV spectrum (270-400 nm wavelength) measurements
   Source: Customer requirement

   2.1 Lens gathers light from $\pm$ 15^o in the altitude and azimuth field of view
   Source: Customer defined pointing range requirement
   Validation: Inspection; lens specification sheet

   2.2 Rotating polarizer allows for light spectrum measurements at variable polarization angles
   Source: Customer requirement
   Validation: Implementation; outdoor telescopic attitude testing on test frame

   2.2.1. Polarizer mount rotates to sub-arcminute accuracy
   Source: Customer requirement
   Validation: Inspection; polarizer mount specification sheet

   2.3 Light is focused into a clear image plane
   Source: System requirements; needed for accurate spot isolation
   Validation: Test; optical alignment provides a non-diffuse light spot

   2.4 10 arcsecond spot on simulated sun is isolated
   Source: Customer requirement
   Validation: Test

   2.4.1. Actuators can move a pinhole in the dimensions of the image plane
   Source: System requirement; needed for scanning abilities
   Validation:Test

   A. Pinhole actuators can move with micrometer accuracy
   Source: System requirement; needed for move from one 10 arcsecond spot to the other
   Validation: Inspection; pinhole actuator specification sheet

   2.5 Isolated light is fed into the spectrometer
   Source: Customer requirement
   Validation: Test; check that spectrometer reads expected light intensity corresponding to the light source and system transmission loss

   2.5.1. Light enters the spectrometer via a fiber optic cable
   Source: Design requirement; spectrometer is designed to be fed with a fiber optic cable
   Validation: Inspection

   A. Fiber optic core size is larger than the isolated spot size
   Source: Design requirement; needed for good fiber coupling
   Validation: Inspection; fiber optic specifications sheet

3. The system shall determine its attitude
   Source: Design need; attitude information is crucial for taking the desired instrument measurements

   3.1 The off-sun angle attitude shall be determined to within 0.05 degree of sun center (3 arcminute)
   Source: Customer requirement
   Validation: Demonstration; expose system to light source at known relative orientations

   3.2 Attitude data shall be recorded synchronously with instrument data
   Source: Customer requirement; helpful for post-processing of instrument data
   Validation: Characterization; perform ADS measurements with instrumentation

   3.3 Attitude data shall be interfaced with instrumentation pointing control
   Source: Customer requirement
   Validation: Characterization; perform ADS measurements in known orientation and examine instrumentation control sequencing

4. The system shall take environmental measurements
   Source: Customer requirement

   4.1 The system shall measure internal pressure and temperature
   Source: Customer requirement and design need; the temperature of STOUT must be monitored to provide information to the thermal control system
   Validation: Analysis; pressure and temperature measurements will be taken in a known environment and verified for accuracy

   4.1.1. Measurements shall be recorded at a rate of 1 Hz
   Source: Customer requirement
   Validation: Demonstration

4.2 Environmental data shall be stored on RADIANCE
Source: Customer requirement; environmental data will aide in the post-processing of optical data by the customers
Validation: Demonstration

5. The system shall survive the environmental conditions of a high altitude balloon flight to 40 km
Source: Customer requirement; STOUT will fly on a NASA high-altitude balloon

5.1 During ascent and descent the system shall survive temperatures ranging from -70°F to 50°F
Source: Design need; these are the known thermal conditions of the atmosphere
Validation: Demonstration; thermal vacuum chamber testing will be performed at UCAR

5.2 During cruise the system shall operate at temperatures ranging from -10°F to 0°F
Source: Design need; these are the known thermal conditions of the atmosphere at 40 km
Validation: Demonstration; thermal vacuum chamber testing will be performed at UCAR

5.3 The system shall survive pressure values of 100 kPa to 10 Pa
Source: Design need; these are the known pressure conditions of the atmosphere
Validation: Demonstration; thermal vacuum chamber testing will be performed at UCAR

6. The system shall record data
Source: Customer requirement

6.1 The system shall record temperature data
Source: Customer requirement
Validation: Characterization; test data will be taken and verified against known quantities

6.1.1. The system shall record external temperature using 2 sensors at 1Hz sampling frequency
Source: Customer requirement
Validation: Characterization; sensors will be tested outside apparatus to verify correct measurements

6.1.2. The system shall record internal temperature using 4 sensors at 1Hz sampling frequency
Source: Customer requirement
Validation: Characterization; sensors will be tested outside apparatus to verify correct measurements

6.2 The system shall record external pressure data at 1Hz sampling frequency
Source: Customer requirement
Validation: Characterization; test data will be taken and verified against known pressure

6.3 The system shall record Attitude Data at 1Hz sampling frequency
Source: Customer requirement
Validation: Characterization; measured data will be compared with known test apparatus attitude

6.4 The system shall record Raspberry Pi Camera Images at 0.1Hz sampling frequency
Source: Customer requirement
Validation: Characterization; test images will be taken and confirmed to capture correct scene

6.5 The systems shall record attitude data at the same rate as spectrometer readings during measurement
Source: Customer requirement
Validation: Characterization; test data will be taken and verified for duration and frequency

6.6 The system shall time-stamp all measured data
Source: Customer requirement; necessary for post-processing of data
Validation: Characterization; test data will be taken and verified against known time

7. The system shall interface with the NASA balloon gondola
Source: Customer Requirement

7.1 STOUT shall have dimensions of 30cm x 10cm x 10cm
Source: Customer Requirement
Validation: Inspection

7.2 The mass of STOUT shall not exceed 6 kg
Source: Customer Requirement
Validation: Inspection

7.3 STOUT's 10cm x 10cm face shall be sun facing
Source: Design Need; necessary for collection of instrument data
Validation: Inspection; assumption given by customer

7.4 The system shall be able to interface with NASA Gondola power source
Source: Customer requirement
Validation: Demonstration; simulate Gondola Power source interface using a lab power supply

7.5 The structure linkages shall comply with all requirements and provisions of "Structural Requirements and Recommendations for Balloon Gondola Design"
Source: Customer requirement
Validation: Characterization; model simulated structure constraints, test systems, and validate

7.6 STOUT structure shall preserve structural integrity up to a 5g shock force
Source: Customer requirement
Validation: Characterization; model simulated structure constraints, test systems, and validate

7.7 The storage medium shall preserve data up to a 5g shock force
Source: Customer requirement; the flight is of no value without usable data
Validation: Characterization; model simulated structure constraints, test systems, and validate

8. The system shall be delivered with a user's manual
Source: Customer requirement, helps groups in the future build off of STOUT and RADIANCE
Validation: Inspection

8.1 Instrumentation and control operations shall be explained in detail

8.2 Environmental control and monitoring operations shall be explained in detail

8.3 Data acquisition operations shall be explained in detail

8.4 Electrical power system operations shall be explained in detail

8.5 Attitude determination system operations shall be explained in detail

8.6 Structural system shall be explained in detail

3. Design Options

The design options listed below, include all options considered for the STOUT baseline design. Here, the section is broken into functional groups examined to meet the functional requirements of the system. These groups include: Instrument and Control, Environmental Monitoring and Control System, Attitude Determination System, Electrical Power System, Structural System, and Data Acquisition. For each section, several design options are outlined within their functional group, and a pros/cons list is developed to highlight the option's characteristics.

3.1. Instrument and Control

Due to the complex nature of an optical system, it is necessary to have a basic system design before investigating individual components. The necessary functions of the instrument module itself can be separated into 3 categories.

1. Light Delivery
2. Polarization
3. Spatial Filtering

3.1.1. Light Delivery

To investigate possible designs we start by looking at general types of telescopes. The main distinction between telescope types are whether they use lenses or mirrors and are respectively classified as refracting or reflecting telescopes. The basic configurations are shown below in Figures 7 and 8.

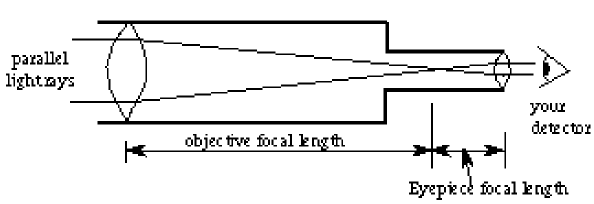

Figure 7: Basic refractor design[81]

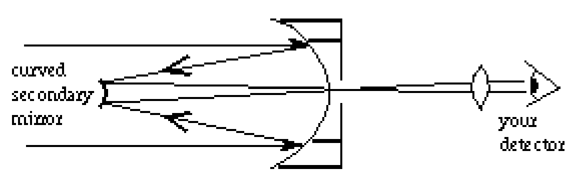

Figure 8: Basic reflector configuration - cassegrain design [81]

The pros and cons of these two types derive primarily from the use of lenses vs. mirrors and their corresponding aberrational effects. Chromatic aberrations arise because different wavelengths of light refract differently. Since STOUT aims to study a broadband of wavelengths these effects can be significant. In order to correct for chromatic aberration certain lens geometries or two lens systems can be used. On the other hand, mirrors reflect all light the same regardless of wavelength and so do not cause chromatic aberrations. Both the mirrors and lenses employed in these systems are typically spherical and the geometry itself creates inherent aberrations as well. Spherical aberration is an optical effect which causes light to focus at different points which creates a blur when forming an image [12]. Components with aspheric shapes can correct for these effects but are typically expensive.

Even though using mirrors would eliminate some aberrations, reflecting mirror telescopes can easily become misaligned and they need to be open to the environment. Having an open module presents a thermal problem because the ascent phase of a high altitude balloon passes through regions of extremely low temperatures. With an open module the surfaces of the optics equipment could accumulate dust and severely hinder measurement resolution. Finally, precision mirrors on the size scale needed for a CubeSat are not widely available.

Using lenses comes with significant design and budget complications. Lenses that provide a reasonable transmission in ultraviolet range are expensive and typically don't correct for aberrational effects. However, because lenses are more available than mirrors and lenses can be used in a closed environment this type of telescope will be the basis for the instrument design. Moving forward with a refracting telescope based design the light delivery function can be accomplished with the following components.

3.1.1.1. Lenses

The purpose of the lens in our system is to focus divergent light entering the system into an image plane. The lens must provide high transmission in the ultraviolet range which limits the lens material to materials such as UV grade fused silica, calcium fluoride, and zinc selenide. UV grade fused silica is the ideal choice for deep-UV applications because it offers the highest transmission [52]. For this reason UV grade fused silica lenses can be purchased from numerous manufactures with various geometries, diameters, and focal lengths. The following design options will focus on lens geometries and it will be assumed that our design will incorporate a lens made from UV grade fused silica. The lens geometries considered for our applications are:

1. Plano-Convex
2. Aspheric
3. Achromatic (Doublet)

3.1.1.1.1. Plano-Convex

The geometry of a plano-convex lens is shown in Figure 9. These lenses are used for light collimation or focusing applications utilizing monochromatic light sources [60]. For broadband wavelength applications multiple lenses are typically used to reduce spherical aberrations.

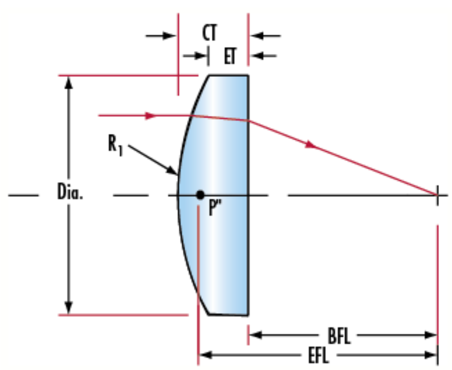

Figure 9: Plano-convex lens geometries [83]

Pros	Cons
Cheap price Widely available	No spherical aberration correction No chromatic aberration correction

Table 1: Pros & Cons of Plano-Convex Lenses

3.1.1.1.2. Aspheric

Aspheric lenses are also used for light culmination and focusing applications but the geometry of the lenses correct for spherical aberrations thus improving image quality. A single aspheric lens eliminates the need for multiple spherical lenses in a system.

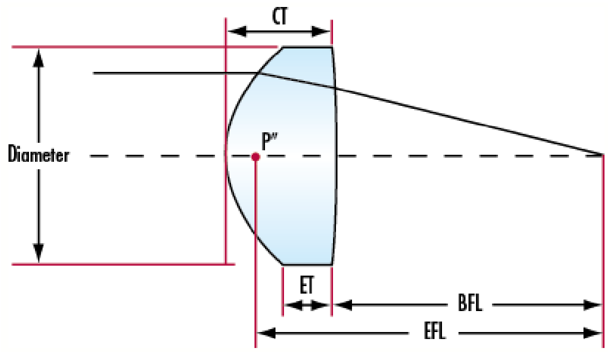

Figure 10: Aspheric lens geometries [83]

Pros	Cons
Spherical aberration correction Less components/higher transmission	Moderate price No chromatic aberration correction

Table 2: Pros & Cons of Aspheric Lenses

3.1.1.1.3. Achromatic

Achromatic lenses typically consist of two optical components cemented together. The second optical piece provides another design freedom that is used to optimize performance by decreasing chromatic aberration, much like a multiple spherical lens system. While common cements used cause highly degraded transmissions in the UV range other solutions catered to this wavelength range are available such as air filled pieces [87].

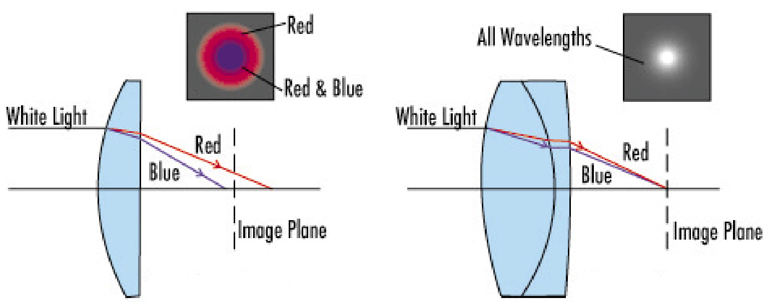

Figure 11: Plano-convex (left) vs. achromatic (right) [87]

Pros	Cons
Chromatic aberration correction Less components/higher transmission	High price No spherical aberration correction

Table 3: Pros & Cons of Achromatic Lenses

3.1.1.2. Filters

While the materials used to make the optical components in this system will be designed for the ultraviolet range, they don't completely extinct lights of other wavelengths. Because the intensity of light emitted by the Sun in the ultraviolet range is dwarfed by that of the visible spectrum, as shown in Figure 12, it is possible that a significant amount of light in wavelength ranges outside of our desired will reach the spectrometer. The noise accompanied by these readings has the ability to hamper the signals in our desired range. If so, an optical filter could be coupled with our lenses to extinct these unwanted signals.

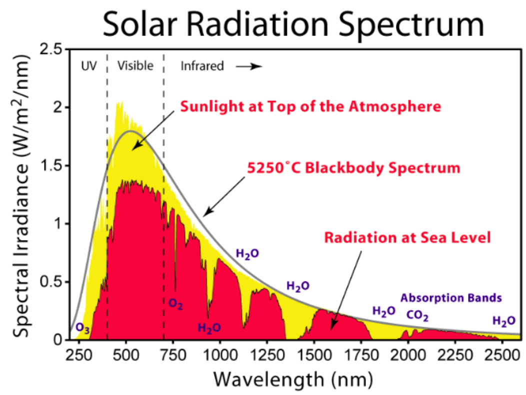

Figure 12: Blackbody radiation spectrum of the Sun [37]

The two most common types of optical filters are absorption and dichroic filters. Absorption filters absorb specific wavelengths based on the absorption properties of the glass used while dichroic filters reflect unwanted wavelengths [51]. These design options will focus on short-pass filters of these two types since we want to transmit the low end of the Sun's black body radiation spectrum. An example of the transmission spectrum for a UV short-pass filter is shown in Figure 13. Band-pass filters are also available but they typically have narrow pass bands (∼20 nm) and are 10x more expensive than short-pass filters. Also, since the solar emissions below our desired wavelength are relatively weak and for the most part will be rejected by the main lens, a short-pass filter will be sufficient for STOUT's applications.

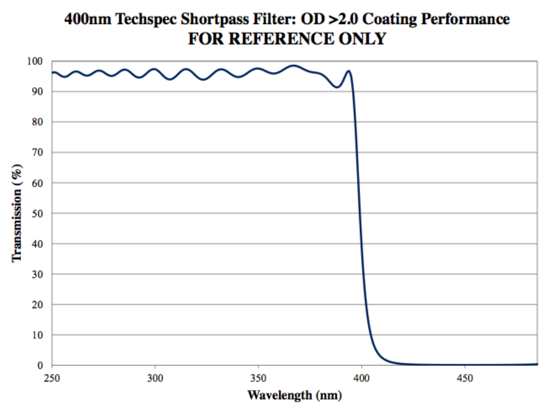

Figure 13: Example UV short-pass optical filter [71]

3.1.1.2.1. Absorption Filters

The main concern regarding absorption filters is the heating associated with absorbing high intensity visible light. Otherwise, these filters can be integrated into the optical easily because they are designed for a 0° incident angle and their performance is not particularly angle dependent. They are also relatively inexpensive (∼$100) and provide high transmission in the pass band (∼85%).

Pros	Cons
Easily integrated	Heating from long term exposure

Table 4: Pros & Cons of Absorption Lenses

3.1.1.2.2. Dichrotic Filters

For these filters to obtain functional reflectance properties they are designed to be mounted at a significant incidence angle (45°) which poses a problem for system integration as it eliminates the possibility for a linear optics path. Along with the mounting issues, the reflectance properties are highly dependent on that incident angle so they require precise alignment. These filters have approximately the same cost and transmission in the pass band. Utilizing the reflectance properties of the filters also pose a problem to an enclosed system because it is not ideal to have the rejected light bouncing throughout the system. Due to these considerations there is no positive effect of using these types of filters.

Cons
Difficult to integrate Require precise alignment Internal reflections pose problem to system

Table 5: Cons of Dichrotic Lenses

3.1.1.3. Optical Mounts

The main purpose of STOUT is to view polarized Solar UV radiation. This is accomplished by focusing UV light into the spectrometer on board RADIANCE. Specialized optics are required to accomplish this task. An optical mount will need to be utilized to ensure proper optical alignment during data collection. A misalignment of the optics could result in invalid data, and compromise STOUT's mission.

3.1.1.3.1. Optics Cage

An optics cage is a mounting system in which all components are placed in square mounts, and then secured with metal rods. The metal rods are placed at the four corners of the square mounts. This mounting system provides ideal optical stability, but at a higher cost. An optics cage without components can be seen in Figure 14

Figure 14: Optics Cage [55]

Pros	**Cons**
Stable platform Compatible with multiple optical devices Optical devices are easily aligned	High price point

Table 6: Pros & Cons of Optics Cage

3.1.1.3.2. Optics Bench

An optics bench is a mounting system in which all components are placed on a rail type systems with one point of contact. The optical components are mounted to the rail with adjustable clamps. An example of an optics bench can be seen in Figure 15. The components in Figure 15 are not representative of the components that will be on board STOUT.

Figure 15: Optics Cage[53]

Pros	Cons
More cost effective Compatible with most optical devices	Less reliable Optics easily misaligned Single contact point for all optical devices

Table 7: Pros & Cons of Optics Cage

3.1.1.3.3. Optics Breadboard

An optics breadboard is a mounting system comprised of a flat surface with with holes ordered in a uniform grid pattern. The optical components are seated in these holes, and can be placed anywhere on the grid. An example of an optics breadboard can be seen in Figure 16.

Figure 16: Optics Breadboard[54]

Pros	Cons
Parts are easily moved Easy to test component combinations	Parts are not secured firmly Not cost effective

Table 8: Pros & Cons of Optics Breadboard

3.1.1.4. Fiber Optic

The Avantes Mini 2048 spectrometer on-board RADIANCE is the crutch of the optical system because it can separate different wavelengths of light and record their corresponding intensities. The spectrometer is designed to be fed with a fiber optic cable. In most applications choosing a suitable fiber optic cable is a trivial matter but it becomes complicated for ultraviolet and polarization studies. Certain types of colorless, transparent glass used to manufacture fiber optic cables develop a coloring when exposed to UV radiation for extended periods. This process is called solarization and it leads to significant transmission degradation in optical fibers. The magnitude of solarization effects is dependent on the power of the input light, wavelength of the input light, and exposure time. Solarization-resistant fibers are manufactured by adding decolorizing materials such as manganese dioxide into the glass [50].

Fiber optic cables can also affect the polarization of the input light. This happens because the light is split into two different paths due to slight asymmetry in the fiber core cross-section. The asymmetry arises because of external stresses applied to the fiber through bending [61]. Since the light will be polarized at a known angle before entering the fiber the change in polarization shouldn't affect our measurements. However, if the spectrometer or the fiber itself transmits select polarization angles differently this could affect the intensity readings made by the spectrometer. Ideally, the fiber optic will be stationary and well mounted so that any induced polarization effects are constant. This way the effects can be determined experimentally prior to flight and be factored into the data analysis process.

For our trade study purposes it is necessary to know the difference between single-mode and multi-mode fiber optics. The difference between the types is the size of the fiber core which provides the path for light propagation.

Different modes of light propagation arise when light travels down an optical fiber due to the wave nature of light. Single-mode fibers have small core sizes on the order of a couple microns and they only allow a single mode of light to travel through at once. Single-mode fibers provide lower attenuation and greater signal strength, but because of the small core sizes, they require intricate calibration and fiber coupling is difficult. Multi-mode fibers have larger core diameters on the order of micrometers and allow multiple modes of light to propagate at once. The difference in core sizes means that a multi-mode fiber can collect more light than a single mode fiber. Multi-mode fibers experience more attenuation, especially over long distances, but the system integration process is simple[43].

With these considerations, only multi-mode solarization resistant fibers will be compared. Achieving good fiber coupling with a single mode fiber is beyond the scope of this project and so polarization maintaining fibers will not be considered.

Solarization-resistant fiber optic cables from Thorlabs and Newport are considered because they dominate the market for optical components and because they provide experimental results pertaining to transmission degradation.

3.1.1.4.1. Newport Solarization Resistant Fiber Cable

Figures 17 and 18 show the Newport cable and a plot of the transmission degradation over time for various UV wavelengths. The price of this cable is $534 for 1 meter and the transmission degrades to <40% at shorter wavelengths. The shortest wavelength in our desired observation range (266nm) degrades to approximately 80% but these values need to be analyzed with caution because the input power is not specified. Our applications are low power and the solarization effects will likely be less than that shown in Figure 18.

Figure 17: Newport Solarizaiton-resistant fiber [74]

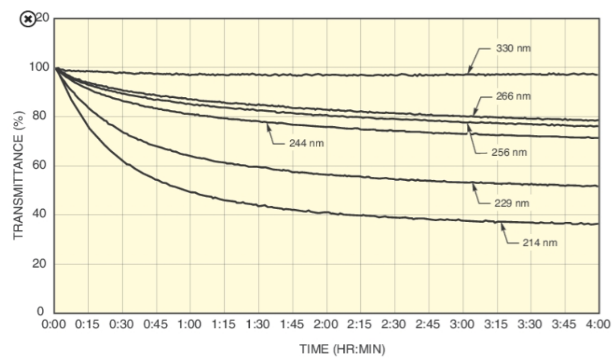

Figure 18: Transmission degradation over time. The input power is not specified[74]

3.1.1.4.2. Thorlabs Solarization Resistant Fiber Cable

Figures 19 and 20 show the Thorlabs cable and a plot of the transmission degradation over time for a 25W light input at 215 nm. This cable is priced at $86 for a 1 meter cable and is shown to be extremely solarization resistant at high input powers and at shorter wavelengths where these effects are most notable. At 215 nm the transmission degrades to approximately 80%.

Figure 19: Thorlabs cable [73]

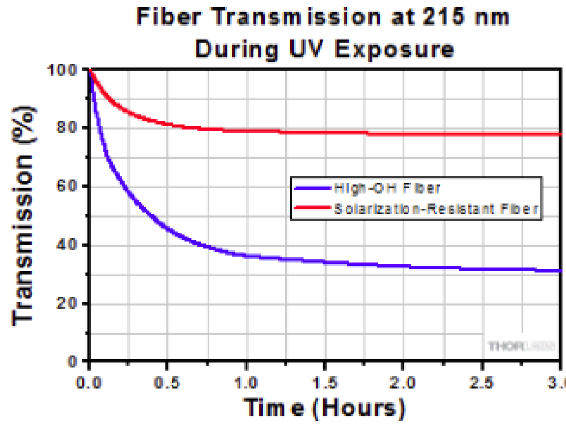

Figure 20: Transmission degradation over time from an input power of 25W from a deuterium lamp [73]

3.1.2. Polarization

3.1.2.1. Polarizers

The science data that STOUT aims to collect relies on the ability to measure how sunlight intensity changes as polarization angle changes. A polarizer with high transmission in the ultraviolet spectrum is extremely expensive (>$1000) and so will be provided by our customer. The polarizer to be used for the STOUT mission is a 25 mm diameter broadband mounted polarizer from Thorlabs. This polarizer provides >75% transmission in the desired wavelength range.

Figure 21: Customer provided polarizer [88]

3.1.2.2. Polarizer Mounts

3.1.2.2.1. Stepper Mount

A stepper mount is a polarizer mount that rotates 360^o. The rotation is accomplished through the use of a stepper motor, hence its name. In addition, most polarizors require a secondary control box to operate properly. An example of a stepper polarizer with an internal controller can be seen in Figure 22.

Figure 22: Stepper Mount [78]

Pros	Cons
Accurate 360^0 polarization Internal Controller	Slow movement Expensive

Table 9: Pros & Cons of Stepper Mounts

3.1.2.2.2. Piezo Mount

Similar to a stepper mount, a piezo mount is and polarizer mount that rotates 360^o in order to gather data over all polarizing angles. The rotation in the polarizer mount is accomplished through the use of the piezoelectric effect. An example of a piezo mount can be seen in Figure 23.

Figure 23: Piezo Mount [10]

Pros	Cons
Accurate 360^0 polarization Lower Cost	Slow movement External Controller

Table 10: Pros & Cons of Piezo Mounts

3.1.2.2.3. Belt Driven Mount

The belt driven mount is a polarizer mount capable of 360^o polarizer rotation. The rotation in belt driven mounts is accomplished through the use of a drive belt, motor combination. This can produce a high accuracies for a high price. An example of a belt driven mount can be seen in Figure 24.

Figure 24: Belt Driven Mount [16]

Pros	Cons
Extremely Accurate 360^0 polarization Fast Moving	Expensive External Controller

Table 11: Pros & Cons of Belt Driven Mounts

3.1.3. Spatial Filtering

3.1.3.1. Pinholes

The pinhole will be used to select small portions of incoming light for readings by RADIANCE's spectrometer. In order to select a pinhole size and type for use on STOUT, modeling of the full optics system must by completed in Zemax, an optical design program, in order to understand total light intensity passing through the main lens. As a result, more information on the pinhole, including its size, power rating and relevant trade studies will be provided in future reports and presentations.

3.1.3.2. Pinhole Actuators

Accurately positioning the pinhole is one of the most important aspects of the requirements for STOUT. The positioning will serve two different purposes. First, it will coarsely position the pinhole on the center of the Sun inside the image plane created by the lens. Due to the fact that the image plane spans many degrees of the sky, and that the sun is only 32 arc minutes across, this alone will require sub-millimeter accuracy from the actuators. In addition, the sun will moving at a slow rate across the image plane due to the expected pendulum motion of STOUT the customer expects in their application. This means that the actuators must not only be accurate, but have a high enough actuating speed to account for this. The second purpose of the actuators is to finely position the pinhole, the viewing size of which will range between 10 to 60 arc seconds across, on smaller portions of the Sun's image. This size pinhole will range from approximately 5 to 30 μm, as a result the selected actuators will require an extremely high level of accuracy. The position inside the image will need to be held long enough for the spectrometer to read a complete spectrum, which could take as long as one second depending on the incoming light intensity. After each measurement, the pinhole will position itself on another small portion of the sun using a scanning algorithm that will be developed later in the project.

3.1.3.2.1. Vertical and Horizontal Linear Positioning

A vertical and horizontal linear positioning system would consist of two different actuators, mounted in a manner such that the horizontal actuator moves the vertical actuator back and forth inside STOUT. Once the vertical actuator is positioned by its counterpart, it will actuate the pinhole mount into position. Ideally, both motors would be able to move simultaneously. Shown below in Table 12 are the pros and cons of using this system.

Pros	Cons
Simple control algorithm Can easily block light not collected by pinhole	Vertical motor carries larger load Will require bracing to reduce vibrations

Table 12: Pros & Cons of a vertical and horizontal positioning system

3.1.3.2.2. Diagonal Linear Positioning

A diagonal positioning system would consist of two linear actuators mounted in the lower corners of the STOUT module. The two motors would work together in order to position the pinhole mount, both being able to pivot to accommodate the other actuators movements. This type of system would require a much more complex control algorithm than the vertical and horizontal positioning system, and may also require a custom pinhole mount, as most off the shelf units only have one mounting location. This system comes with the benefit of reduced vibrations, and lower actuator loads. Shown below in Table 13 are the pros and cons of such a system.

Pros	Cons
Uses least amount of space	Complex control algorithm Custom pinhole mount

Table 13: Pros & Cons of a diagonal positioning system

3.1.3.2.3. Actuator Types

Both of the above systems can utilize several different types of actuators, all of which have a large range of cost, accuracy, and positioning speed. The first type of actuator discussed is the induction stepping type. An example of a relatively middle of the road priced actuator, as well as a cheap actuator, are shown below in Figures 25 and 26 respectively.

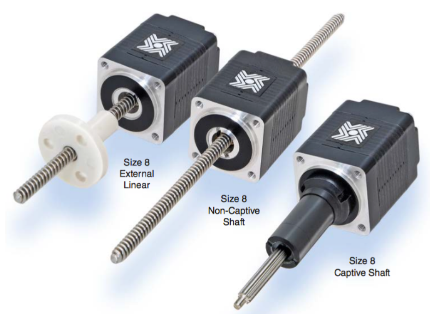

Figure 25: Example of an induction stepping actuator [38]

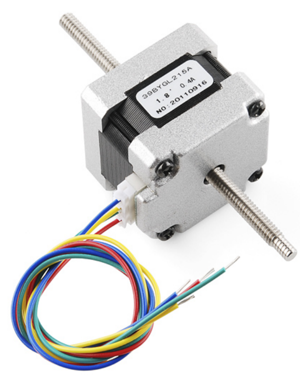

Figure 26: Example of a cheap stepping actuator [79]

Although many of the cheap actuators found quote accuracy equivalent to the more expensive versions, the validity of the claims, as well as the durability of the motors, is questionable. In addition, none of the cheap motors found have any indication that they would be able to operate in a high vacuum environment, such as the one that will be simulated to meet the customer requirement of operation at an altitude of 40 km. Although these actuators are slightly slower and less accurate than the types that will be discussed later, they do have the benefit of not requiring the use of a separate controller purchased from the manufacturer. Instead, a simple controller can be added to STOUT's power board, which would be controlled by the on board computer. Shown below in Tables 14 and 15 are the pros and cons of both the mid ranged and cheap versions of this actuator type, respectively.

Pros	Cons
Relatively inexpensive Fast accurate actuation Does not require OEM controller Vacuum compatible	Custom control circuit

Table 14: Pros & Cons of an induction stepping actuator

Pros	Cons
Fast actuation Cheap Does not require OEM controller	Questionable reliability Questionable accuracy No vacuum compatibility Custom control circuit

Table 15: Pros & Cons of a cheap induction stepping actuator

The next type of stepping actuator discussed is the piezo electric type. Although these motors carry a high price tag and require an OEM supplied controller, they are extremely accurate and have very fast actuation speed. Two different types of systems will be discussed. First, is a linear actuator similar in its action to the ones described above, shown below in Figure 27. The other type is an actuator that replaces the screws installed in a standard optics translation mount. The actuator and mount are shown below in Figures 28 and 30, respectively. Although an OEM supplied controller would likely increase the accuracy of the actuators tremendously, their drawbacks include their additional cost, lack of vacuum readiness, their large size, and their inability to control more than one actuator at a time. An example of an OEM controller is shown below in Figure 29.

Figure 27: Example of a piezo stepping motor [44]

Figure 28: Example of an optics mount motorized piezo actuator [59]

Figure 29: Example of an OEM supplied controller [27]

Figure 30: Example of a translation pinhole mount [89]

Shown below are the pros and cons of both a piezo stepping actuator and a motorized translation optics mount, in Tables 16 and 17, respectively.

Pros	**Cons**
Accuracy	Cost
Speed	OEM Controller
Positioning repeatability	Controller not vacuum compatible
Actuator vacuum compatible	Single controller only positions one actuator at a time

Table 16: Pros & Cons of a piezo stepping motor

Pros	**Cons**
Accuracy	Speed
Positioning repeatability	Cost
Actuator vacuum compatible	Single controller only positions one actuator at a time
Positioning repeatability	Not enough range
Off the shelf pinhole mount	

Table 17: Pros & Cons of an actuated translation mount

3.2. Environmental Monitoring and Control System

3.2.1. Insulation

Insulation will be an important passive aspect of the STOUT thermal system. Good insulation reduces the speed and magnitude of temperature changes, which is vital during a balloon flight to 40 km. Insulation will be especially important during the ascent and descent phases of flight, as temperatures can reach values of -70° F. It will be critical to regulate the temperature changes to prevent thermal stressing of the optical system and ensure the data acquisition system continues to function. Descriptions for several different insulation options can be seen below.

3.2.1.1. Space Blankets

Space blankets are made by spraying aluminum onto extremely thin plastic films. The result is a material which effectively reflects infrared radiation. They are commonly used on satellites as a radiative insulator, but are not designed to prevent conductive loses. Space blankets could be used along with another insulation option to provide radiative and conductive insulation, which are both necessary. [68]

Pros	Cons
Can be layered for better radiative insulation Lightweight and easily manipulated	Doesn't provide conductive insulation

Table 18: Pros & Cons of Space Blankets

3.2.1.2. Polystyrene Foam

Polystyrene is a rigid foam which is typically used for insulating the walls and roofs of houses. This form of plastic insulation is hard, brittle and has good shock absorption properties. It is also lightweight, inexpensive and tends to be sold in large quantities. [66]

Pros	Cons
Works well at low temperatures Good shock absorption properties	Prone to static electricity build-up Highly flammable without flame-retardant coating

Table 19: Pros & Cons of Polystyrene Foam

3.2.1.3. Polyisocyanurate Foam

Polyisocyanurate is similar to polystyrene in both structure and typical application. However, polyisocyanurate is denser, less flammable and has a lower thermal conductivity. [85]

Pros	Cons
Inexpensive Increased insulation qualities at low temperatures	Difficult to get in small quantities

Table 20: Pros & Cons of Polyisocyanurate Foam

3.2.1.4. Silica Aerogel

Silica aerogel is an ultralight material made up of approximately 98% air. This composition leads to very low thermal conductivity, making aerogels an excellent insulator. The structural qualities of silica aerogels vary greatly depending on their densities. Low density aerogels are spongy, delicate, and have a hard time supporting their own weight; high density aerogels are hard and rubbery. The production process for silica aerogels is quite complicated, which results in a large price-tag. However, they have been used in several aerospace applications. [72]

Pros	Cons
Lightweight Extremely low thermal conductivity	Expensive Easily fractured

Table 21: Pros & Cons of Silica Aerogel

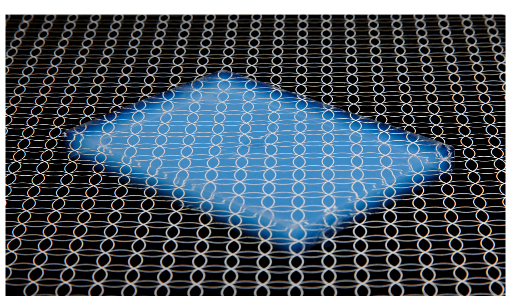

Figure 31: Silica aerogel panel [21]

3.2.1.5. *Vacuum Insulated Panels*

Vacuum insulated panels (VIPs) are made up of a gas-tight enclosure surrounding a rigid core. Air is evacuated from the enclosure, creating a vacuum. They have low thermal conductivity and are typically quite thin. If vacuum insulated panels are punctured in any way, they lose their insulating qualities. Thus, the size of any vacuum insulated panels cannot be modified after production. [67]

Pros	Cons
Low profile Low thermal conductivity	Expensive Cannot be manipulated

Table 22: Pros & Cons of Vacuum Insulated Panels

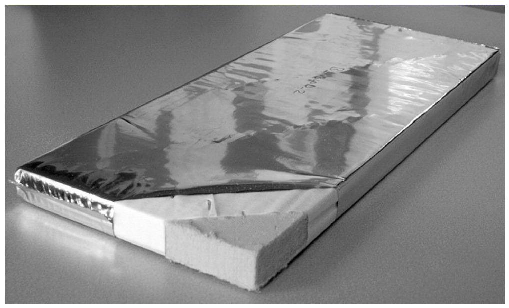

Figure 32: Vacuum insulated panel[86]

3.2.2. Active Control

In addition to insulation, STOUT will need an active thermal control system to provide heating and possibly cooling. Insulation alone will not be suitable for maintaining survivable temperatures within STOUT during ascent and descent. Additionally, the optical system will potentially need cooling as it receives focused radiation from the Sun. The active thermal control system will utilize data from temperature sensors to determine when heating or cooling is necessary. Possible options for active thermal control devices are described below.

3.2.2.1. *Point Resistive Heaters*

Point resistive heaters utilize the heat output of individual resistors to provide thermal control. They are extremely low-cost and easy to implement; the only necessary components are a voltage source and high-power resistors. RADIANCE's thermal system includes point resistive heaters. The main issue with this option is that the heat output is localized, which can result in uneven heating. [65]

Pros	Cons
Low cost Easy implementation and control	Heat output is localized Requires a moderate FOS on power output

Table 23: Pros & Cons of Point Resistive Heaters

3.2.2.2. *Pad Resistive Heaters*

Pad resistive heaters represent an improvement in the heat distribution of point resitive heaters. Instead of using individual resistors, a flexible pad with distributed restive lines is employed. This allows the heat release to spread out more and evenly heat the immediate area. [41]

Pros	Cons
Heat output is distributed Easy implementation and control	Requires a moderate FOS on power output

Table 24: Pros & Cons of Pad Resistive Heaters

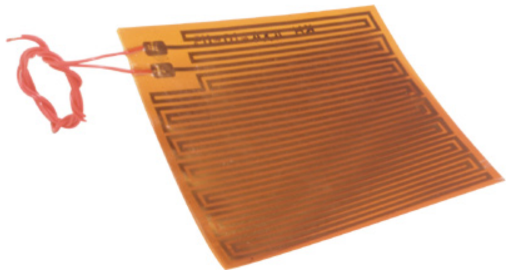

Figure 33: Pad resistive heater [41]

3.2.2.3. Peltier Devices

Peltier devices are also known as thermo-electric coolers; they operate according to the Peltier effect. This effect involves the transfer of heat between two electrical junctions. A voltage applied between two conductors creates an electric current. When this current flows through the junctions of the two conductors, heat is removed from one junction and deposited at the other. Peltier devices require a steady DC voltage and a heat sink to operate. [4]

Pros	**Cons**
Can provide heating or cooling	Requires a heat sink
High energy efficiency	Susceptible to cyclical stressing

Table 25: Pros & Cons of Peltier Devices

Figure 34: Peltier device [58]

3.2.2.4. Pumped Fluid Loops

Pumped fluid loops move heat via convection. A mechanical pump pushes a fluid from the area to be thermally controlled to a heat sink. The fluid obtains heat energy as it moves past the hot area and dissipates this heat when it reaches the heat sink. [17]

Pros	**Cons**
Tight temperature control	Requires additional hardware
Low power usage	Susceptible to leaks

Table 26: Pros & Cons of Pumped Fluid Loops

3.3. Attitude Determination System

3.3.1. Photodiodes

RADIANCE incorporated an ADS system consisting of four photodiodes placed 45 degrees off the spectrometer boresight, and developed an algorithm for attitude determination. Since STOUT is being integrated with RADIANCE, the current ADS systems on RADIANCE can be used and improved. Photodiodes are semi-conducting devices which generate a potential difference when exposed to light. These current outputs can be quantified by the following relationship:

$$I = I_{max}\cos(\theta)[32]$$

Where θ is the incidence angle on the photodiode. These sensors are extremely affordable, several dollars a sensor. However, these sensors are susceptible to noise, the Earth's albedo, and require an algorithm for attitude determination. Furthermore, the current ADS on RADIANCE was tested to plus/minus 1 degree (60 arcmin) accuracy and found that noise contributed less than 1% error. Although this accuracy is not within the attitude requirement of 0.05 deg (3 arcmin), it can be improved with further photodiode use, as well as expanding the photodiode algorithm.

Table 27: Pros & Cons of RADIANCE ADS

Pros	Cons
ADS Built Algorithm Developed Photodiodes Cheap	Accuracy Needs Improvement Susceptable to Noise

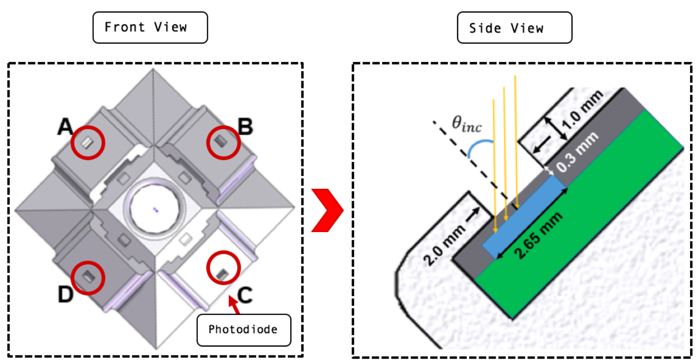

Figure 35: RADIANCE Photodiode ADS

3.3.2. Inertial Measurement Unit (IMUs)

Gyroscopes, acceleromteters, or Inertial Mass Units (IMU) are very useful options for determining attitude based on how the reference position changes with time. An IMU consists of three accelerometers to measure linear acceleration in all three axes, and three gyroscopes for three-axis angular velocity determination. Most models are extremely accurate for slight changes, but using them to determine the angular position over the course of the entire mission would require a secondary ADS to calibrate the system. Since the IMU only measures changes, which are numerically integrated to determine angular position, the process can become erroneous due to imperfections in the IMU resolution. Another issue with IMU's occurs when considering there are two concerned attitudes: that of STOUT and RADIANCE CubeSat, and the attitude of the telescope. Knowing the attitude of either does not necessarily tell if the telescope is pointing in the direction of the sun, and pre-programmed sun tracking data would be needed to determine the orientation of the telescope relative to the sun. Furthermore, if sun tracking data is incorporated into the ADS system, the IMU alone will be incapable of confirming if solar light is reaching the system. In summary, the ADS will be operating effectively "blind." In order to confirm sun pointing, the use of IMU's would most likely be integrated with photodiodes or a camera ADS.

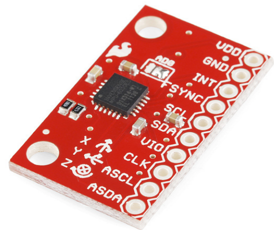

Figure 36: Typical Gyroscope/IMU Sensor [75]

Pros	Cons
Precise for small changes Easy to use	Needs to be calibrated Does not know location of the Sun Needs internal storage

Table 28: Pros & Cons of IMU

3.3.3. GPS

Another option for attitude determination is the use of a GPS receiver. This is a device capable of receiving information from GPS satellites and then calculating the device's geographical position. Since the primary goal of the ADS system is to locate and track the Sun, a GPS receiver would be used as a monitoring device for CubeSat altitude, rather than attitude. If incorporated for attitude determination, a database of Sun position with height at various times would need to be programmed into the DAQ system. A GPS device is easy to use and integrate into an electric power system, lightweight, but does come with several drawbacks. The cost of a GPS receiver can range from fifty dollars to several thousand, with cheaper models having lower positioning accuracy. Furthermore, for applications in this project, a GPS receiver would need to be integrated with a pre-loaded Solar positioning DAQ system. Lastly, due to COCOM regulations a GPS receiver stops receiving positioning information at 18 km, well below the missions flight window.[64]

Pros	Cons
Easy to Integrate Lightweight	Expensive Turns off at 18 km Needs extensive storage

Table 29: Pros & Cons of GPS Receiver

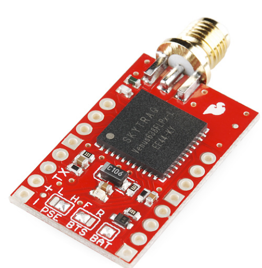

Figure 37: Typical GPS Receiver [76]

3.3.4. Camera

A camera would be an excellent option for ADS because it would work with the same principle as the photo diodes, but with far more data points as each data point would correspond to one pixel, instead of one photodiode. The camera would be mounted in the exact direction as the telescope, when the image of the Sun is centered in the camera's field of view, then the telescope would know that it is pointing directly at the Sun. The issue with a camera is that in order for it to be an accurate ADS, multiple images must be taken per second, which is a lot of data for the computer to process. This would require more computing power and a method to discard image data after it is used for ADS. Mounting the camera such that the direction it is pointing is the same as the telescope's direction will prove to be very challenging. Although this is challenging with photodiodes, the averaged data from multiple photodiodes can smooth out the error, whereas, if the camera is improperly mounted, the whole ADS system is erroneous.

Pros	Cons
Multiple brightness data points Variable field of view	Expensive Requires a lot of data to be processed Needs to be mounted perfectly

Table 30: Pros & Cons of Camera

3.4. Electrical Power System

3.4.1. Batteries

The driving requirement of the STOUT power system is providing uninterrupted and consistent power to the various instrument and processor components. Batteries perform the primary function of providing and maintaining the power supply to the other components of STOUT. Design of the STOUT power system batteries depends on one primary choice: should on-board batteries or gondola based battery systems be used. On-board batteries have many more configurations available, can be developed for CubeSat use, and are overall more flexible. However, they also add weight to the instrument body, take up space within the instrument, and are not provided by NASA free of charge. The gondola power supply is much less flexible, but it not have to be carried within the instrument, is tested for the thermal and environmental variations the balloon goes through, and is provided to scientific groups free of charge.

3.4.1.1. On-board Batteries

On-board batteries come in two main categories, primary (non-rechargeable) and secondary (rechargeable). Primary batteries are typically lighter and less expensive but have lower capacity and have variable voltage discharge as they go through their life cycle. Secondary batteries are more expensive and heavier, but they have more consistent discharge and higher voltages.

3.4.1.1.1. Non-rechargeable

Figure 38: Lithium-primary battery [69]

Primary, or non-rechargeable, batteries are used in a wide variety of everyday applications, particularly when recharging is impractical or impossible. Primary batteries are relatively light, hold higher storage than secondary batteries, and are cost efficient. Typical primary batteries include alkaline batteries and lithium-primary batteries. Specific characteristics of lithium-primary batteries can be seen below in Table 31.

Specification	**Value**
Nominal Voltage	3.0 V
Self Discharge	5 % p.m.
Operating Temperature	-30°C to 60 °C

Table 31: Table of selected Lithium-primary battery properties [46]

Pros and cons of on-board primary batteries are listed below in Table 32.

Pros	**Cons**
Performs well within temperature restrictions	Inconsistent voltage discharge throughout life
Cheap and light compared to rechargeable	Would need gondola for emergency power
Flexible in configuration	Would need replacement every use

Table 32: Pros & Cons of Primary Batteries

3.4.1.1.2. Rechargeable

Secondary, or rechargeable, batteries have a history of being used in space applications. While providing many benefits, rechargeable batteries would create issues within the instrument. Rechargeable batteries are relatively expensive and heavy compared to primary batteries, and additionally they would not be self-sufficient. Some interaction with the balloon gondola power system would be required to recharge the batteries. The batteries go through cycles of discharge and recharge where they lose between 20% to 40% efficiency during the recharging. Examples of widely used primary batteries include Nickel-Cadmium and Lithium-Ion.

Figure 39: Nickel-cadmium rechargeable battery [47].

Selected properties of nickel-cadmium batteries can be seen in Table 33. The batteries operate in the proper temperature range and would be relatively unaffected by self discharge.

Specification	**Value**
Nominal Voltage	1.2 V
Self Discharge	10 % p.m.
Operating Temperature	-20°C to 40 °C

Table 33: Table of selected Nickel-Cadmium battery properties [46]

Pros	Cons
Performs well within temperature restrictions Provides consistent voltage throughout battery life Flexible in configuration	Relatively heavy Requires connection to gondola to recharge Expensive

Table 34: Pros & Cons of Rechargeable batteries

3.4.1.2. Gondola Batteries

NASA provides battery packs available for scientific groups on balloons launched out of the Colombia Scientific Balloon Facility. [70] The provided battery packs contain G62 Lithium-Sulphur Dioxide batteries which are set into three different configurations. The available configurations are B7901-10, B7901-11, and B7901-12. The configurations contain 10, 11, and 12 G62 1 cell batteries respectively, provide nominal 30, 33, and 36 V, and they weigh 8.5, 9.0, and 9.5 pounds each. While this weight is quite a bit higher than the on-board battery weights, these batteries would not be housed within the instrument and would thus not contribute to the limited mass on-board. These batteries are designed to be used on the balloon gondola and have been tested and the requisite thermal and environmental conditions by NASA for use on their balloons. [70] While the G62 battery packs do not provide a clear basis for future CubeSat design, they provide a viable option for using the available on-board gondola power.

Specification	Value
Nominal Voltage	3 V
Typical Operating Voltage	2.65 to 2.80 V
Self Discharge	2 % p.a.
Operating Temperature	-50°C to 70 °C

Table 35: Table of selected G62 Lithium-Sulphur Dioxide battery properties [70]

Figure 40: Lithium-Sulphur Dioxide battery [56].

Pros	Cons
Provided by NASA for free Does not take any space or weight within the instrument Tested for thermal and environmental conditions	Only available in specific configurations Does not help future CubeSat design

Table 36: Pros & Cons of NASA G62 batteries

3.4.2. Power Boards

In order to distribute power to the system, it is vital for STOUT to have a printed circuit board. Printed circuit boards (PCBs) contain connects of electrical and electronics components through a thin layer of conducting material (typically copper) on a insulating substrate. Two primary techniques are used in order to connect the electrical components to the circuits: through-hole and surface-mount. Through-hole requires soldering both ends of a wire lead to components to ensure the connection. Surface-mount techniques involve many small leads getting soldered straight onto the circuit board which reduces the space needed for the circuit. This allows the board to execute at a lower weight and faster speeds than through-hole techniques. [24] There are three primary types of PCB: single sided, double sided, and multilayer.

3.4.2.1. Single sided PCB

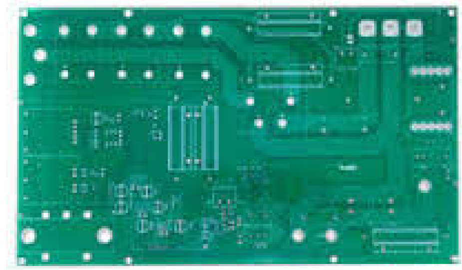

Figure 41: Example of a single sided PCB [30]

Single sided PCBs contains electric components and circuits on only one side of the insulating substrate. Single sided PCBs work best for easy electronics and as such it is typically used in introductory circuit electronics. These boards are much cheaper to mass produce than other varieties, however they are rarely implemented due to the design limitations of using only a single side.

Pros	Cons
Cheap to produce Easy to design for	Only simple designs are possible Impractical for in-depth designs

Table 37: Pros & Cons of single sided PCBs

3.4.2.2. Double sided PCB

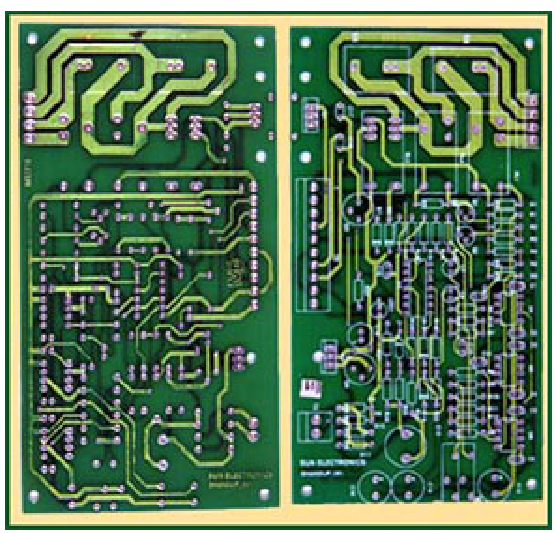

Figure 42: Example of a double sided PCB [57]

Double sided PCBs are much more common than single sided PCBs. For double sided PCBs, both sides of the substrate contain conductive layers and electronic components. The circuits on both sides are connected through holes in the substrate. Double sided PCBs are more expensive and harder to design for than single sided PCBs; however, their design flexibility, efficiency, and manufacturing familiarity makes them an important design option. RADIANCE used a double sided PCB, and circuit integration between two double sided PCBs should be more simple than with single sided or multilayer PCBs.

Pros	Cons
Allows for complicated designs Fairly compact	More expensive to manufacture Requires design integrating two sides

Table 38: Pros & Cons of double sided PCBs

3.4.2.3. Multilayer PCB

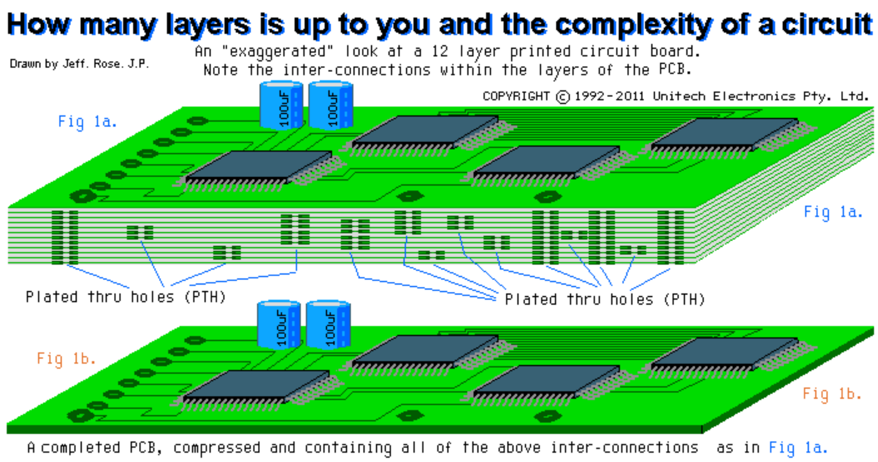

Figure 43: Example of a multilayer PCB [20]

Multilayer PCBs are similar to double sided PCBs, but they also include at least one conducting layer between the top and bottom sides of the PCB. These extra layers typically serve as power planes which provide the circuits with power and decrease the electromagnetic interference by placing signal levels into the power planes. Multilayer PCBs allow for highly complex, dense circuits but are also more expensive and harder to design for than single and double sided PCBs.

Pros	Cons
Allows dense, complex designs Separates power supply Reduces levels of EMI	Much more expensive Difficult to design for several levels.

Table 39: Pros & Cons of multilayer PCBs

3.5. Structural System

3.5.1. Aluminum 6061

The first material to consider is Aluminum 6061, a highly popular metal used in almost every facet of aerospace industry. Aluminum 6061 was originally called ”Alloy 61S” and was developed in 1935. It is commonly used for aircraft structures like wings and fuselages, boat construction, automotive chassis, flashlights, beverage cans and water bottles, Scuba tanks, bicycle frames, ultra-high vacuum chambers, rifle upper and lower receivers, firearm sound suppressors, and of course CubeSat structural components. The alloy composition of 6061 consists mostly of aluminum, silicon, iron, copper, manganese, magnesium, chromium, zinc, and titanium. The variety of metals that make up the alloy give it mostly desirable properties. As summarized below in Table 40, aluminum 6061 is lightweight, inexpensive, very corrosion resistant, easily machinable, highly weldable using TIG and MIG welding, easily extrudable, and suitable for hot forging. However, compared to other metals that will be considered, it is not very strong as the trade study will show. Aluminum 6061 also does not work well as thin sheet metal.

Pros	Cons
Lightweight Inexpensive Very corrosion resistant	Cannot be used as sheet metal

Table 40: Pros & Cons of Aluminum 6061

3.5.2. Aluminum 7075

The second material to consider is Aluminum 7075, another aluminum alloy that has a strong presence in the aerospace industry. Aluminum 7075 was developed in secret by Sumitomo Metal in 1943. It is commonly used in rock climbing equipment, bicycle components, hang glider airframes, M16 rifle upper and lower receivers, and sports equipment. The alloy composition is similar to 6061; it contains aluminum, zinc, magnesium, copper, silicon, iron, manganese, titanium, and chromium. As summarized below in Table 41, aluminum 7075 is lightweight, has strength comparable to steel, moderately corrosion resistant, average machinability, and highly polish-able. It is however much more expensive than typical aluminum 6061 and is brittle in comparison.

Pros	Cons
Lightweight Strong Corrosion Resistant	Brittle Moderately expensive

Table 41: Pros & Cons of Aluminum 7075

3.5.3. Titanium 6al-4v

The third metal to consider is Titanium 6al-4v. It is commonly used blades, airframes, fasteners, structural and surface components, biomedical implants, performance car components and spacecraft components. The titanium alloy consists of titanium, aluminum, and vandium. As summarized below in Table 42, titanium 6al-4v is lightweight, incredibly strong, highly corrosion resistant, and able to withstand extreme temperatures. However, it is very expensive limiting its use and is very difficult to machine.

Pros	Cons
Lightweight Incredibly strong	Expensive Very difficult to machine

Table 42: Pros & Cons of Titanium 6al-4v

3.5.4. Stainless Steel 15-5PH

The forth metal to consider is Stainless Steel 15-5PH. It is commonly used in gears, shafts, fittings, valves, and fasteners. The alloy consists of stainless steel, chromium, nickel, copper, carbon, manganese, phosphorus, sulfur, silicon, and columbium. As summarized below in Table 43, stainless steel 15-5PH is very strong, highly corrosion resistant, and able to withstand high pressure environments. However, it is expensive and not as easy to machine.

Pros	Cons
Very strong Highly corrosion resistant	Expensive Difficult to machine

Table 43: Pros & Cons of Stainless Steel 15-5PH

3.5.5. Nickel 718

The final metal to consider is Nickel 718, known more commonly as Inconel 718. It is used in settings where extreme pressure, heat, corrosion, and oxidation hazards are present. Common applications include heat exchanger tubing, pressure vessels, gas turbine blades, exhaust valves in Formula One and NASCAR cars. Its most famous applications include the skin used on the Mach 6.72 X-15 aircraft, chamber in the Saturn V rocket, and the engine manifold on the SpaceX Falcon 9 rocket. The Nickel 718 alloy consists of nickel, chromium, iron, molybdenum, niobium, cobalt, manganese, copper, aluminum, titanium, silicon, carbon, sulfur, phosphorus, and boron. As summarized below in Table 44, nickel 718 is very strong, highly corrosion resistant, creates a protective oxide layer when heated, retains its strength over a wide temperature range, and does not succumb to creep as a result of thermally induced crystal vacancies. However, it is incredibly difficult to machine as a result of work hardening, difficult to weld, and expensive.

Pros	Cons
Very strong Highly corrosion resistant Protective oxide layer	Difficult to machine Difficult to weld Expensive

Table 44: Pros & Cons of Nickel 718

3.6. Data Acquisition

3.6.1. Number of Processors

The number of processors used to accomplish memory management, thermal control, attitude determination, and pointing control is a critical design decision. A primary concern is the storage of the Raspberry Pi camera data. This operation stores a 5 megapixel resolution image onto the storage medium discussed in 3.6.3. This could cause a latency of up to 0.15 seconds [3]. Using only one processor will dramatically impact performance of the pointing control system. The thermal control system could still operate because thermal conditions don't require high levels of precision. Therefore, we consider the options of using one, two, or three processors.

3.6.1.1. One Processor

Using one processor greatly simplifies the problem. All data is read into and written to memory by this processor. This requires that the processor can handle writing data at the required rates. Then, the processor will need to determine control responses for the thermal system, calculate relative orientation to the sun, determine controls for the pointing system, and finally store the data when the sun is being scanned. This will create a complex analysis of time consumption by each system because the processor will be switching its attention between each task according to the operating systems process scheduler. This option introduces a single heat source on the processing side for thermal analysis which reduces complexity of the internal temperature profile. It requires a singular voltage supply.

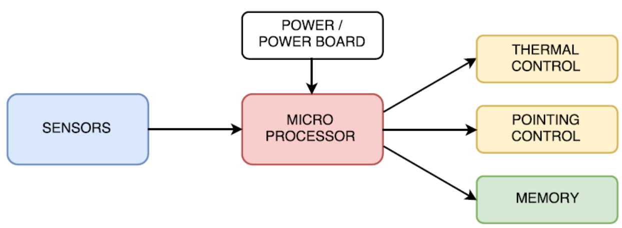

Figure 44: One Processor Layout

Pros	Cons
All information is centralized Reduced design complexity	Might have slow control responses Processor operates at max temperature

Table 45: Pros & Cons of One Processor

3.6.1.2. Two Processor

Two processors allow data storage and control computation to be divided into logical systems. This reduces latency from writing to memory. With this option, the two major control system responses can be computed simultaneously. In this configuration, the data for the thermal system (pressure and temperature) can be passed to one of the processors which will write it to memory and determine the thermal response for the current state. This processor will also handle writing the camera image because the thermal system doesn't require quick response. The other processor will read and store the attitude measurements from the photodiodes and compute the pointing response. This option will speed up the response time for the pointing system. It reduces the operating temperatures of the processors. Error recovery can be isolated to the individual processor and not cause the entire system to fail. However, it adds complexity to power supply and system communication.

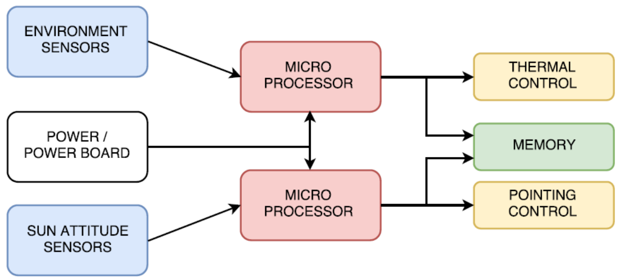

Figure 45: Two Processor Layout

Pros	Cons
The control systems can be divided Faster control response	Increased thermal complexity from two sources and their impact on each other More expensive

Table 46: Pros & Cons of Two Processors

3.6.1.3. Three Processor

Three processors allows data storage and control computation to be divided further. In the described configuration, the processor are divided to one of the following: data storage, thermal control, and attitude and pointing control. This option frees the two control system processors from having to write data. However, these two processors are still required to perform a read on the data so, the speed up comes strictly from preventing the interruption of calculations of attitude and control responses. This enables the fastest response time but, may be a waste of computing power. It reduces the operating temperatures of the processors. However, this reduction might not be significant compared to the heat produced by two processors. Again, any errors occurring during control response computation are isolated and the data can continue to be recorded. It adds complexity to power supply, system communication, and thermal modeling. It also requires a larger space allocation.

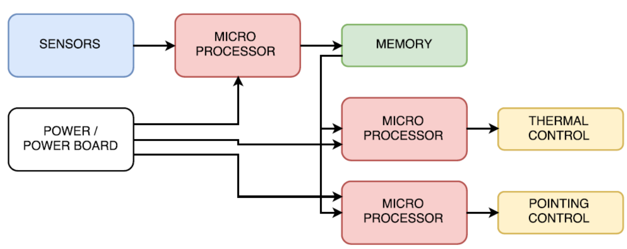

Figure 46: Three Processor Layout

Pros	Cons
Data storage separate from control response Faster control response System failures can occur in control systems and not affect data recording (good for post flight troubleshooting)	Most expensive Relies on storage medium for data access Space requirement is three times that of inherited RADIANCE project

Table 47: Pros & Cons of Three Processors

3.6.2. Processor

The processor is the electrical component that will run the software to control all systems and record data. These systems include the Environmental Monitoring and Control System and the Attitude determination system. The processor will have to measure and save six temperatures, a pressure, and attitude data at a sampling frequency of 1Hz and a Raspberry Pi camera image at a rate of 0.1Hz. Then, the processor will have to record the spectrometer data when the system is in position to make measurements. The processor must have the sufficient processing speeds to handle all of these things at the same time.

3.6.2.1. Microcontroller

The Raspberry Pi micro-controller is required to be used, so this system will contain at least one microcontroller. The microcontroller has sensor inputs and outputs. Most allow for digital I/O devices but, this project will require analog I/O as well. So, an Analog to Digital Converter (ADC) can be used to accommodate these microcontrollers. However, this makes the electronics in the system more complex and reduces parallizability. The Raspberry Pi from RADIANCE handles the temperature, pressure, camera, and attitude data, so their circuit designs could be extended to make another microcontroller compatible with the improvements made to the attitude sensor system. The Raspberry Pi contains a 1.2GHz 64bit Quad Core CPU.

Figure 47: Raspberry Pi 3 Microcontroller [63]

Pros	**Cons**
Already programmed and onboard RADIANCE Easy to replicate sensor input protocols	May not perform system response fast enough Writes to memory interrupt control computations

Table 48: Pros & Cons of Microcontroller

3.6.2.2. FPGA

A FPGA board (Field-Programmable Gate Array) is programmable hardware which can read sensors and execute processes and is extremely fast. This is very valuable for reading and analyzing the attitude data from the photodiodes. Theoretically, they could all be read and geometric computations could be done synchronously. This would allow the pointing control system to respond very fast. However, this hardware can be difficult to program because it requires knowledge of specific programming languages.

Figure 48: Altera Stratix IV FPGA [28]

Pros	Cons
Fast Processing Parallel Processing	Expensive for customer Hard to program Can't behave dynamically

Table 49: Pros & Cons of FPGA

3.6.2.3. Microcontroller + FPGA

The National Instruments myRIO board is a microcontroller and FPGA. These type of processors allows for a microcontroller to utilize the fast, parallel processing to accomplish more tasks. In our case, the FPGA would be used to read and process the attitude data. Then, the microcontroller could use this information to compute responses without having to write and read or pass through by data communication. Once again, the combination is more difficult to program. The NI myRIO, suggested and discussed with Trudy Schwartz, requires the software to be programmed in C or Labview.

Figure 49: NI myRIO microcontroller + FPGA [45]

Pros	Cons
Fast, Parallel Processing Handles simple and complex processes	Expensive Hard to program

Table 50: Pros & Cons of Microcontroller + FPGA

3.6.3. Storage Medium

The storage medium is the physical component that will store all of the data taken by the various sensors on STOUT. The storage medium is very important to STOUT because the whole reason of the flight is to obtain Solar UV data. Without the data the flight will be seen as a failure. The storage medium must be able to store all of the data taken in the duration of the flight, and survive all flight conditions, e.g. temperature. Most importantly the storage medium must be able to survive a 5g force of landing because above all else, the data must be recoverable. The medium used by RADIANCE is flash memory in the form of USB flash drives, however these may not have the capacity to store the amount of data STOUT needs to record.

3.6.3.1. Hard Disk Drives

Hard Disk Drives(HDD) are the type of hard drives found in most computers, and use a magnetic arm to read and store data on spinning rigid disks, and have two standard from factor sizes. The 2.5in form factor is 100mm by 69.85mm and the 3.5in form factor is 146mm by 101.6mm. They have quite a large data capacity, however take up a large amount of space because of all of the mechanical moving parts. The main concern with using a HDD for STOUT is the fact that it has a higher chance to break or corrupt the data upon landing, because of the mechanical parts. In a particularly hard landing, it is possible that the disks could collide inside the HDD enclosure which runs the risk of corrupting the data. Another benefit of using a HDD is the fact that they are becoming cheaper every year, so cost would be less of an issue. It is also worthy to mention that the transfer speeds of HDDs are slower than those of other storage media such as Solid State Drives. Typically HDDs are hardwired into the inside of a computer, but also come in external hard drive format, which connects to a computer via USB 3.0. Figure 50 is a picture of the inside of typical HDDs.[35][33]

Figure 50: Inside of typical HDD[35]

Pros	Cons
Low-Cost High Storage Capacity	Slower Transfer Speeds Lower Survivability Large

Table 51: Pros & Cons of HDD

3.6.3.2. Solid State Drive

Solid State Drives(SSD) are storage medium that do not operate with mechanically moving parts like a HDD, but rather utilizes flash memory to store data on an integrated circuit. SSDs are similar in size to HDDs, but since there are no moving internal parts, SSDs are much more shock resistant and have faster transfer speeds. The main benefit of using a SSD is the survivability, it has a much higher chance of keeping the data safe when shock loaded. SSDs have very large storage capabilities but are more expensive than HDD. SSDs can come in external hard drive format, connecting to the computer via USB 3.0, which is especially applicable to STOUT. Figure 51 shows the inside of a typical SSD.[34]

Figure 51: Inside of typical SSD[34]

Pros	Cons
Large Storage Capacity High Survivability Fast Transfer Speeds	Expensive Large Size

Table 52: Pros & Cons of SDD

3.6.3.3. Flash Drives

The last storage media considered are Flash Drives. Despite their small size, they have the capability to store a fairly large amount of data, which make them a very likely candidate for STOUT. Like SSDs, these storage devices utilize flash memory and therefore have no moving parts, giving them a high survivability factor. Devices like these come in the form of USB drives, which give them a high transfer speed as well as ease of connection. Flash Drives are able to handle a large amount of shock loading due to their size and mechanism, and would have the highest chance of preserving the data taken during the flight. The cost is highly dependent on the storage capacity, but in general they are much cheaper than SSDs. Flash drives also come in a variety of sizes, so fitting them onto STOUT would not be a problem. Figure 52 shows how small flash drives can be.

Figure 52: Low Profile Flash Drive[22]

Pros	Cons
Small Fast Transfer speeds Inexpensive High Survivability	Lower Storage Space

Table 53: Pros & Cons of Flash Drives

4. Trade Study Process and Results

The following section outlines the trade study process as well as the results of the trade study itself. For each design option category, a custom weighted matrix is developed for scoring. Then, each design option is weighted by the parameters set from the weight matrix and scored. Here, scores can range from 0-5, 5 being the ideal design option.

4.1. Instrument and Control

4.1.1. Lenses

At this point in the design process there are too many unknowns to provide a valuable trade study on lenses. The main factors effecting lens choice are price, transmission in the UV range, aberration correction, and available diameters and focal lengths. While it is generally true that out of the types considered plano-convex lenses are cheapest and achromatic lenses are the most expensive, prices vary by hundreds of dollars for different focal lengths and diameters. Rough calculations show that for the system to generate an image plane large enough to isolate a spot on the sun of significantly small size with a pinhole the lens diameter and focal length would have to be approximately 75mm and 100mm respectively. If this is the case aspheric and achromatic lenses might not be a viable option because they don't have long enough focal lengths. Therefore to make an informed decision the team needs access to high fidelity modeling in Zemax. Modeling is also needed to determine the effect of chromatic and spherical aberrations so that an accurate weighting can be assigned. For example, the aberration might not effect image quality enough to hinder the accuracy of spot isolation but it could have such a large effect that it must be accounted for to form any kind of clear image. The team has just not been provided the tools needed to determine this yet. Modeling would also be helpful to determine the weighting for the transmission category too. The spectrometer onboard RADIANCE is built to integrate measurements for as long as needed to achieve a signal to noise ratio of 200. Since STOUT aims to take measurements at multiple different spots on the sun and at multiple different polarization angles a short integration time is ideal. However, the sun's radiation intensity is already meager in the UV range and we have to block most of it to isolate a spot on the sun. If the power is too low and the spectrometer takes to long to take measurements and adding a larger diameter lens with high transmission could improve the integration time. Once more modeling work has been done on the optical system an in depth trade study on lenses will be provided.

4.1.2. Filters

Whether or not a filter is necessary to extinct stray light of wavelengths outside of the UV range is dependent on the transmission properties of the chosen lens. Ideally the the lens and polarizer will have such low transmission values outside of the UV range that a filter isn't necessary to efficiently extinct these signals. The customer provided polarizer operates in the 250nm - 4μm range and the extinction ratio increases exponentially at wavelengths above 300 nm. Coupled with a lens tailored to the UV light range a filter might not be necessary but more modeling work is needed to ultimately determine this. Once the lens trade study is complete the need for a filter will be investigated further.

4.1.3. Optical Mount

STOUT's main mission requires the focusing and data collected of polarized UV light. This is accomplished by focusing the UV light into the spectrometer on board RADIANCE. Specialized optics are required to accomplish this task. An optical mount will need to be utilized to ensure proper optical alignment during data collection. A misalignment of the optics could result in invalid data, and compromise STOUT's mission. A trade study was conducted to determine the best optical mount method. This trade study is comprised of 5 criteria: cost, stability, ease of use, component compatibility and optical alignment. This trade study and an explanation of its values can be seen in Tables 54 and 55. Stability is weighted the highest due to the STOUT's environment. The optics must be aligned at all times, and the alignment must withstand flight vibrations and landing impacts. This criteria should not be confused with optical alignment. The optical alignment covers how difficult it is to align the components in the mount. Ease of use is not a mandatory mission criteria, but it will make the vehicle construction smoother and more modular. Its low score is because it is not critical. The last criteria is the component compatibility, which covers the availability and reciprocity of the mounts.

Criteria (ranked by weight)		Optics Cage		Optics Bench		Optics Breadboard	
Cost	0.20	3	0.60	4	0.80	2	0.40
Stability	0.40	5	2.00	3	1.20	2	1.20
Ease of Use	0.05	3	0.15	3	0.15	5	0.25
Component Compatibility	0.20	4	0.80	3	0.60	3	0.60
Optical Alignment	0.15	5	0.75	3	0.45	2	0.30
Total	1.00		4.30		3.20		2.35

Table 54: Optic optical mount trade study

Value	Cost ($)	Stability	Ease of Use	Component Compatibility	Optical Alignment
1	>180	Small vibrations and movement cause complete optic misalignment	Requires custom machined parts Optics are secured in parts specific fittings Fittings require locking mechanism	Each Optical component requires an individual mount	Simple Optical alignment requires specialized equipment
2	160 to 180	Violent vibrations and movement cause complete optic misalignment	Requires some machined parts Optics are second in part specific fittings Fittings require locking mechanism	N/A	N/A
3	140 to 160	Small vibrations and movement cause no optic misalignment Violent vibrations and movement cause small optic misalignment	Requires no machined parts Optics are secured in part specific fittings Fittings require locking mechanism	Similar optical components use the same mount	Precise optical alignment requires specialized equipment
4	120 to 140	N/A	Requires no machined parts Optics are secured in generic fittings Fittings require locking mechanism	N/A	N/A
5	<120	All Vibrations and movement have no effect on optic alignment	Requires no machined parts Optics are secured in generic fittings Fittings do not require locking mechanism	All optical components use the same mount	Precise optical alignment does not require specialized equipment

Table 55: Values for each level in the optical mount trade study

From table 54, it is evident that the optics cage will best suit STOUTs mission.

4.1.4. Fiber Optic Cable

The main factors effecting the choice of fiber optic cable are price and degradation of transmission over time. Cables are hard to compare because the transmission degradation over time is wavelength dependent and input power dependent. The provided resources for the considered cables are not comprehensive with respect to these factors. The Thorlab's cable specifications lists input power but only shows the transmission degradation at 215 nm. The Newport cable specifications show the degradation of multiple wavelengths over time but the input power is not specified. The areas scored in this study are price and transmission degradation. The weighting for the two categories are given as:

Transmission degradation at 215nm (60%) is weighted the most heavily because the ultimate goal of the STOUT mission is to collect data over a two week flight. For a long duration UV observation the fiber optic cable needs to be resistant to solarization effects or the quality of data collected will decrease dramatically over the course of the flight.

Price (40%) is also weighted heavily because the majority of our budget needs to be reserved for high accuracy components for the instrument control and specialized UV optical components.

Criteria (ranked by weight)		Thorlabs		Newport	
Cost	0.40	4	1.60	3	0.40
Transmission degradation @ 215nm	0.60	1	1.80	1	0.60
Total	1.00		3.40		1.00

Table 56: Fiber optic cable trade study

Value	Cost ($)	Transmission Degradation @ 215nm (%)
1	> 400	< 60
2	300 to 400	70 to 60
3	200 to 300	80 to 70
4	100 to 200	90 to 80
5	< 100	> 90

Table 57: Values for each level in the fiber optic cable study

4.1.5. Polarizer Mounts

As previously stated, the main mission of STOUT is to map the magnetic field lines of the sun. This is accomplished by viewing polarized light with RADIANCE'S spectrometer. A rotating polarizer is used in order to produce a full range of polarization angle measurements.A trade study, seen in table 58, is comprised of three possible polarizer mount candidates. Table 75 outlines the values used in the trade study. The most important criteria in the study was the accuracy, however cost was a close second. The accuracy was specified by the customer and can be seen in the design requirements. The cost is a significant design criteria due to the price of the mounts. The rotation rate of the polarizer has a lower weight. This is because the rotation rate does not have a significant effect on the data gathering process. The last study criteria was how compatible each mount was with STOUT's mission and components.

Criteria (ranked by weight)		Stepper		Piezo		Belt Driven	
Cost	0.30	4	1.20	3	0.90	2	0.60
Compatibility	0.20	4	0.80	2	0.40	2	0.40
Accuracy	0.40	3	1.20	5	2.00	3	1.20
Rotation Rate	0.10	3	0.30	2	0.20	5	0.50
Total	1.00		3.50		3.50		2.70

Table 58: Polarizer Mount Trade Study

Value	Cost (Total with mounts)	Compatibility	Accuracy (minutes)	Rotation Rate (degree/s)
1	> 4000	No Controller Not Vacuum Compatible	> 8.4	$> 5E\text{-}3$
2	4000 to 3000	N/A	N/A	N/A
3	3000 to 2000	Controller Included Not Vacuum Compatible	> 0.90	> 2
4	2000 to 1000	N/A	N/A	N/A
5	< 1000	Controller Include Vacuum Compatible	> 0.18	> 5

Table 59: Values for each level in the polarizer mount study

As seen in Table 58, two mounts are suitable to be used with STOUT's polarizer. Each mount provides advantages, however the stepper seems most suitable for STOUT's needs. The stepper polarizer is initially more expensive than the piezo, however it does not require a separate controller. The piezo control unit would add roughly $1000 to the cost of the component. The accuracy of the studied stepper is significantly lower than the accuracy of the studied piezo, however it still falls within the design requirements set by the customer. With this is mind, the stepper motor should be selected for use on board STOUT.

4.1.6. Pinhole Actuators

Shown below in Table 60 is an explanation of the scores given for different value ranges for actuator and system types. The area scored are the following: cost per actuator, accuracy, controller requirements, vacuum compatibility, pinhole mounting options, actuator range, and actuator speed.

Value	Cost ($)	Accuracy (um)	Controller	Vacuum Capability	Pinhole Mounting	Range (mm)	Speed (mm/s)
1	> 800	> 10	OEM Required	Not Vacuum compatible	Requires actuated mount	< 5	< 1
2	600 to 800	5 to 10	N/A	No vacuum rating	N/A	5 to 10	1 to 2
3	400 to 600	2.5 to 5	Team Assembled	Vacuum modifiable	Custom Mount	10 to 15	2 to 4
4	200 to 400	1 to 2.5	N/A	Vacuum available (OEM)	N/A	15 to 20	4 to 5
5	< 200	< 1	Build In	Vacuum Ready	Standard cage/post mount	> 20	> 5

Table 60: Values for each level in the pinhole actuator trade study

The following explains the weighting given to each of the different categories:

Accuracy (25%) received the highest weighting as it is considered to be vital to the ability for STOUT to take precise spectrometer readings of the sun. Without a high degree of accuracy, the science value of any measurements taken is greatly reduced, as the area of the sun being measured is not known with certainty.

Range (20%) received the second highest rating because an increased range in the actuator increases the size of an image plane that it can cover. I larger image plane translates to a larger viewing area of the sky, meaning that measurements can be taken for longer periods of the mission profile.

Controller (15%) tied with cost for the third highest weighting because an OEM required controller would significantly increase the cost and complexity of STOUT. OEM required controllers typically run above $1000, and are large and not compatible with a vacuum environment. Ideally actuators would allow for simple circuitry to control the unit, or a small built in controller.

Cost (15%) is ranked mid way through the range of ratings. While cost is a very important aspect of staying on budget for this project, the requirements simply cannot be met without the required level of accuracy from the actuators.

Pinhole mounting (10%) is weighted low in comparison to the above categories because the overall cost and complexity of the pinhole actuation system does not depend heavily on this factor. While an actuated mount would raise costs, it would not be significant compared to the price of a controller. In addition, post mounted and custom solutions are very cheap and readily available.

Speed (10%) received the weighting it did because while it is an important aspect of an actuators performance, it is not nearly as important as the above categories. Speeds above 1-2 mm/s should be more than sufficient for our purposes, so an increase in speed over this does not provide much benefit.

Vacuum readiness (5%) received the lowest rating due to the fact that most vacuum rated components are rated well below the operating pressures STOUT is expected to experience. Having vacuum readiness would only increase the reliability of the actuation system, not necessarily whether it can function at all. In addition, vacuum rating an actuator can increase its cost by over three times, putting most of the studied components well outside the projects budget.

Shown below in Table 61 is the trade study conducted for the pinhole actuation system. Seven different combinations of actuator type and system type were studied. Both the vertical/horizontal actuation method and the diagonal actuation method were studied for both types of induction actuators, as well as the piezo actuator. The motorized translation mount was only studied with one type of actuator, as it is the only actuator type compatible with this method. The score for each system's respective categories was multiplied by that categories weighting and summed in order to obtain the final score of the system. Note that each type of actuator scored relatively similar to each other across the different actuation methods. This indicates that there is certainly an optimal actuator type from this study, but further studies will need to be carried out in the future to determine the ideal method for actuation.

Criteria (Ranked by Weight)		V/H Linear Piezo		V/H Linear Induction		Diagonal Linear Piezo		Diagonal Linear Induction		Motorized Translation Mount		V/H Cheap Linear Induction		Diagonal Cheap Linear Induction	
Accuracy	0.25	5	1.25	4	1.00	5	1.25	4	1.00	5	1.25	1	0.25	1	0.25
Range	0.20	5	1.00	5	1.00	5	1.00	5	1.00	2	0.40	5	1.00	5	1.00
Controller	0.15	1	0.15	3	0.45	1	0.15	3	0.45	1	0.15	3	0.45	3	0.45
Cost	0.15	1	0.15	4	0.60	1	0.15	4	0.60	3	0.45	5	0.75	5	0.75
Pinhole Mounting	0.10	5	0.50	5	0.50	3	0.30	3	0.30	1	0.10	5	0.50	3	0.30
Speed	0.10	4	0.40	3	0.30	4	0.40	3	0.30	1	0.10	2	0.20	2	0.20
Vacuum Readiness	0.05	2	0.10	4	0.20	2	0.10	4	0.20	5	0.25	1	0.05	1	0.05
Total	1.00		3.55		4.05		3.35		3.85		2.70		3.20		3.00

Table 61: Trade study of different pinhole actuation methods

4.2. Environmental Monitoring and Control System

The Environmental Monitoring and Control System is vital to the success of the each of the other components of STOUT. Temperature, pressure, and possibly humidity sensors will be utilized to monitor the interior conditions of STOUT. Insulation will be used to reduce the magnitude of temperature changes that STOUT will experience. An active thermal control system system will be used to provide heating and possibly cooling for the optical instruments. The trade studies for the insulation and active thermal control system options considered can be seen below.

4.2.1. Insulation

Insulation will help keep the heat produced from the active thermal control system within STOUT. It will also reduce the speed at which its temperature changes, especially during the extremes of ascent and descent. The trade study for insulation involves five different parameters: thermal conductivity, work-ability, cost, vacuum rating, and structural durability. The most important parameter for the trade study is thermal conductivity; this is the ability for a material to conduct heat. Thus, a lower value of thermal conductivity means that heat transfer occurs at a lower rate. Low conductivity insulation is therefore desirable for STOUT. Work-ability is also a critical element for the insulation. The selected insulation needs to be able to be modified in order to find inside the 10 x 10 x 30 cm structure. Additionally, the insulation may need to be modified into strange shapes to accommodate the components. Due to the budget constraints of the project, cost is also a relatively important consideration for the insulation. Some of the options are very cheap while others are cutting-edge and extremely expensive. Of lesser importance are vacuum rating and structural durability. STOUT needs to be able to operate in a near-vacuum environment, so it would be ideal to have insulation which has been proven under such conditions. Structural durability needs to be considered so the insulation remains intact during testing and its eventual flight. Table 62 shows the result of the trade study for insulation. Note that a 5 in the table denotes to most ideal case while a 1 is the least ideal.

Criteria (ranked by weight)		Polystyrene		Polyisocyanurate		Silica Aerogel		VIPs		Space Blankets	
Thermal Conductivity	0.35	3	1.05	3	1.40	5	1.75	4	1.40	0	0.00
Work-ability	0.25	4	1.00	4	1.00	3	0.75	1	0.25	5	1.25
Cost	0.20	4	0.80	4	0.80	1	0.20	2	0.40	5	1.00
Vacuum Rating	0.10	3	0.30	3	0.30	5	0.50	3	0.30	5	0.50
Structural Durability	0.10	3	0.30	3	0.30	2	0.20	2	0.20	4	0.40
Total	1.00		3.45		3.80		3.40		2.55		3.15

Table 62: Trade Study of Options for STOUT Insulation

A breakdown for the scoring in this trade study can be seen in Table 63.

Value	k (W/(m·K))	Work-ability	Cost ($/m^2)	Vacuum Rating	Structure Durability
1	0.06 to 0.05	Not workable	> 1000	Not vacuum capable	Very low strength
2	0.05 to 0.04	Minimally workable	100 to 1000	N/A	Easily damaged
3	0.04 to 0.03	Workable	10 to 100	Vacuum capable	Moderate strength
4	0.03 to 0.02	Minimal limitations	1 to 10	N/A	Not easily damaged
5	< 0.02	Easily workable	< 1	Vacuum proven	High strength

Table 63: Explanation of Trade Study Scoring for Insulation

4.2.2. Active Control

An active thermal control system will provide real-time heating and cooling (if necessary) to STOUT. The temperature will be monitored in STOUT which will provide feedback to the selected active thermal system. The trade study for this part of STOUT's EMCS has five relevant parameters: functionality, cost, ease of implementation, reliability, and vacuum rating. Functionality is the most important parameter. It would be ideal to have an active thermal control system which allows for distributed, variable, and precise temperature control. Otherwise, some parts of STOUT will not receive the thermal management they need. The next most critical aspect is the cost. As stated previously, the EMCS should not account for a large portion of the overall budget. A lower price for the active control system will open up more funds for the structure and optical elements of STOUT. Ease of implementation is also important. Some active thermal systems require additional hardware such as heat sinks. Ideally, the selected system will involve a minimal amount of components; this will allow for more space within STOUT and take less time to create. Less important is the reliability of the active thermal system. Systems which are prone to malfunctions will not be optimal for STOUT's eventual flight. Just as for the insulation, vacuum applicability should also be considered. Table 64 below shows the completed trade study for the active thermal control system options.

Criteria (ranked by weight)		Point Res. Heaters		Pad Res. Heaters		Peltier Devices		Pumped Fluid Loops	
Functionality	0.30	3	0.90	4	1.20	3	0.90	4	1.20
Cost	0.25	5	1.25	3	0.75	4	1.00	2	0.50
Ease of Implementation	0.25	5	1.25	5	1.25	2	0.50	1	0.25
Reliability	0.10	3	0.30	5	0.50	3	0.30	1	0.10
Vacuum Rating	0.10	5	0.50	5	0.50	5	0.50	3	0.30
Total	1.00		4.20		4.20		3.20		2.35

Table 64: Trade Study for STOUT Active Thermal Control System

Value	Functionality	Cost per Unit ($)	Ease of Implementation	Reliability	Vacuum rating
1	Fixed, Point Heating or Cooling	> 100	Significant additional hardware needed	High potential for problems	Not vacuum capable
2	Fixed, Dispersed Heating or Cooling	50 to 100	Some additional hardware needed	N/A	N/A
3	Variable, Point Heating or Cooling	20 to 50	Can't receive pulsed power	Medium potential for problems	Vacuum capable
4	Variable Distributed Heating or Cooling	5 to 20	Can be driven easily	N/A	N/A
5	Variable, Distributed Heating and Cooling	< 5	Plug and play	Minimum potential for problems	Vacuum proven

Table 65: Explanation of Trade Study Scoring for Active Thermal Control System

4.3. Attitude Determination System

The attitude determination system is critical for both obtaining orientation data and understanding how it varies over time. For this project in particular, attitude is the orientation of STOUT relative to the location of the Sun. Therefore, knowing the position and pointing of STOUT relative to the sun is paramount, and without an effective ADS the mission of the project is un-achievable. As a result, it is important to choose an accurate and robust ADS. For this trade study, the parameters of cost, mass, accuracy, mission operation, and integration were used to score the design options. The first weighting factor is cost. Since the main objective of STOUT is to measure polarized UV spectrum light, it can be expected that a significant portion of the project's budget will be allocated to optics instrumentation. In this trade study, cost was considered the second highest factor. As a result, lower costing ADS design options are ideal. Next, the mass of the design options was considered a design factor. Since STOUT will be transported to 40 km by a NASA weather balloon, NASA governed weight limits and restrictions must be met. Therefore, the lower the mass the better. However, since STOUT is being integrated with RADIANCE, and certain redundant systems have the potential to be removed, mass is not the most pressing design factor. Furthermore, many of the ADS design options are relatively lightweight (no more than 60 grams). Considering this information, mass was weighted the least of the design factors. Third, ADS accuracy was weighted as a design factor. Since the pointing accuracy of STOUT is required to a precise degree (+/- 3 arcmin) an accurate ADS system is paramount to mission success. The ADS must be accurate enough to both locate the sun, but also determine the system's orientation relative to the sun. Therefore, this design factor was weighted the highest. Additionally, mission operation was considered a design factor. This factor accounts for the operation of ADS systems during ascent, float, and ascent. A poor design option is one which wouldn't operate during float, while an excellent operation would work during ascent, float, and descent. This factor was weighted as the third most important factor largely due to the fact that cost and accuracy are much more pressing. Lastly, design integration was a pressing factor and was ranked equally as the third highest with mission operation. This factor weighted the complexity of integrating the option into the ADS system. A poor integration design option is one in which requires an ADS algorithm to be built and/or cannot determine sun location alone. An excellent design option would be one that requires little to no ADS algorithm development and can determine the location of the sun and STOUTS relative orientation.

Criteria (ranked by weight)		RADIANCE ADS		Gyroscope/IMU		GPS Reciver		Camera	
Cost	0.225	4	0.90	3	0.675	3	0.675	4	0.90
Mass	0.05	3	0.15	5	0.25	5	0.25	5	0.25
Accuracy	0.325	5	1.625	1	0.325	1	0.325	5	1.625
Mission Operation	0.20	4	0.80	2	0.40	2	0.40	5	1.00
Integration	0.20	3	0.60	1	0.20	1	0.20	1	0.20
Total	1.00		4.075		1.85		1.85		3.975

Table 66: Trade Study of ADS Design Options

Value	Cost ($)	Mass (g)	Accuracy	Mission Life Operation	Integration
1	≥ 80	≥ 150	Sensor needs to be integrated with 1 or more additional sensor, and Solar database	Operate During Ascent	ADS algorithm will need to be developed
2	80 to 60	150 to 100	Sensor needs to be integrated with Solar database	Operate During Ascent & Float	N/A
3	60 to 40	100 to 60	Sensor independently locates sun	N/A	ADS algorithm will need to be enhanced
4	40 to 20	60 to 35	Sensor Independently locates sun w/ pointing accuracy $<\pm$ 0.05 deg (3 arcmin)	Operate During Float	N/A
5	< 20	< 35	Sensor Independently locates sun w/ pointing accuracy $>\pm$ 0.05 deg (3 arcmin)	Operate During Ascent, Float, and Descent	No ADS algorithm will need to be developed

Table 67: Explanation of Trade Study Scoring for ADS Design Options

4.4. Electrical Power System

4.4.1. Batteries

For the battery trade study, parameters of cost, weight, voltage consistency, and configuration flexibility were used to score the design options. The first and largest weighted category is cost. The EPS is a support system on STOUT and as such can only support a small percentage of the budget. Thus, the most important criteria for the batteries is cost. The second category of criteria is weight. There is a strict weight limit for STOUT if it is to fly on the NASA gondola and an even more strict requirement for CubeSat development. Weight is the second most highly weighted criteria. Voltage consistency is the third criteria, and it focuses on the reliability of the battery voltage output throughout a discharge. If the voltage output changes, some of the vital components to STOUT might not receive enough power. The final, and lightest weighted, criteria is configuration flexibility. This criteria defines the number of configurations that the batteries can be placed in to vary the input current and voltage to STOUT.

Criteria (ranked by weight)		Primary		Secondary		G62 Gondola	
Cost	0.45	4	1.80	2	0.90	5	2.25
Weight	0.30	2	0.60	1	0.30	5	1.50
Voltage Consistency	0.15	1	0.15	4	0.60	5	0.75
Configuration Flexibility	0.10	4	0.40	4	0.40	2	0.20
Total	1.00		2.95		2.20		4.70

Table 68: Battery Trade Study

A breakdown for the scoring in this trade study can be seen in Table 69.

Value	Cost ($)	Weight (lbs)	Voltage Consistency	Configuration Flexibility
1	>150	> 4	Battery needs to operate consistently for the first quarter of discharge	1 configuration
2	150 to 100	4 to 3	Battery needs to operate consistently for the first half of discharge	2 to 3 configurations
3	100 to 50	3 to 2	Battery needs to operate consistently for the first three quarters of discharge	4 to 7 configurations
4	50 to 25	2 to 1	Battery needs to operate consistently throughout discharge	8+ configurations
5	< 25	< 1	Battery needs to operate consistently throughout discharge and recharge	No specific configuration needed

Table 69: Explanation of Trade Study Scoring for Battery Options

4.5. Structural Systems

4.5.1. Materials

The structure of the STOUT system is key to the overall deisgn, as it is responsible for containing all other STOUT subsystems as well as mounting to the existing RADIANCE system and the NASA WASP high-altitude balloon. When designing the structure of STOUT, the first aspect to consider is the material that is to be used. There are a variety of materials that are possible. The trade study, shown below in Table 70, compares five different metals that have a presence in the Aerospace Engineering field due to their desired properties: Aluminum 6061, Aluminum 7075, Titanium al6-4v, Stainless Steel 15-5PH, and Nickel 718 (Inconel 718). The material which is determined best suited for the STOUT structure is selected using the following criteria, which are weighed more or less given the needs and requirements for the STOUT project. The primary design driver of the structure is the material cost. Since there is a limited project budget, cost is the most important of the criteria. For this reason, it is weighed at a hefty 35%. The second most important driver is the manufacturability. Because of cost restraints, the STOUT structure will have to be manufactured in-house using the ITLL machine shop. It is simply not feasible to have the parts custom ordered. Since the metal will have to be machined in-house, the material chosen should be easy to machine and work with. It must also be compatible with the tooling available in the ITLL machine shop; attempting to machine a material that is not compatible will wear down or break tooling. Given the need to machine in-house, manufacturability commands 20%. The third and forth most important design driver is the strength of the material used; namely the tensile and shear strength. The structure of STOUT does not need to endure much stress, ultimately. Certain components will bear most of the stress, like the mounting tabs that connect the STOUT/RADIANCE systems to the WASP gondola. The material chosen must be able to meet the strength requirements specified by NASA; able to handle a 5g vertical and 7g lateral acceleration/deceleration. Most aerospace-proven metals will exceed the requirements if designed correctly. The tensile and shear strength each command 10%. Relating to manufacturability is familiarity. This design driver is quantifies how familiar the team is with each material. Familiarity is important because it concerns the manufacture, handling, etc. Familiarity commands 10%. The last three design drivers are still important, but not critical to mission success. Each commands a weight of 5%. The density of the material is important because it is closely related to total weight. While a material with a lower density may initially sound like less weight, it may also be weaker, requiring more mass to equal a material that is more dense, but much stronger. The thermal conductivity of the structure are important to the thermal model and how heat will transfer about the STOUT subsystems. However, due to the amount of unknowns, thermal conductivity was not weighted highly. Corrosion resistance also plays an important part in the structure. STOUT may be subjected to a variety of environments; each with different conditions that may prevent or enable corrosion. The flight at high altitude will subject STOUT to a thin atmosphere, where there is little moisture to enable corrosion. However, upon descent, the gondola may contact a body of water, which certainly will enable corrosion. While corrosion appears to be highly important, the materials chosen are aerospace proven and not likely to corrode due to properties of each alloy.

Criteria (ranked by weight)		Aluminum 6061		Aluminum 7075		Titanium 6al-4v		Stainless Steel 15-5PH		Nickel 718	
Cost	0.35	5	1.75	4	1.40	1	0.35	2	0.70	1	0.35
Manufacturability	0.20	4	0.80	4	0.80	1	0.20	3	0.60	2	0.40
Tensile Strength	0.10	1	0.10	3	0.30	4	0.40	5	0.50	5	0.50
Shear Strength	0.10	1	0.10	2	0.20	3	0.30	4	0.40	4	0.40
Familiarity	0.10	5	0.50	4	0.40	1	0.10	3	0.30	2	0.20
Density	0.05	4	0.20	4	0.20	3	0.15	2	0.10	1	0.05
Thermal Conductivity	0.05	1	0.05	2	0.10	5	0.25	5	0.25	5	0.25
Corrosion Resistance	0.05	5	0.25	4	0.20	3	0.15	5	0.25	4	0.20
Total	1.00		3.75		3.60		1.90		3.10		2.35

Table 70: Trade Study of Materials for STOUT Structure

Value	Cost ($/lb)	Manufacturability	Tesnile Strength (MPa)	Shear Strength
1	< 6	Requires outsourcing to have component manufactured	< 300	< 200
2	6 to 10	Very difficult material to machine	300 to 500	200 to 400
3	10 to 30	Difficult material to machine	500 to 700	400 to 600
4	30 to 50	Moderately difficult material to machine	700 to 900	600 to 800
5	> 50	Easy material to machine	> 900	> 800

Value	Familiarity	Density (g/cm^3)	Thermal Conductivity (W/m/K)	Corrosion Resistance
1	No experience with material	> 8	> 150	Not corrosion resistant
2	Knowledge of material	8 to 6	150 to 100	Slightly corrosion resistant
3	Used material before	6 to 4	100 to 75	Moderately corrosion resistant
4	Very experienced with material	4 to 2	75 to 50	Highly corrosion resistant
5	Expert with material	< 2	< 50	Extremely corrosion resistant

Table 71: Explanation of Trade Study Scoring for Structural Materials

As can be seen in Table 70, the material to be chosen is Aluminum 6061. The desired qualities and low cost are proven though aerospace and CubeSat heritage. Aluminum 6061 has a proven track record as a material that is light, strong, inexpensive, as well as very easy to work with. Aluminum 7075 stronger, but has the disadvantage of increased cost. While the Titanium al6-4v alloy combines the qualities of being lightweight and incredibly strong, it is very costly and difficult to machine. Stainless Steel 15-5PH and Nickel 718 are both resistant to corrosion, but are costly and can be difficult to machine.

4.6. Data Acquisition

4.6.1. Number of Processors

The number of processors trade study aims to determine if a singular processor is the best solution for our requirements of recording data and operating the thermal and pointing control systems. Division of processing is the primary factor (50%) because the goal of this trade study is to spread out the processing required for each system. Next, the cost (30%) is included to make sure that the solution's cost is reasonable. Then, the complexity (20%) is included because with more processors, there will be more reads, writes, and communications between memory and processor.

Criteria (ranked by weight)		One Processor		Two Processors		Three Processors	
Division of Processing	0.50	1	0.50	4	2.00	5	2.50
Cost	0.30	5	1.50	3	0.90	1	0.30
Complexity	0.20	5	1.00	3	0.60	2	0.40
Total	1.00		3.00		3.50		3.20

Table 72: Number of Processors Trade Study

Value	Division of Processing	Cost ($)	Complexity
1	Writes and Computation by one	> 500	Share Memory Across All Devices
2	Writes by two, Computation by one	500 to 400	Access from Same Location
3	Writes Dependent, Computation by two	400 to 300	Store and Access from Same Location
4	Writes and Computation Independent	300 to 200	Add without Intercommunication
5	Write Independent of Computation	< 200	Nothing to Add

Table 73: Values for each level in the polarizer mount study

4.6.2. Processors

The processor trade study is used to determine the most effective processor type to handle the writes and computations of the control systems. RADIANCE's primary factor in this trade study was power consumption. However, STOUT is being provided with enough batteries from NASA to ensure full power throughout flight. Therefore, the processor's primary goal is to store the data and compute the thermal and pointing control systems response at the necessary speeds: quick for pointing and slower for thermal. So, processing power (50%) is the most important because it has the greatest impact on system response calculations. Next, the ability to parallelize (30%) operations is included because this allows the processor to write to memory and compute control responses simultaneous which is crucial for fast response times. Then, the cost (10%) is included because the telescope and pointing system already take a large portion of the budget and processors are expensive. However, CU offers lots of resources for processors and we could definitely find one to use for the project and tell the customer our plan. Finally, the compatibility (10%) is included because it needs to interface with the Raspberry Pi from RADIANCE. However, this compatibility will be achievable with almost all choices.

Criteria (ranked by weight)		Microcontroller		FPGA		Microcontroller + FPGA	
Processing Power	0.50	2	1.0	3	1.50	5	2.50
Parallelizable	0.30	3	0.90	4	1.20	5	1.50
Cost	0.10	5	0.50	3	0.30	2	0.20
Compatibility	0.10	5	0.50	3	0.30	3	0.30
Total	1.00		2.90		3.30		4.50

Table 74: Processors Trade Study

Value	Processing Power	Parallelizable	Cost	Compatibility
1	Single Software Process	None	$> \$1000$	Not Compatible
2	Multiple Software, Single Hardware	2 Processes	\$750 to \$1000	Extremely Difficult
3	Single Software, Multiple Hardware	4 Processes	\$500 to \$750	Difficult
4	Multiple Software, Multiple Hardware, not connected	More than 4 hardware processes	\$500 to \$250	Research Available
5	Multiple Software, Multiple Hardware	More than 4 hardware processes Multiple software processes	<\$250	No Difficulty

Table 75: Values for each level in the polarizer mount study

4.6.3. Storage Medium

In order to decide what type of storage medium to implement into STOUT's design, a trade study was conducted using five different criteria. The different criteria and explanation of scoring can be seen in Table 77. The most important factor chosen for this trade study is the Survivability of landing, and was weighted at 30%. This was chosen to be the most important factor because the data is the main purpose of the mission, and above all else needs to be recovered. Various different HDDs, SSDs, and flash drives were researched to determint their relative shock resistance, which is given in Gs. For most SSDs, the shock resistance was found to be rated to at least 1000G of shock loading, and every flash drive researched had a rating of 1500G. The shock rating for HDDs varied with whether or not the device was operating, storage capacity, and size of hard drive, but ratings as low as 40G were found for HDDs. Values typically found were anywhere in between 200-1000G [15][26][29][48][49][84]. The next highest weighting factor was how much data the storage medium could hold, and was weighted at 25%. At this point in the design process it is unknown how much total data will be taken on the flight, so it is important to maximize capacity. Some very basic calculations were done to determine roughly the order of magnitude of data that will be taken, and it was determined that the upper limit will be in the hundreds of gigabytes. The third factor considered was price, and was weighted at 20%. Storage medium is far from the most expensive component of STOUT, but it is important to minimize cost because of the limited project budget. The fourth factor, rated at 15%, is the physical size of the storage medium. Since the STOUT module is designed to be a 3U Cube-Sat(10cmX10cmX30cm), there is limited space inside of STOUT and it is necessary to get the smallest components that still meet the requirements. The fifth and final factor used in the trade study for storage medium is the transfer speed of the media, specifically the write speed. Since most of the data will simply be recorded and saved, the data write speed of various media was considered. The DAQ system will not only have to save spectrometer data, but also monitor environmental data and attitude data all at the same time. For this reason it is important to consider how fast the system can save the data. The results of the trade study can be seen below in Table 76.

Criteria (ranked by weight)		Hard Disk Drive		Solid State Drive		Flash Drive	
Survivability	0.30	3	0.90	4	1.20	5	1.50
Storage Capacity	0.25	5	1.25	5	1.25	2	0.50
Price	0.20	4	0.80	2	0.40	5	1.00
Size	0.15	2	0.30	4	0.60	5	0.75
Transfer Speeds	0.10	3	0.30	5	0.50	3	0.30
Totals	1.00		3.55		3.95		4.05

Table 76: Trade Study for Storage Medium

Value	Survivability (g)	Storage Capacity	Price ($)	Size (cm^3)	Transfer Speeds (Mb/s)
1	< 100	$<$ 120Gb	> 500	> 250	< 100
2	100 to 500	120Gb to 250Gb	400 to 500	200 to 250	100 to 200
3	500 to 1000	250Gb to 500Gb	300 to 400	150 to 200	200 to 300
4	1000 to 1500	500Gb to 1Tb	200 to 300	100 to 150	300 to 400
5	> 1500	$>$ 1Tb	< 200	< 100	> 400

Table 77: Explanation of Trade Study Scoring for Storage Medium

5. Selection of Baseline Design

The final section of the Conceptual Design Document consists of the choice for the baseline design. Here, each design option is examined and a final choice is made for which options will be chosen for the STOUT baseline design.

5.1. Instrument and Control

5.1.1. Lenses

Until optical system modeling is done in Zemax a lens type cannot be chosen as explained in Section 4.1.2. A detailed trade study on lenses will be included in future documents.

5.1.2. Filters

Optical system modeling in Zemax is also needed to determine if a filter is needed to reject light outside of the UV spectrum. A detailed study on lens types will be included in future documents if modeling reveals the need for one.

5.1.3. Polarizer Mounts

The trade study for polarizer mounts revealed two possible options, the stepper and piezo polarizers. While both of the mounts had the same score, the stepper mount is better suited to STOUT. The stepper mount examined in this study has a smaller accuracy when compared to the piezo, however it would be easier to integrate into STOUT's platform. In addition, the stepper motor comes equiped with an internal controller, a part that would have to be order separately if the piezo motor was chosen. The inclusion of the internal controller allows for a cheaper overall component, which allows funds to be allocated to other areas of design.

5.1.4. OPTICAL MOUNTS

The trade study for optical mounts revealed that the optics cage would best suit STOUT for its mission. The optics cage falls in between the other two mounting options, but the price range for mounting systems is low compared to the other critical components. The main benefits of the optics cage is its stability and its ease of optical alignment. The cage is held together with four rods in the corners of each component mount. These metal rods provide structural stability, which will minimize warping or component damage in flight. In addition, the four points of contact, ensuring that each component will remain aligned during all flight stages in the mission.

5.1.5. PINHOLE ACTUATORS

Based on the trade study conducted on pinhole actuation methods, it was determined that the system will use a nicer induction type stepping actuator like the ones shown in Fig. 25. This actuator provides the necessary accuracy and control method, while being relatively affordable in comparison to other actuators. In addition, it can be cheaply upgraded by the manufacturer for vacuum compatibility. Due to the fact that the scores for the vertical/horizontal and diagonal system actuation methods were so close for this actuator type, the exact system configuration will be left open so that further studies can be conducted to determine which is optimal.

5.1.6. FIBER OPTIC CABLE

Well documented solarization-resistant fiber optic cables are not plentiful on the market so the trade study was confined to two options from two large scale optical hardware manufacturers. Based on the results of the trade study the Thorlabs solarization-resistant fiber optic cable is best for our applications shown by its score of a 3.4 compared to a score of 1 for the other option. This cable was significantly cheaper than the cable produced by Newport and the transmission degraded to approximately $\%80$ after a few hours of high power (25 Watts) UV light input. The degradation of the Newport cable was found to be much more significant at the same wavelength but the input power was not specified so it could have been much greater than the 25 Watts that the Thorlabs cable was tested under. Even with this possible discrepancy the results of the trade study reveal the best solution for our applications. The transmission degradation of the Thorlabs cable was managable at much higher input powers than our applications and it costs much less. Due to the lower price point and documented, low degradation as a result of UV light input the Thorlabs fiber optic cable will be incorporated in the design rather than the Newport cable.

5.2. Environmental Monitoring and Control System

5.2.1. INSULATION

The trade study for insulation reveals that polyisocyanurate foam panels are the best option. This type of rigid foam board offers the best thermal conductivity of any currently available. Additionally, it is low-cost, can be modified relatively easily, and is safe to use in a vacuum. Polyisocyanurate is commonly used in refrigeration applications, so its performance is actually better at lower temperatures; this is also ideal. Although space blankets did not obtain a high score in the trade study, they present a good option for a supplement to the polyisocyanurate. Space blankets are incredibly thin and could be placed on the inside of the foam board to provide reduced radiative heat loss from the system. The exact thickness and composition of the insulation in STOUT will depend on the results of thermal modeling. This will be carried out in the next stage of the design.

5.2.2. ACTIVE CONTROL

Based on the trade study for active thermal control systems, both the point and pad resistive heaters are viable options. However, the main reason for the tie between the two is pricing. Pad resistive heaters are more expensive each, but less of these will be required to heat STOUT. Pad resistive heaters are also more functional, as they provide distributed, variable heating as opposed to the point, variable heating provided by point resistive heaters. Thus, pad heaters are a better option for balanced heating within STOUT. The customers also suggested that pad resistive heaters be implemented, so the choice between these two options is clear. It is not yet known whether or not STOUT will require cooling as well as heating; this will be determined during thermal modeling. However, if a cooling device is necessary to regulate the temperature of the optical system during its operation, then Peltier devices will be utilized. Peltier devices lost points in ease of implementation due to their need for a heat sink. Even with this in mind, Peltier devices are still the best option for cooling. Pumped fluid loops require far more additional components and have unsettling potential for malfunctions.

5.3. Attitude Determination System

5.3.1. PHOTODIODES

RADIANCE is already equipped with photodiodes that determine it's orientation with respect to inertial space. Because STOUT and RADIANCE will effectively have the same orientation, the photodiodes on RADIANCE will be used. The photodiodes scored well in the trade study so our first option for ADS will be improve the accuracy from RADIANCE's photodiodes by using more photodiodes. The main attitude problem that sets our project apart from RADIANCE is that we are concerned with the attitude of the telescope along with the entire STOUT/RADIANCE configuration. With this in mind, RADIANCE's ADS would be used to tell the telescope where to find the sun, then our photodiodes will be mounted on the telescope and will help it zero in on the sun with the desired accuracy.

5.3.2. GLOBAL POSITIONING SYSTEM (GPS)

The GPS has a poor score from the trade study. This is not necessarily due to the cost or weight, but how the GPS would be used as an ADS in general. The GPS would not necessarily determine the attitude, but the location of STOUT. Sun tracking data that is dependent on location from GPS will be used to find the sun. With this configuration, the GPS must be integrated with another ADS which would make it pointless if integrated with the photodiodes or camera because then the location of the sun is already known. If integrated with IMUs, the configuration would be accurate assuming the IMU does not lose accuracy over time, which it does. The lack of advantage of using the GPS and the integration complexity proves why the GPS would not be a good tool in the ADS. This design option will no longer be considered in this project.

5.3.3. INTERTIAL MASS UNITS (IMUS)

The IMU scored very low, along with the GPS, for the same reason. The integration complexity does not make it worthwhile and the mission life operation is poor due to the numerical integration used by the IMU. Both the GPS and IMU are effectively "blind", never actually knowing where the sun is but relying on something else. Although the IMU are not considered to be used independently, if we find that integrating photodiodes with a camera is possible, we will consider mounting an IMU on the body of STOUT. This will be useful for displaying any sudden shifts in the attitude, which will help our clients analyze the data. The IMU will no longer be considered a design option for the project.

5.3.4. CAMERA

The camera is the second best ranking design option, it is cheap, light weight, and the most accurate option. The only drawback for the camera is it is challenging to integrate due to the large amounts of data that must be processes to use it as an ADS. If integration of new photodiodes goes well, the camera will be considered to improve the accuracy of our project. The camera and photodiodes determine attitude with the same principle, so it will be considered as we work with the photodiodes initially. It is either considered to mount a camera on the telescope, very precisely, and determine the telescopes attitude as it hones in on the sun. Or, it is considered to use the camera mounted on RADIANCE to precisely determine the attitude of the STOUT/RADIANCE configuration. This way, we will have redundancy on determining the the STOUT/RADIANCE orientation, because of RADIANCE's camera and off-diagonal photodiodes, and then we would need photodiodes mounted on the telescope. As a result the Camera is being considered as a possible design option for further ADS accuracy improvement.

5.4. Electrical Power System

5.4.1. BATTERIES

The G62 lithium-sulphur dioxide batteries provided by NASA appear to be the best choice for the power system batteries. These battery configurations are housed outside of the instrument, causing no increase in weight and taking up no space within the instrument. Additionally, NASA provides these battery packs for scientific missions on their gondolas, so we will not need to include the batteries into the budget. These batteries have been thoroughly tested and documented and will provide secure power for STOUT. RADIANCE relies upon gondola power as well so the usage of one power supply will streamline integrating the power supply of the two instruments. The specific configuration of G62 batteries (10, 11, or 12 in a pack) will be chosen when the power requirements of all of the STOUT components are known in order to best fit the given requirements.

5.4.2. POWER BOARDS

A double sided printed circuit board (PCB) is the best option for STOUT. By utilizing both sides, it will be possible to design a circuit with enough power converters for all of STOUT's components, however it will still be within budget and will not require a dense, convoluted circuit design like a multilayer PCB would. RADIANCE used a double sided PCB for its power-board and maintaining consistency will allow easy integration between the two instruments. Design for the double sided PCB will depend on the voltage and wattage requirements of the individual STOUT components and will commence in the next design step.

5.5. Structural Systems

5.5.1. Materials

Aluminum 6061 was determined to be the best material to use for the structural components on STOUT. The second are third best materials are Aluminum 7075 and Stainless Steel 15-5PH, respectively. The STOUT addition on RADIANCE is mostly constrained by cost. Unsurprisingly, the cheapest material, aluminum 6061, was determined best based mostly on the cost. Because STOUT will not be subjected to incredible heat, stress, pressure, or corrosive environments, the strength and corrosion resistance of the material is less important. While aluminum 6061 is the weakest of the metals, it is certainly strong enough to handle the stresses that STOUT will endure as evident in the heritage of aluminum 6061 use in aerospace applications. Aluminum 6061 is also very easy to machine and manipulate, and is familiar to the group. The desire to keep STOUT lightweight is accomplished using a low-density material like aluminum 6061.

5.6. Data Acquisition

5.6.1. Number of Processors

The number of processors trade study resulted in two processors being the most successful. Then it was three, followed by one. This outcome was heavily influenced by division of processing and cost. In the division of processing, the two processor system received a 4 and the three processor system received a 5. The reason for this ranking is because the three processor solution will almost certainly have excess processing power. The processor devoted to reading the sensors and writing the data will be very busy at the required rates but, there will certainly be time when this processor isn't busy with a process. The one processor solution simply lacked the division of processing required for STOUT. The two processor approach will be utilized to create average thermal response time on one processor and fast pointing response on the other processor.

5.6.2. Processors

Our baseline design will include two processors as decided from the number of processors analysis. From the processor trade study, the microcontroller and FPGA combo appears to be the best solution. It out performs both the microcontroller and FPGA in processing power and parallizability. These traits were weighted highly because they determine the control response time. The cost was a major drawback to this option but, Trudy said that we could use a NI myRIO Student Edition that they purchased for future labs if we decide to use this option. This will provide our system with the greatest processing speed but, forces us to contact the customer to confirm that borrowing equipment is acceptable. The microcontroller and FPGA combo will have sufficient power to handle the incoming attitude sensor measurements and quickly compute the pointing system response. The Raspberry Pi is inherited from the RADIANCE project and is required by the customer to be reused. This processor is already programmed and wired to handle all the environmental data and thermal control system. Therefore, the attitude data will be rewired to the NI myRIO. These two processors won't need to communicate with each other because they handle different systems. These processors will achieve the required data storage rates and effectively control their respective systems.

5.6.3. Storage Medium

Not surprisingly, the result of the trade study for storage medium resulted with flash drives as the highest scoring design option. Flash drives are inexpensive, small, lightweight, and have the highest chance of surviving a harsh landing out of all of the three design options. Flash drives also offer a high rate of data transfer, and most are integrated with USB 3.0 connections which are easy to connect to the processor. The storage capacity of flash drives is fairly small when compared to HDDs and SSDs. The larger capacity flash drives are typically 128Gb-256Gb, while HDDs and SSDs can reach up to 10TB in data storage. For STOUT, it is likely that the amount of data taken will not reach into the terabytes, so for all intents and purposes flash drives will be chosen storage medium for STOUT.

References

[1] *15-5 PH Stainless Steel*. Webpage. Altemp Alloys, Inc. URL: http://www.altempalloys.com/15-5-ph-stainless-steel.html (visited on 09/22/2017).

[2] *15-5 Stainless Steel - Sheet, Plate, Bar AMS 5659, AMS 5862, ASTM A564 UNS S15500*. Webpage. California Metals. URL: http://www.californiametal.com/Stainless_15_5_Sheet_Plate_Rod_Bar.htm (visited on 09/27/2017).

[3] *5 Megapixel Write calculation*. webpage. Standford Operating Systems. URL: https://web.stanford.edu/~ouster/cgi-bin/cs140-spring14/lecture.php?topic=flash (visited on 09/30/2017).

[4] *6. HOW DO THERMOELECTRIC COOLERS (TECS) WORK?* How Do Thermoelectric Coolers Work? (TEC) — II-VI Marlow. URL: http://www.marlow.com/resources/general-faq/6-how-do-thermoelectric-coolers-tecs-work.html.

[5] *6061 Aluminum Plate — Midwest Steel & Aluminum*. Webpage. Midwest Steel & Aluminum. URL: https://www.midweststeelsupply.com/store/6061aluminumplate.

[6] *6061-T6 or 7075-T6: Pros, Cons, and Decisions - American Weapons Components*. Webpage. American Weapons Components. URL: http://www.americanweaponscomponents.com/6061-t6-or-7075-t6-pros-cons-and-decisions/ (visited on 09/27/2017).

[7] *7075 Aluminum Plate — Midwest Steel & Aluminum*. Midwest Steel & Aluminum.

[8] *718 (Inconel Equivelant) Nickel Sheet*. Webpage. Online Metal Store. URL: http://www.onlinemetals.com/merchant.cfm?pid=9842&step=4&showunits=inches&id=827&top_cat=0.

[9] Administrator. *Thermal Conductivity of XPS (Extruded Polystyrene) Foam - C-Therm - Thermal Conductivity Instruments*. C-Therm Technologies. Sept. 2012. URL: http://ctherm.com/resources/blog/thermal_conductivity_of_xps_extruded_polystyrene_foam2/.

[10] *Agilis Piezo Motor Driven Rotation Stage Image*. webpage. Newport. URL: https://www.newport.com/f/agilis-series-piezo-rotation-mount (visited on 09/28/2017).

[11] *AISI Type S15500 (15Cr-5Ni) Precipitation Hardening Stainless Steel tested at 205°C (400°F), condition H1025*. Webpage. ASM Aerospace Specification Metals Inc. URL: http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MQM15AM (visited on 09/22/2017).

[12] *All About Aspheric Lenses*. webpage. Edmund Optics. URL: https://www.edmundoptics.com/resources/application-notes/optics/all-about-aspheric-lenses/ (visited on 09/27/2017).

[13] *Aluminum 6061-T6; 6061-T651*. Webpage. ASM Aerospace Specification Metals Inc. URL: http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=ma6061t6 (visited on 09/22/2017).

[14] *Aluminum 7075-T6; 7075-T651*. Webpage. ASM Aerospace Specification Metals Inc. URL: http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA7075T6 (visited on 09/22/2017).

[15] *barracuda-2-5-ds1907-1-1609us.pdf*. PDF. Seagate. URL: http://www.seagate.com/www-content/product-content/barracuda-fam/barracuda-new/files/barracuda-2-5-ds1907-1-1609us.pdf (visited on 10/01/2017).

[16] *Belt Driven Rotation Stage Image*. webpage. Newport. URL: https://www.newport.com/p/URB100CC (visited on 09/28/2017).

[17] Pradeep Bhandari. *Mechanically Pumped Fluid Loops for Spacecraft Thermal Control: Past, Present Future Past, Present Future*. Sept. 2004. URL: https://tfaws.nasa.gov/TFAWS04/Website/program/Speakers/TFAWS2004PresentationonMechLoops-v1.pdf.

[18] *BU-106: Advantages of Primary Batteries*. Webpage. Battery University, 2011. URL: http://batteryuniversity.com/learn/article/primary_batteries (visited on 10/02/2017).

[19] *Cage Systems - Thorlabs*. Webpage. Thorlabs. URL: https://www.thorlabs.com/navigation.cfm?guide_id=2002 (visited on 09/26/2017).

[20] *Circuit Board Layout and Design*. Website. Unitech, 2011. URL: http://www.unitechelectronics.com/ourservices.htm (visited on 10/02/2017).

[21] *Classic Silica™ Tile*. URL: http://www.buyaerogel.com/product/classic-silica-tile/.

[22] *Cruzer Fit USB Flash Drive*. Webpage. SanDisk. URL: https://www.sandisk.com/home/usb-flash/cruzer-fit (visited on 09/28/2017).

[23] *Development of Composite and Polymer Material CubeSat Structure with focus on Materials*. PDF. Norwegian University of Science and Technology, 2012. URL: http://nuts.cubesat.no/upload/2013/03/01/nuts_mechanical_report_kimsandvik.pdf (visited on 09/21/2017).

[24] *Different Types of Printed Circuit Boards*. Article. ElProCus, 2015. URL: https://www.elprocus.com/different-types-printed-circuit-boards (visited on 10/01/2017).

[25] Digikey. *Digikey Photodiode*. Website. Digikey. URL: https://www.digikey.com/product-detail/en/luna-optoelectronics/PDB-C160SM/PDB-C160SMCT-ND/481717 (visited on 09/20/2017).

[26] *DS1914.5a-1707US$_I$ronWolfPro.indd*. PDF. Seagate. URL: http://www.seagate.com/www-content/product-content/ironwolf/files/ironwolfpro-ds1914-5a-1707us.pdf (visited on 10/01/2017).

[27] *E-870 PIShift Drive Electronics*. Website. Physik Instrumente. URL: https://www.physikinstrumente.com/en/products/controllers-and-drivers/motion-controllers-for-piezomotors/e-870-pishift-drive-electronics-900640/ (visited on 09/23/2017).

[28] *Field-programmable gate array*. webpage. Wikipedia. URL: https://en.wikipedia.org/wiki/Field-programmable_gate_array (visited on 10/01/2017).

[29] *firecuda-2-5-ds1908-1-1609us.pdf*. PDF. Seagate. URL: http://www.seagate.com/www-content/product-content/firecuda-family/firecuda/files/firecuda-2-5-ds1908-1-1609us.pdf (visited on 10/01/2017).

[30] *FR-1 1.6mm Single Sided PCB Manufacturing*. Site Store. Zhejiang Zapon Electronic Technology Co., Ltd, 2008. URL: http://zbpcb2008.en.made-in-china.com/product/AbQJqahLIGHK/China-FR-1-1-6mm-Single-Sided-PCB-Manufacturing.html (visited on 10/02/2017).

[31] *Grade 2 Titanium Plate*. Webpage. Online Metal Store. URL: http://www.onlinemetals.com/merchant.cfm?pid=12676&step=4&showunits=inches&id=322&top_cat=1353.

[32] Melles Griot. *Fundamentals of Power and Energy Measurement*. Website. California Institute of Technology. URL: http://www.astro.caltech.edu/%20lah/ay105/pdf/e1-photodiode.pdf (visited on 09/20/2017).

[33] *Hard Disk Drive*. Webpage. wikipedia. URL: https://en.wikipedia.org/wiki/Hard_disk_drive#Form_factors (visited on 09/28/2017).

[34] *Hard Disk Drive Versus Solid State Drive: What's the Diff?* Webpage. backblaze. URL: https://www.backblaze.com/blog/hdd-versus-ssd-whats-the-diff/ (visited on 09/28/2017).

[35] *Hard Drive*. Webpage. Computer Hope. URL: https://www.computerhope.com/jargon/h/harddriv.htm (visited on 09/28/2017).

[36] HiLetgo. *HiLetgo Photodiode*. Website. HiLetgo. URL: https://www.amazon.com/dp/B00M1PMHO4/ref=asc_df_B00M1PMHO45185141/?tag=hyprod-20&creative=395033&creativeASIN=B00M1PMHO4&linkCode=df0&hvadid=167121005230&hvpos=1o1&hvnetw=g&hvrand=12627965199899617456&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9060040&hvtargid=pla-314219796120 (visited on 09/20/2017).

[37] *How can it be that the sun emits more than a blackbody?* webpage. Physics Stack Exchange. URL: https://physics.stackexchange.com/questions/130209/how-can-it-be-that-the-sun-emits-more-than-a-black-body (visited on 09/24/2017).

[38] *Hybrid Linear Stepper Linear Actuator*. Website. HaydonKerk Pittman. URL: http://www.haydonkerkpittman.com/products/linearactuators/hybridstepper/size8 (visited on 09/23/2017).

[39] *Implant biomaterials: A comprehensive review*. Webpage. US National Library of Medicine National Institutes of Health. URL: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4295219/ (visited on 09/26/2017).

[40] indiamart. *Avalanche Photodiode*. Website. indiamart. URL: https://dir.indiamart.com/impcat/photodiode.html (visited on 09/20/2017).

[41] Jorge M. *Polyimide Film Insulated Flexible Heater*. Omega Engineering. Oct. 2016. URL: https://www.omega.com/pptst/KHR_KHLV_KH.html#order.

[42] *Metal Fabrication With Aluminum Alloys - Fab2Order*. Webpage. Fab2Order. URL: http://www.fab2order.com/aluminum-alloys/ (visited on 09/26/2017).

[43] *Mode Theory*. webpage. Integrated Publishing. URL: http://www.tpub.com/neets/tm/106-10.htm (visited on 09/28/2017).

[44] *N-422 Linear Actuator with PIShift Piezomotor*. Website. Physik Instrumente. URL: https://www.physikinstrumente.com/en/products/linear-stages-and-actuators/compact-linear-stages-with-piezomotor-drives/n-422-linear-actuator-with-pishift-piezomotor-1000130/ (visited on 09/23/2017).

[45] *NI myRIO 1900 Image*. webpage. National Instruments. URL: http://www.ni.com/en-us/support/model.myrio-1900.html (visited on 10/01/2017).

[46] *NiCad Battery Charging Basics*. Webpage. PowerStream Technology, 2000. URL: https://www.powerstream.com/NiCd.html (visited on 10/02/2017).

[47] *Ni-cd battery*. PDF. Greenmax Battery, 2017. URL: http://greenmaxbatteryindia.weebly.com/ni-cd-battery.html (visited on 10/02/2017).

[48] *nytro-3000-sas-ssd-family-ds1942-1-1708us.pdf*. PDF. Seagate. URL: http://www.seagate.com/www-content/product-content/ssd-fam/nvme-ssd/nytro-3000-sas-ssd/docs/nytro-3000-sas-ssd-family-ds1942-1-1708us.pdf (visited on 10/01/2017).

[49] *nytro-xf1230-sata-ds1889-2-1708us.pdf*. PDF. Seagate. URL: http://www.seagate.com/www-content/product-content/ssd-fam/nvme-ssd/nytro-xf1230-sed/datasheet/nytro-xf1230-sata-ds1889-2-1708us.pdf (visited on 10/01/2017).

[50] *On the technologies of Polymicro*. webpage. Polymicro Technologies. URL: https://issuu.com/molex/docs/polymicro-technolgies (visited on 09/28/2017).

[51] *Optical Filters*. webpage. Edmund. URL: https://www.edmundoptics.com/resources/application-notes/optics/optical-filters/ (visited on 09/27/2017).

[52] *Optical Materials Used for Optical Components*. webpage. Eksma Optics. URL: http://eksmaoptics.com/optical-components/optical-materials/optical-materials-used-for-optical-components/ (visited on 09/25/2017).

[53] *Optics Bench Image*. webpage. Newport. URL: https://www.newport.com/f/opticscageplus-segments (visited on 09/28/2017).

[54] *Optics Breadboard Image*. webpage. Newport. URL: https://www.newport.com/f/opticscageplus-segments (visited on 09/28/2017).

[55] *Optics Cage Plus Pressembled Segments Image*. webpage. Newport. URL: https://www.newport.com/f/opticscageplus-segments (visited on 09/28/2017).

[56] *OSI Batteries - Saft O26SX Battery*. OSI Batteries, 2017. URL: https://www.osibatteries.com/p-25327-saft-lo26sx-battery-d-lithium-sulfur-dioxide.aspx (visited on 10/02/2017).

[57] *Pcb Double Sided Pcb Factory custom 2 layer*. Site Store. ourPCB, 2017. URL: http://www.ourpcbte.com/products-detail/pcb-double-sided/ (visited on 10/02/2017).

[58] *Peltier Devices*. URL: http://www.cui.com/catalog/components/thermal-management/peltier-devices.

[59] *Picomotor Piezo Linear Actuators*. Website. Newport. URL: https://www.newport.com/f/picomotor-piezo-linear-actuators (visited on 09/22/2017).

[60] *Plano-Convex Lenses*. webpage. Eksma Optics. URL: https://www.edmundoptics.com/optics/optical-lenses/plano-convex-pcx-spherical-singlet-lenses/ (visited on 09/25/2017).

[61] *Polarization in Fiber Optics*. webpage. Newport. URL: https://www.newport.com/t/polarization-in-fiber-optics (visited on 09/28/2017).

[62] *RASPBERRY PI 3 MODEL B*. Webpage. Raspberry Pi. URL: https://www.raspberrypi.org/products/raspberry-pi-3-model-b/ (visited on 09/26/2017).

[63] *RASPBERRY PI 3 MODEL B Image*. webpage. Raspberry Pi. URL: https://www.raspberrypi.org/products/raspberry-pi-3-model-b/ (visited on 10/01/2017).

[64] Ravtrack. *COCOM GPS Tracking*. Website. Ravtrack. URL: http://ravtrack.com/GPStracking/cocom-gps-tracking-limits/469/ (visited on 09/20/2017).

[65] *Resistors as Heaters*. Riedon.com. URL: https://riedon.com/technical/using-power-resistors-as-heaters/.

[66] *Rigid Foam*. Rigid Foam Insulation Machining - Trymer Solimide Machining — American Micro Industries. URL: http://www.americanmicroinc.com/rigid-foam/.

[67] Kevin Roderick. *Vacuum Insulation Panels (VIPs)*. NanoPore Incorporated. URL: http://www.nanopore.com/vip.html.

[68] Debra Ronca. *How Space Blankets Work*. The Science of Space Blankets - The Science of Space Blankets — HowStuffWorks. Nov. 2009. URL: http://adventure.howstuffworks.com/survival/gear/space-blanket1.htm.

[69] *Saft LS-14250-BA 1/2 AA 1100mAh 3.6V Lithium Thionyl Chloride (LiSOCI2) Button Top Battery*. Site Store. Battery Junction, 2017. URL: http://www.batteryjunction.com/plc-ls14250-ba.html (visited on 10/02/2017).

[70] Robert Salter. *Typical Lithium Sulphur Dioxide batteries supplied to Scientific Groups*. PDF. Columbia Scientific Balloon Facility, Jan. 2013. URL: https://www.nsbf.nasa.gov/documents/conventional/EC-500-20-D.C.pdf.

[71] *Shortpass Filters*. webpage. Edmund Optics. URL: https://www.edmundoptics.com/optics/optical-filters/shortpass-edge-filters/shortpass-filters/ (visited on 09/25/2017).

[72] *Silica Aerogel*. Go to Blog. URL: http://www.aerogel.org/?p=16.

[73] *Solarization Resistant Fibers*. webpage. Newport. URL: https://www.newport.com/f/solarization-resistant-fibers (visited on 09/28/2017).

[74] *Solarization-Resistant Multimode Fiber Optic Patch Cables: SMA-SMA*. webpage. Thorlabs. URL: https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=5591 (visited on 09/27/2017).

[75] SparkFun. *Triple Axis Accelerometer and Breakout*. Website. SparkFun. URL: https://www.sparkfun.com/products/11028 (visited on 09/20/2017).

[76] SparkFun. *Venus GPS with SMA Connector*. Website. SparkFun. URL: https://www.sparkfun.com/products/11058 (visited on 09/20/2017).

[77] *Special Metals INCONEL® Alloy 718*. Webpage. ASM Aerospace Specification Metals Inc. URL: http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=NINC34 (visited on 09/22/2017).

[78] *Stepper Driven Rotation Stage Image*. webpage. Thor Labs. URL: https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=8750 (visited on 09/28/2017).

[79] *Stepper Motor - 29 oz.in (200 steps/rev, Threaded Shaft)*. Website. Sparkfun. URL: https://www.sparkfun.com/products/10848 (visited on 09/20/2017).

[80] *Titanium Ti-6Al-4V (Grade 5), Annealed*. Webpage. ASM Aerospace Specification Metals Inc. URL: http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=mtp641 (visited on 09/22/2017).

[81] *Types of Telescopes*. webpage. AstronomyNotes. URL: http://www.astronomynotes.com/telescop/s3.htm (visited on 09/28/2017).

[82] *Udoo x86 Advanced Image*. webpage. Udoo. URL: https://www.udoo.org/udoo-x86/ (visited on 10/01/2017).

[83] *Understanding Lens Geometries*. webpage. Edmund Optics. URL: https://www.edmundoptics.com/optics/optical-lenses/plano-convex-pcx-spherical-singlet-lenses/ (visited on 09/25/2017).

[84] *USB 3.0 Flash Drive FIT 128GB*. webpage. Samsung. URL: https://www.samsung.com/us/computing/memory-storage/usb-flash-drives/usb-3-0-flash-drive-fit-128gb-muf-128bb-muf-128bb-am/#specs (visited on 10/01/2017).

[85] Super User. *ISO-C1/2.5 Polyisocyanurate Insulation*. Polyisocyanurate (Polyiso) Insulation for LNG Low Temperature Mechanical Insulation. URL: http://www.dyplastproducts.com/general-site-content-format/81-iso-c1-articles/23-iso-c1-2-5-table.

[86] WasteAdvantage. *Vacuum Insulated Panels: A Challenge for the Fridge Recycling Sector*. Dec. 2015. URL: https://wasteadvantagemag.com/vacuum-insulated-panels-a-challenge-for-the-fridge-recycling-sector/.

[87] *Why Use an Achromatic Lens*. webpage. Edmund Optics. URL: https://www.edmundoptics.com/resources/application-notes/optics/why-use-an-achromatic-lens/ (visited on 09/25/2017).

[88] *WP25M-UB - Ø25.0 mm Mounted Wire Grid Polarizer, 250 nm to 4 µm*. webpage. Thorlabs. URL: https://www.thorlabs.com/thorproduct.cfm?partnumber=WP25M-UB (visited on 09/28/2017).

[89] *XY Translation Mounts for 30 mm Cage Systems*. Website. Thor Labs. URL: https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=184 (visited on 09/20/2017).