University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Conceptual Design Document

RADIANCE
Research at high Altitude on Distributed Irradiance Aboard an iNexpensive Cubesat Experiment

1 Information

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Acronym Definitions

ABS Acrylonitrile Butadiene Styrene

ADS Attitude Determination System

CCD Charge Coupled Device

C&DH Command and Data Handling

CNC Computer Numerical Control

COTS Consumer Off The Shelf

CSS Course Sun Sensor
EOL End of Life
EPDS Electrical Power and Distribution System
FBD Functional Block Diagram
FDM Fused Deposition Modeling
FPGA Field Programmable Gate Array
GPIO General Purpose Input-Output
GPS Global Positioning System
GPU Graphics Processing Unit
HAO High Altitude Observatory
HDD Hard Disk Drive
HDL Hardware Description Language
ICD Interface Control Document
IMU Inertial Measurement Unit
LASP Laboratory for Atmospheric and Space Physics
Li Lithium
Li-ion Lithium Ion
Li-Po Lithium Polymer
M.2 Advanced Peripheral Component Interconnect Express Specification
MUV Middle Ultraviolet
NCAR National Center for Atmospheric Research
NIR Near Infrared
NiCd Nickel Cadmium
NiMh Nickel Metal Hydride
NUV Near Ultraviolet
OEM Original Equipment Manufacturer
OS Operating System
RAM Random Access Memory
RTG Radioisotope Thermoelectric Generator
RH Relative Humidity
SATA Serial Advanced Technology Attachment
SD Secure Digital
SSD Solid State Drive
TCS Thermal Control System
USB Universal Serial Bus
UVC Ultraviolet C

Nomenclature

I	Current [A]
θ	Incidence angle [rad]

2 Project Description

In the field of climate science, measurements of solar irradiance inform modern climate models by accounting for normal fluctuations in solar output. These measurements have traditionally been done from high-budget, full-scale satellites, beginning with the Nimbus-7 mission in 1978 [1]. Since then, numerous spacecraft have been launched to measure solar irradiance. From a scientific perspective, it is desirable to have continuous irradiance measurements, due to the constraints imposed by the nature of irradiance instrument calibration and the constantly changing nature of the sun. This has been a problem for scientists, as the spacecraft designed for this purpose have not been able to provide these constant measurements due to factors such as cost and instrument failure [2][3]. Additionally, since different organizations launch these spacecraft, calibration is often different, resulting in discrepancies of 0.5% in data sets [4].

This project looks to solve that issue through the use of low-cost, 10cm x 10cm x 30cm small satellites (called "cubesats") capable of measuring solar irradiance. **R**esearch at high **A**ltitude on **D**istributed **I**rradiance **A**board an i**N**expensive **C**ubesat **E**xperiment (RADIANCE) will be the first prototype developed for a future cubesat system. The goal of RADIANCE is to measure solar irradiance in a 3U-sized cubesat-style payload (each "U" is a 10cm x 10cm x 10cm cube), to be launched on a high-altitude balloon to prove that this technology is feasible. The design of RADIANCE will be driven by a need to be simple and repeatable, addressing the need of the science community to produce these instruments regularly. Additionally, RADIANCE hopes to show that since the system can be produced at low cost, many of these systems could be produced simultaneously in the future, in order to cover the entire spectrum by each spacecraft covering a different part of the spectrum.

The balloon gondola RADIANCE will fly on is HiWind, which is designed and built by HAO, with the goal of acquiring scientific data from Earth's polar regions. HiWind's first flight was launched from Kiruna, Sweden in the summer of 2011 to take data near the North pole. A picture of HiWind prior to this flight is shown in Fig. 1. The flight RADIANCE will be on is HiWind's second flight, in a two week circumpolar flight about the South pole.

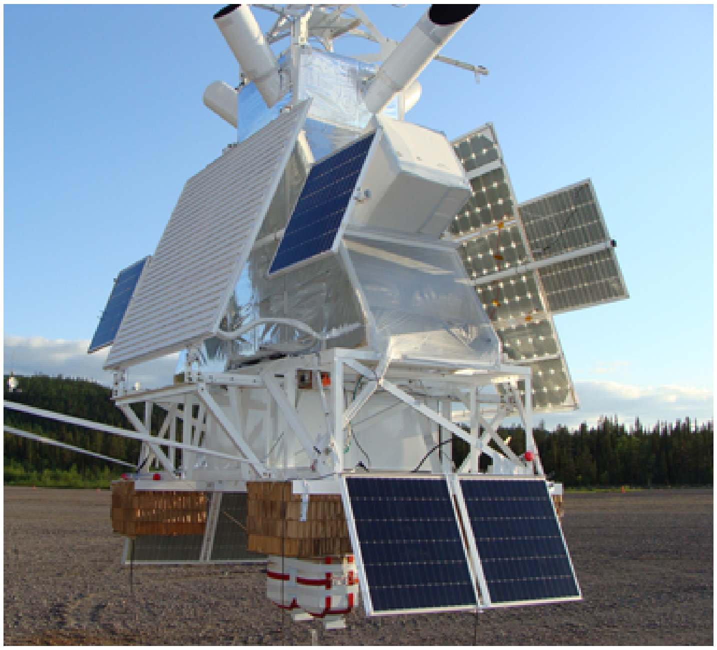

Figure 1: An image of the HiWind gondola [5].

RADIANCE will be integrated on the sun facing side of of the HiWind gondola, as shown in Fig. 2 and Fig. 3. While the details of integration have not been determined by the customer, it's known that there will be a power line connection between HiWind and RADIANCE, where HiWind will provide RADIANCE with

15W and approximately 28V.

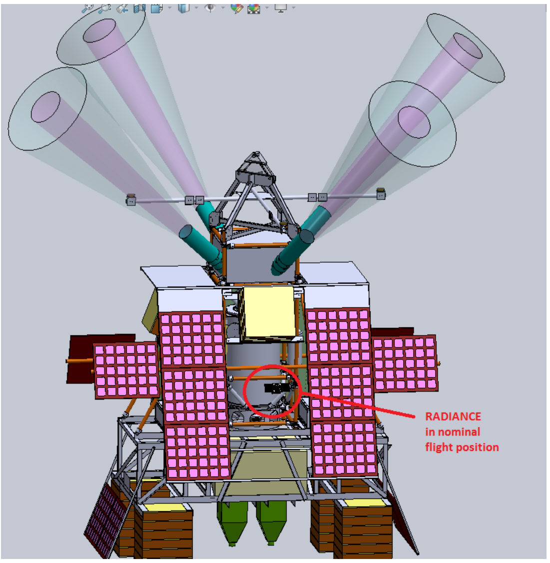

Figure 2: Front view of RADIANCE integration on HiWind [6].

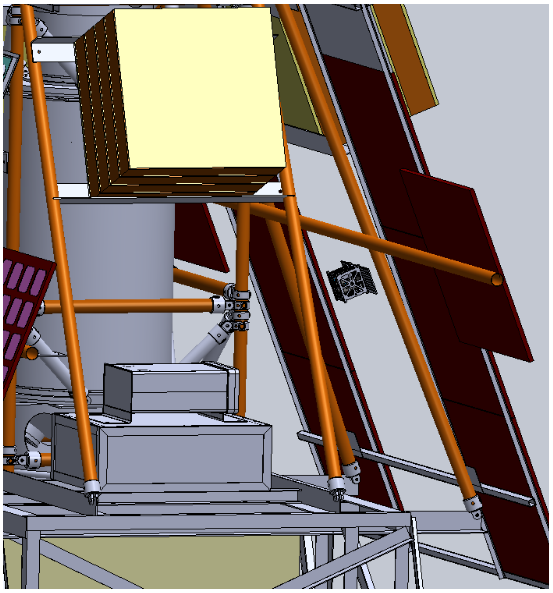

Figure 3: Side view of RADIANCE integration on HiWind [6].

2.1 Project Objectives

The main deliverables for the RADIANCE project are defined as follows:

- A structure that fulfills all requirements listed in Section 3 of this document.
- All design, readiness, and manufacturing reviews shall be given as required of the ASEN 4018/4028 courses. These reviews shall include test plans and test results as appropriate.
- A Fall Final Report (FFR) and Project Final Report (PFR) shall be completed as required by the customer and the course. FFR and PFR shall include test plans and test results as appropriate.
- A "path to space" report that makes recommendations and demonstrates how RADIANCE could be modified to be ready for spaceflight. This document may be incorporated into the PFR.

Additionally, rigorous testing of RADIANCE will be required to verify that all requirements have been met. The specifics of what testing will depend on the ultimate design, but the team will develop test plans and perform tests to prove the successful completion of the project requirements. Furthermore, the testing plan shall take into account vendor-reported operating requirements for all off-the-shelf components used.

2.2 Atmospheric Conditions for RADIANCE

During the flight of RADIANCE, the system will travel from sea level in Antarctica to approximately 40km above the surface of the Earth. The ascent phase of the flight will last approximately 24 hours, the cruise will last approximately 2 weeks, and the descent will last approximately 12 hours. During ascent and descent, RADIANCE will travel through the tropopause, a region of the atmosphere where conditions are harshest (coldest temperatures, highest humidity, more wind) [7]. In this section, a description of the atmospheric conditions is included to inform the remainder of the document.

Figure 4 and Figure 5 show the variation of temperature and pressure with altitude respectively. While the pressure has a steady exponential decrease, the temperature drops significantly through the lower levels of the atmosphere, then rises steadily as the altitude increases. In Figure 4, the smooth lines are various atmospheric models, while the jagged lines are actual data from South Pole and McMurdo station radiosondes. Figure 5 also includes actual data and models, but the actual data is very consistent and close to the models.

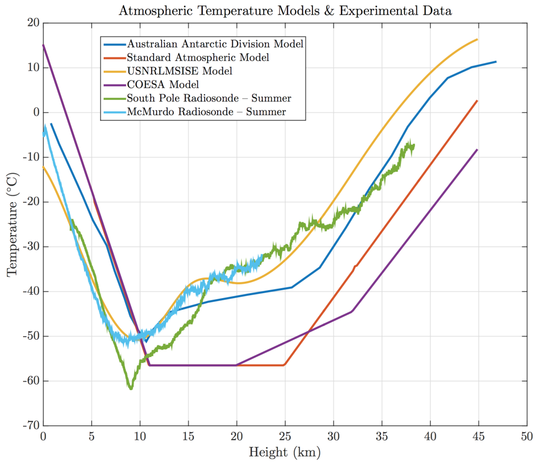

Figure 4: Temperature vs. altitude [9] [10] [11] [13] [12]

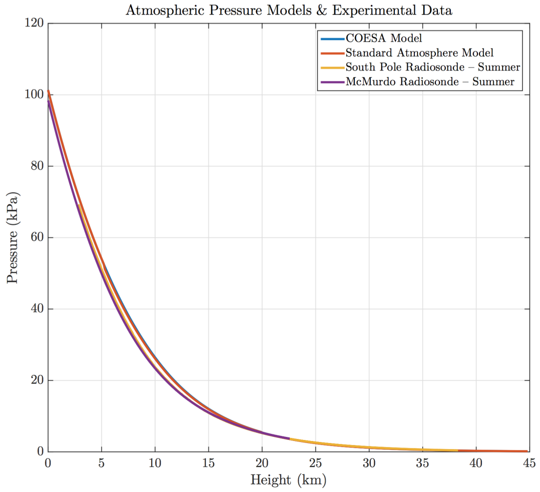

Figure 5: Pressure vs. altitude [11] [10] [12]

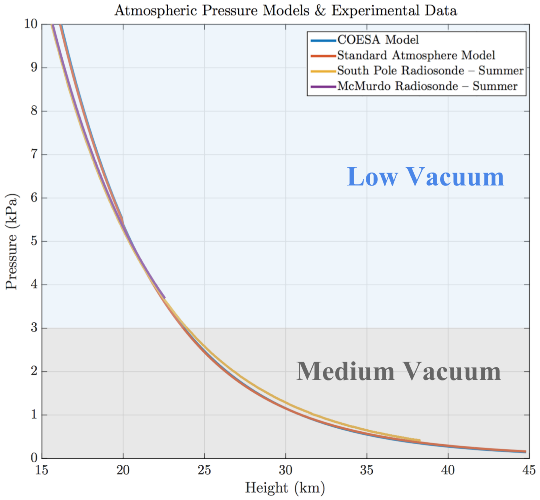

Figure 6: Pressure vs. altitude showing vacuum levels [11] [10] [12] [15]

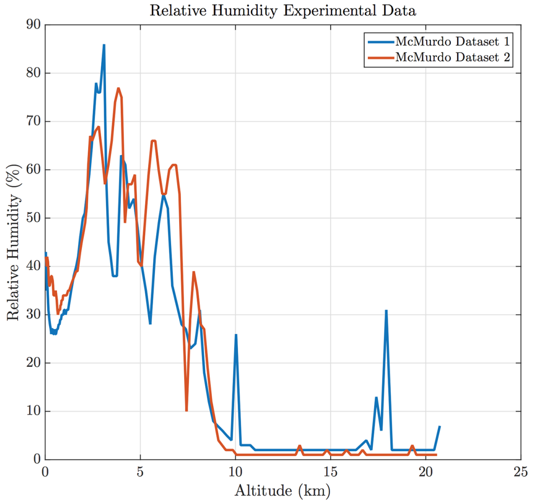

Figure 7: Relative humidity vs. altitude [12]

Importantly, a decrease in pressure implies an increase in vacuum conditions, so it is important to characterize what type of vacuum environment RADIANCE will experience. As shown in Figure 6 (a zoomed-in version of Figure 5), RADIANCE will experience low vacuum conditions until about 3 kPa of pressure, and then will remain in medium vacuum conditions otherwise. The classifiers of "low" and "medium" vacuum essentially describe the severity of the vacuum environment, and the exact definitions can vary depending on the agency giving the definition [15]. Regardless, systems in the high vacuum of space have to contend with vacuum effects such as molecular or particulate contamination (from off-gassing or propellant usage), solar UV degradation of components, cold welding of metals, and loss of convective cooling [8]. Since RADIANCE has a short mission length, any effects of contamination, degradation, and cold welding will be negligible since these are long-duration effects of a high vacuum [8]. However, RADIANCE is concerned with the loss of convection since the thermal conditions will not act as they would in a lab environment. Any effects of the low pressure environment will be accounted for in the thermal design of the system.

Finally, throughout this document we refer to the three phases of RADIANCE's flight: ascent, cruise, and descent. These stages are defined as follows in terms of atmospheric conditions:

- Ascent: Temperatures between −60°C and 10°C, pressures between 100 kPa and 1 kPa, and relative humidities between 0% and 90%. Duration of ascent is approximately 24 hours.
- Cruise: Temperatures between 0°C and 20°C, pressures between 200 Pa and 1 kPa, and relative humidities between 0% and 5%. Duration of cruise is approximately 2 weeks.
- Descent: Same environmental conditions as ascent; duration is approximately 12 hours.

2.3 Concept of Operations

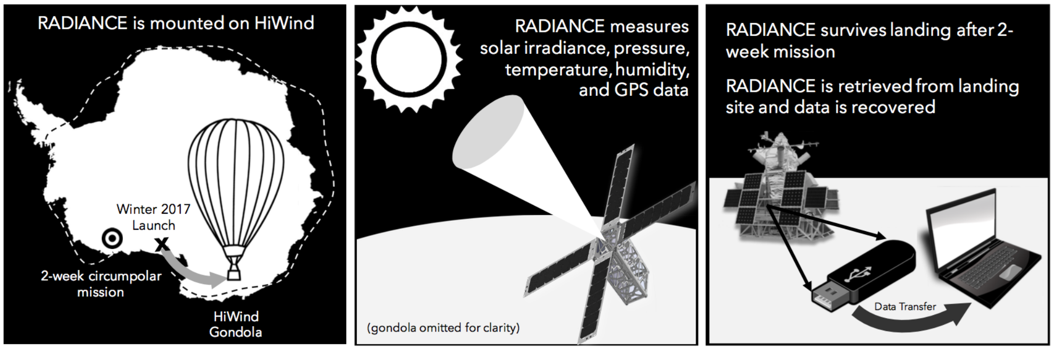

Figure 8: Mission-level concept of operations

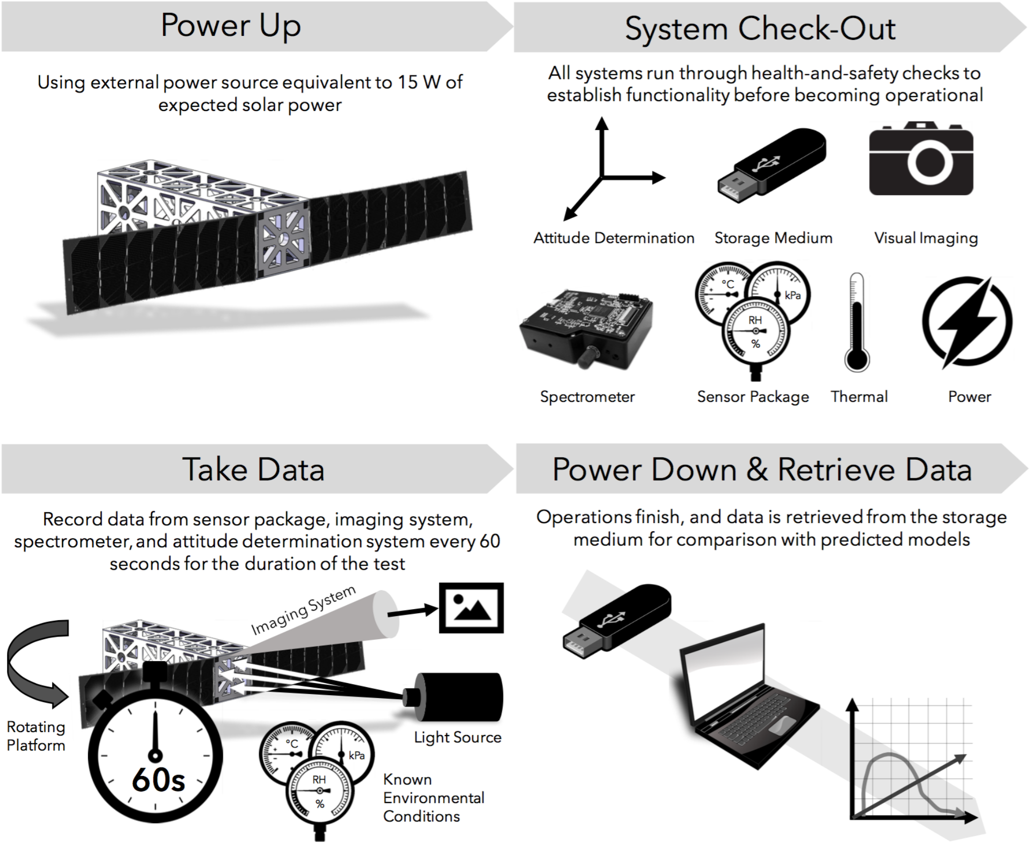

Figure 9: Project-level concept of operations

As shown in Figures 8 and 9, RADIANCE has a mission-level and project-level scope, and therefore has concepts of operations for both scopes. At the mission level, RADIANCE will be mounted to the HiWind gondola and complete a two-week circumpolar high-altitude balloon flight in late 2017. Since the flight will occur during Antarctic summer, the gondola will have 24-hour sunlight, enabling constant data collection throughout the flight. The balloon will be launched with RADIANCE on board, and the system will take data during ascent, cruise, and descent. RADIANCE will take a variety of measurements, including solar irradiance measurements from a spectrometer. Environmental and attitude sensors will also record data on temperature, pressure, relative humidity, and GPS location, as well as determining the off-boresight angle to the sun and capturing images of the sun with a camera. At the completion of the flight, the HiWind gondola will land in Antarctica and the payload will be collected for data retrieval.

Since the flight of RADIANCE will occur beyond the scope of this course, the team has defined a project-level concept of operations that describes how RADIANCE will be proven on the ground. First, the system will be powered up using an external power source equivalent to the 15 W of expected solar power—the team anticipates that test will occur over several days, and so a consistent power source is needed to conduct testing. After the system is powered, the software will conduct a system check-out to determine health and safety of each components. During checkout, each component will be checked by the control software to verify that it is operational and functioning within established limits. Once health and safety has been established, the system will begin taking data at a cadence of once per minute. Components will be tested as follows: the spectrometer will measure a light source with a known wavelength pattern, the environmental sensors will be compared with a known lab environment, the attitude sensors will be tested on rotating servo platform, and the imaging system will take images of the light source. Separate testing will be conducted to verify that the system can withstand the environmental conditions of ascent, cruise, and descent. Finally, at the conclusion of the demonstration, the data will be retrieved from RADIANCE and verified with prediction.

2.4 Functional Block Diagram

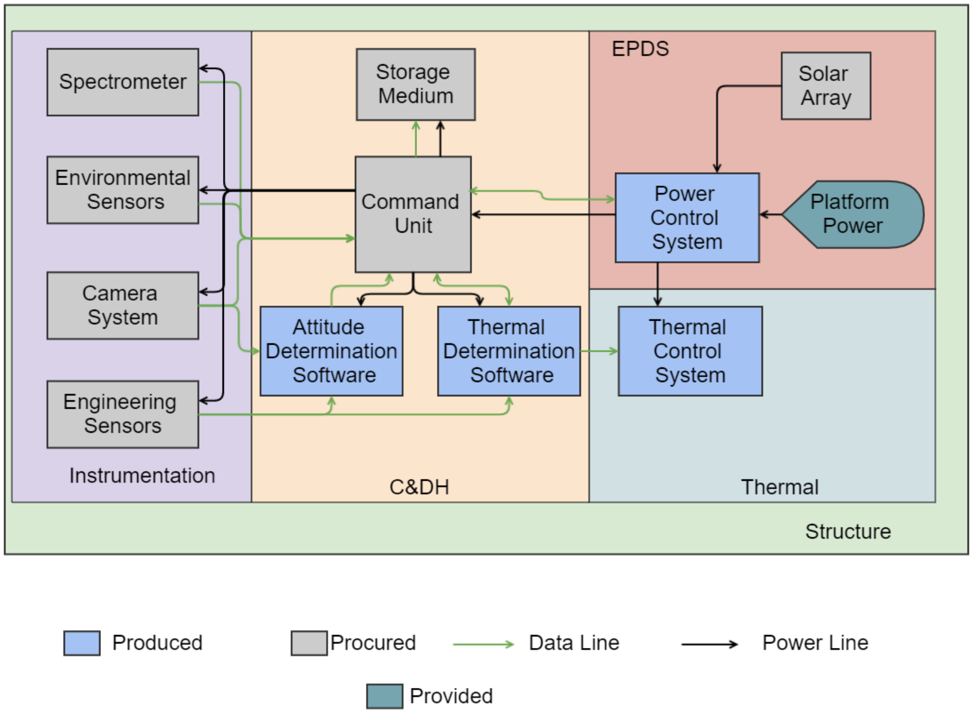

Figure 10: The system functional block diagram

Figure 10 shows the functional block diagram (FBD) of this system. Here, major process groups have been outlined, showing the instrumentation, command and data handling (C&DH), electrical power and distribution system (EPDS), and thermal groups. Within each of these groups, the individual system functions are shown. The coloration represents whether the components will be procured, produced, or are provided, as outlined in the legend.

As can be seen in the FBD, the structure encompasses all of RADIANCE's other subsystems, due to the structure being required to hold all system components in some way. Once inside the structure, the functions of RADIANCE can be broken down into the instrumentation, C&DH, EPDS, and thermal groups. Instrumentation covers the data taking functions of RADIANCE, including the spectrometer, environmental sensors, camera, and engineering sensors. This data than feeds into the C&DH group, to either the relevant software group, such as attitude determination and thermal control, or directly to the command unit for processing. The command unit sends data to the storage medium, as well as to the thermal control and power distribution system. The power distribution system takes the power from HiWind and the solar array to redistribute to the command unit and thermal system. The command unit further redistributes power to the the instrumentation group.

2.5 Functional Requirements

The functional requirements are stated here, and are explained in more detail in Section 3. The section also details design requirements, validation, and verification.

1. The system shall take solar irradiance measurements.

2. The system shall survive the environmental conditions of a high-altitude balloon flight up to 40 km.
3. The system shall return data.
4. The system shall determine its attitude.
5. The system shall interface with the HiWind gondola.
6. The system shall capture images of the sun in the visible spectrum.
7. The project deliverables shall include a Path-To-Space report.

3 Functional & Design Requirements

The following section outlines the functional and design requirements for RADIANCE. Each functional requirement broadly defines what RADIANCE will accomplish, and each design requirements constrains the design space and relates to the specific needs of the project. Additionally, functional requirements include a statement of validation to describe the source of the requirement, and each design requirement includes a statement of verification to describe how the requirement will be satisfied.

1. The system shall take solar irradiance measurements.
   Source: Customer requirement, meant to demonstrate the feasibility of using a small payload to take solar irradiance measurements.
   - 1.1. Solar irradiance measurements shall be taken by a spectrometer.
     Source: Customer requirement.
     Verification: Inspection.
     - 1.1.1. The spectrometer shall measure spectra from 250nm to 1000nm.
       Verification: Inspection of spectrometer data sheet; test of spectrometer by exposing to a light source of known spectrum composition.
     - 1.1.2. The spectrometer shall be calibrated.
       Verification: Test; equipment provided by Dr. Bob Marshall shall be used to calibrate the spectrometer.
   - 1.2. The system shall take environmental measurements.
     Source: Customer requirement; data on environmental conditions will aid customer in post-processing spectrometer data.
     Verification: Demonstration.
     - 1.2.1. The system shall measure temperature, pressure, and relative humidity.
       Verification: Test; each sensor will be tested against known environmental conditions.
     - 1.2.2. The environmental data shall be recorded once per minute, simultaneously with each spectrum measurement.
       Verification: Analysis; software and data subsystem testing and subsequent data inspection
2. The system shall survive the environmental conditions of a high-altitude balloon flight up to 40km.
   Source: Customer requirement; the system will fly on the HiWind gondola flight and therefore must operate in these conditions.
   - 2.1. During ascent and descent, the system shall survive temperatures from $-60°$C to $10°$C.
     Validation: Atmospheric research and modeling.
     Verification: Demonstration; thermal vacuum chamber testing at LASP.
   - 2.2. During cruise, the system shall operate at temperatures from $0°$C to $20°$C.
     Validation: Atmospheric research and modeling.
     Verification: Demonstration; thermal vacuum chamber testing at LASP.

- 2.3. The system shall survive relative humidity (RH) levels from 5% to 90%.
  Validation: Atmospheric research and modeling.
  Verification: Demonstration; low RH survival testing with thermal vacuum chamber, high RH survival testing in a known humid environment.
- 2.4. The system shall survive pressure values of 100 kPa to 0.20 Pa.
  Validation: Atmospheric research and modeling.
  Verification: Demonstration; thermal vacuum chamber testing at LASP.

3. The system shall return data.
   Source: Customer requirement; the flight is of no value without data return.
   - 3.1. The data shall be recorded.
     Verification: Demonstration; ensure all data is recorded onto a storage medium.
     - 3.1.1. Science data shall be recorded at a rate of one measurement per minute.
       Source: Customer requirement; science data includes irradiance data and environmental data.
       Verification: Test; verify that data can be taken at the specified rate.
     - 3.1.2. Measurements from all science instruments shall be recorded within 2 seconds of each other.
       Validation: Customer Requirement. Measurements taken at the same time can be reliably compared and correlated.
       Verification: inspect data timestamps on storage medium after testing science instruments
     - 3.1.3. Camera images shall be recorded at a rate of one image per minute.
       Validation: Customer Requirement.
       Verification: inspect image timestamps on storage medium after testing camera
   - 3.2. The storage medium shall survive landing.
     Verification: storage medium data sheet and vendor information about stress testing

4. The system shall determine its attitude.
   Source: Customer requirement; attitude determination of RADIANCE will help verify the attitude determination provided by HiWind gondola.
   - 4.1. The off-sun angle attitude shall be determined to within one arcminute.
     Source: Customer requirement; the off-boresight angle helps to calibrate the solar irradiance data.
     Verification: text by exposing package to light source at known relative orientations
   - 4.2. Attitude data shall be recorded synchronously with other science data at a rate of one measurement per minute.
     Validation: Customer Requirement. Facilitates correlation with other science data.
     Verification: after integration test compare timestamps on attitude data points with timestamps on other sensors

5. The system shall interface with the HiWind gondola.
   Source: Customer requirement; RADIANCE has a space reserved on the HiWind gondola platform.
   - 5.1. The system (excluding the solar panels) shall have dimensions of 30cm x 10cm x 10cm.
     Source: Customer requirement; RADIANCE is designed to be similar to a 3U cubesat which has the stated dimensions.
     Verification: Inspection.
   - 5.2. The system (including the solar panels) shall not exceed dimensions of 70cm x 70cm x 30cm (height, width, and depth respectively).
     Source: Customer requirement; RADIANCE must fit into the allotted space on HiWind.
     Verification: Inspection.

5.3. The 10cm x 10cm face of the system shall be sun-facing.
Source: Customer requirement.
Verification: Inspection; instruments that need to face the sun will have their boresights on the 10cm x 10cm face.

5.4. The system shall interface with the HiWind power line.
Source: Customer requirement to have a backup power source.
Verification: Demonstration; ensure that the system can accommodate the physical electrical connection (plug) provided by HiWind.

5.4.1. The power interface with HiWind shall include a fail-safe such that RADIANCE failure does not interfere with HiWind.
Verification: Test; intentionally exceed limits on the power system and verify that the source is not disrupted.

5.4.2. The system shall accommodate a 15 W supply.
Source: HiWind gondola requirement.
Verification: Demonstration; a representative power supply will be connected to RADIANCE to verify that the system can handle a 15 W input.

5.4.3. The system shall accommodate a 26-28 V supply.
Source: HiWind gondola requirement.
Verification: Demonstration; a representative power supply will be connected to RADIANCE to verify that the system can handle a 26-28 V input.

5.4.4. The system shall accommodate an approximately 0.5 A supply.
Source: HiWind gondola requirement.
Verification: Demonstration; a representative power supply will be connected to RADIANCE to verify that the system can handle an approximately 0.5 A input.

5.5. The system shall comply with all requirements and provisions of the Interface Control Document (ICD).
Source: This document is under co-creation between the customer and the RADIANCE Systems Engineer.
Verification: Inspection, demonstration, and test; exact details to be determined once ICD is complete.

6. The system shall capture images of the sun in the visible spectrum.
Validation: Customer requirement. Proof of concept for separate future cubesat project focused solely on solar imaging by a small payload.

6.1. The images shall be stored.
Verification: Inspection, test; inspect data on storage medium after tests, view images to ensure they stored properly.

6.2. The field of view of the camera shall be 5° degrees (± 1°).
Source: Customer requirement. Limiting field of view causes solar disk to fill more of the image (this is in the place of a resolution requirement).
Verification: Analysis, test; modeling geometry of the boresight and taking test images to verify the field of view.

6.3. The system shall capture one image per minute.
Verification: Demonstration.

7. The project deliverables shall include a Path-to-Space report.
Source: Customer requirement; ultimate goal for this project is to create a spaceflight-ready version of RADIANCE and this document will provide the crucial first steps and direction.

7.1. The report shall detail recommended design modifications to RADIANCE to make it spaceflight-ready.
Verification: Inspection.
  7.1.1. The report shall include any necessary modifications to the thermal control system.
  Verification: Inspection.
  7.1.2. The report shall include any necessary modifications to the power system.
  Verification: Inspection.
  7.1.3. The report shall include any necessary modifications to the structural system.
  Verification: Inspection.
  7.1.4. The report shall include any necessary modifications to the scientific instrumentation system.
  Verification: Inspection.
  7.1.5. The report shall include any necessary modifications to the command and data handling system.
  Verification: Inspection.

7.2. The report shall include research with references used to determine spaceflight-readiness needs.
Verification: Inspection.

4 Design Options Considered

The design options here include all options considered for the RADIANCE baseline design. This section is broken down into 8 functional groups, covering the functional requirements of the system: spectrometers, processor, power source, batteries, storage medium, attitude determination, structure, materials, and thermal control. Each section outlines several design options within that functional group, some advantages and disadvantages of that particular design option, and if relevant, some technical specifications of the design option for comparison.

4.1 Spectrometer

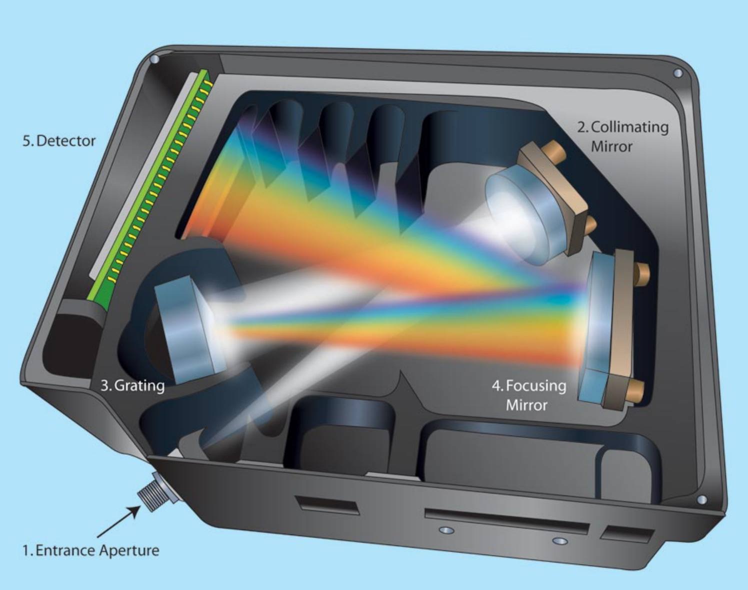

Figure 11: Optical bench of a typical grating spectrometer [21].

A spectrometer is an instrument that takes in light, separates the various wavelengths present, and then digitally records the amount of each wavelength. The three most common spectrometer layouts are the symmetrical Czerny-Turner, the crossed Czerny-Turner and the Concave Holographic configuration. While the Concave Holographic configuration reduces stray light it is typically a much more expensive option [22]. The crossed Czerny-Turner configuration is more compact but introduces more stray light to the detector.

The grating spectrometer in the Czerny-Turner configuration is the most suitable type for this system—Figure 11 shows a simplified version of the inside of a typical grating spectrometer in the crossed Czerny-Turner configuration. Note the flow of light from the slit to the grating, then the collimating mirror, then the focusing mirror and finally the detector. These optics work together to diffract the light, collimate (make parallel) the wavelengths, then finally focus the light onto a detector which is typically a CCD(charge coupled device). The combination of these optics is called an *optical bench.* [21].

Each of these steps can be configured differently to change the output resolution and range of wavelengths that the spectrometer can detect. The *slit* (called the "Entrance Aperture" in Figure 11) controls the amount of light that comes into the spectrometer. With more light, the spectrometer resolution decreases but the range of possible wavelengths it can measure increases. The collimating mirror focuses the light into parallel beams, and then the diffraction grating (or *grooves*) controls the diffraction patterns of light (stations 2 and 3 in Figure 11). Similar to the slit length, a smaller groove density on the grating can decrease resolution but will increase the wavelength range. The focusing mirror aligns the light into discrete wavelengths, and finally the detector records the spectrum composition of the light. A detector with better pixel depth will more accurately measure each wavelength of light and therefore increases overall resolution. Importantly, the spectrometer used for RADIANCE must be pre-configured from the vendor with a specific slit width, groove density, and wavelength range to meet the requirements of the project [21]. This configuration must then be calibrated prior to use. Most vendors can calibrate as well as configure a spectrometer for a specific need.

The spectrometer entrance is another important design variable. A fiber optic cable is typically used to bring light into a spectrometer because it guides light from each end using total internal reflection. This means a spectrometer can be mounted in any direction as long as the other end of the fiber optic cable is accurately pointing a the light source. Fiber optic cables use the SMA connector (SubMiniature version A, a coaxial screw-type coupler) to interface with spectrometers. A fiber optic cable must be carefully chosen so the proper amount of light enters without being absorbed by the cable. A spectrometer can also use a device called a *cosine corrector* to collect light from a much greater (180°) field of view [23]. Most general-purpose spectrometers use USB, ethernet, and/or RS232 (a standard for serial transfer) for transferring data between the spectrometer and the host platform. In this case the microcontroller must be able to record data using an interface such as USB for data transfer. Most spectrometers require a USB connection to a Windows computer with proprietary software for data visualization and recording. This restricts the use considerably because most microcontrollers aren't able to run the Windows OS and interface with the spectrometer visualization software.

4.1.1 Ocean Optics USB 2000+

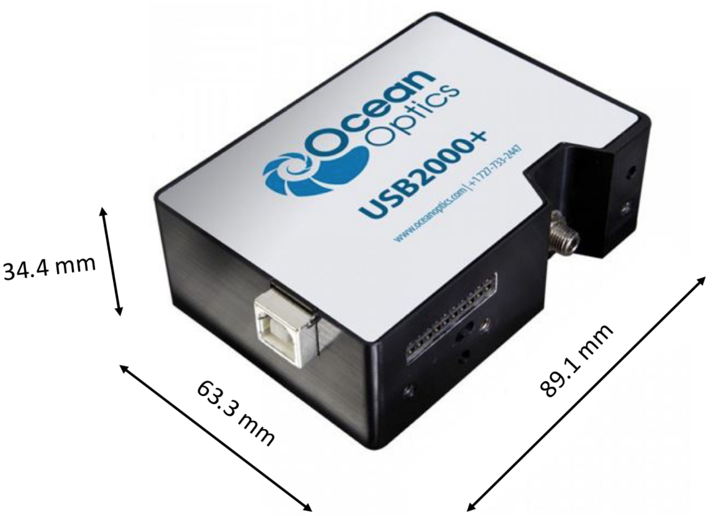

Figure 12: Picture of the Ocean Optics USB 2000+ spectrometer.

The Ocean Optics USB2000+ shown in Figure 12 is an economic general-purpose spectrometer that collects data from near infrared to ultraviolet. The USB2000+ is an updated version of the USB2000 which is featured in a significant amount of scientific literature. The USB2000+ features a phosphor UV coating and quartz detector window which makes it especially suited for measuring UV light (< 350nm) [24]. The longest dimension is below 10cm which fits within our volume constraints and the supported wavelength range satisfies our required range.

Table 1: Specifications of the Ocean Optics USB2000+.

Specification	**Value**
Wavelength Range [nm]	200-1100
Resolution [nm]	0.3-10 (Grating dependent)
Configuration	Crossed Czerny-Turner
Dimensions [mm]	89.1 x 63.3 x 34.4
Power Req.	230mA at +5VDC
Interface	USB, RS232
Price	$3300

Table 2: Pros and Cons of Ocean Optics USB2000+.

Pros	**Cons**
Low power requirement Widely used	Suited best for UV light More expensive

4.1.2 Ocean Optics USB 4000

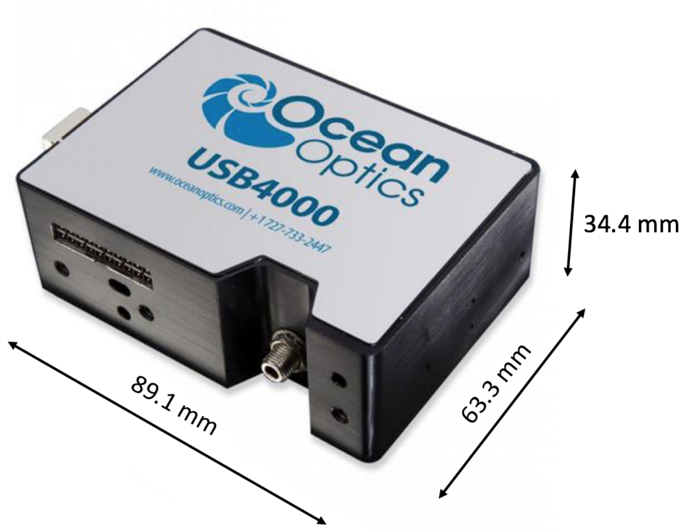

Figure 13: Picture of the Ocean Optics 4000 spectrometer.

The Ocean Optics USB4000 is a redesign of the USB2000 spectrometer and is extremely similar to the USB2000+. The main differences between the USB2000+ and the USB4000 are that the USB4000 has a better detector with better signal to noise ratio which is important in low-light applications. The USB4000 is better suited than the USB2000+ for visible and infrared light applications (> 400nm) [25]. The longest dimension is below 10cm which fits without our volume constraints and the supported wavelength range is beyond our required range.

Table 3: Specifications for Ocean Optics USB4000.

Specification	**Value**
Wavelength Range [nm]	200-1100
Resolution [nm]	0.3-10 (Grating dependent)
Configuration	Crossed Czerny-Turner
Dimensions [mm]	89.1 x 63.3 x 34.4
Power Req.	250mA at +5VDC
Interface	USB, RS232
Price	$3300

Table 4: Pros and Cons of the Ocean Optics USB4000.

Pros	**Cons**
Low power requirement	More expensive
Widely used	
Suitable for the visible-infrared range	
Higher detector resolution	

4.1.3 B&W Tek SpectraRad Xpress

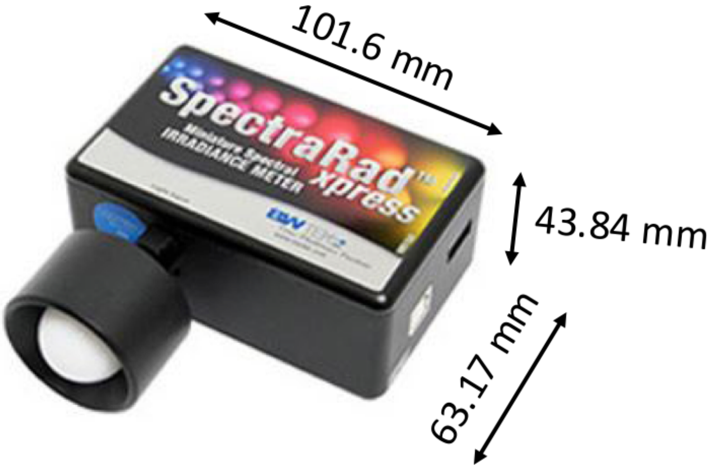

Figure 14: Picture of the SpectraRad Xpress spectrometer.

The SpectraRad Xpress is a miniature spectrometer that comes with a standard grating and slit size. This restricts design options like slit size and grating density. The SpectraRad Xpress also comes standard with a cosine corrector which means a collecting lens is already factored into the cost. However, the largest dimension of the Xpress is over 10cm and therefore will restrict mounting options. Additionally, the Xpress has a worse resolution, wavelength range, and fewer interface options than comparable spectrometers[27].

Table 5: Specifications of the B&W Tek SpectraRad Xpress.

Specification	**Value**
Wavelength Range [nm]	350-1050
Resolution [nm]	4
Configuration	Crossed Czerny-Turner
Dimensions [mm]	43.84 x 63.17 x 101.6 mm
Power Req.	USB at 350mA
Interface	USB
Price	$3000

Table 6: Pros and Cons of the B&W Tek SpectraRad Xpress.

Pros	**Cons**
Comes standard with a cosine corrector	Higher power requirement Doesn’t meet resolution, wavelength range, or size requirements More expensive

4.1.4 Avantes AvaSpec-Mini 2048

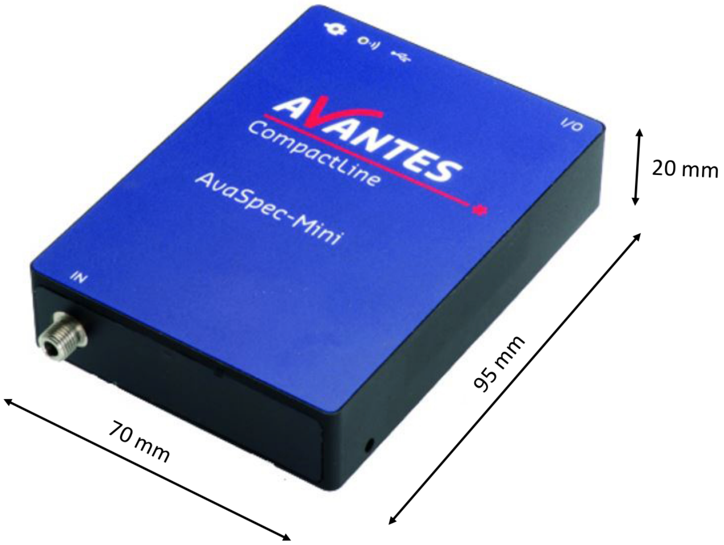

Figure 15: Picture of the Avantes CompactLine AvaSpec-Mini 2048 spectrometer.

The Avantes AvaSpec-Mini 2048 is a very small yet powerful general purpose spectrometer. Avantes is based in Louisville, CO and can provide a demo instrument for short periods of development. The Mini 2048 uses the symmetrical Czerny-Turner configuration which reduces stray light effects compared to the crossed configuration. The Mini 2048 is sized similarly to a deck of cards and fits well within our volume constraints. Similarly, the supported wavelength range is beyond our required range. [26].

Table 7: Specifications of the Avantes Mini 2048.

Specification	**Value**
Wavelength Range [nm]	220-1100
Resolution [nm]	0.1-10.8 (Grating dependent)
Configuration	Symmetrical Czerny-Turner
Dimensions [mm]	95 x 68 x 20
Power Req.	USB at 250mA
Interface	USB, RS232
Price	$2250

Table 8: Pros and Cons of the Avantes Mini 2048.

Pros	**Cons**
Avantes is based locally Small size Varying interface options Much less expensive	Smaller operational temperature range

4.2 Processor

In order to operate all of the instrumentation on the cubesat, a controller will be needed. Initially the customer suggested a Raspberry Pi Model A+, however there are not only many microcontroller options, there are several control options outside of that. Major categories are outlined below.

For this project the most important factors to look for is the ability to do parallel processing, the ability to store memory for a small amount of time but all at once (RAM), low power, and a package that will fit inside a 3U cross section. Data will be taken and stored all at once but does not require a large amount of processing. This means that a sufficient amount of RAM can temporarily store this data before it is written to the storage medium. Due to the lack of on board processing of the data, the controller does not need fast processing speeds. Parallel processing is the result of how many threads a computer can run. Computers with more cores can run more threads and many modern CPUs (central processing unit) even allow multiple threads. In addition, without all other components being selected, the controller needs to be flexible in terms of compatibility. The controller needs to be able to handle many different forms of input and possible drivers.

4.2.1 Netbook

Netbooks are smaller versions of standard laptops. They can in fact be regular laptops but are normally much smaller and have significantly less power. Netbook computers have a long history as controllers on portable systems and especially robotics. They are compatible with all operating system options. As a result they easily integrate with many hardware options and their respective drivers. They are able to do a large amount of parallel processing due to the powerful CPUs netbooks come with as opposed to other smaller options. Netbooks also come complete with their own reusable power source. They are also powerful and self contained. However Netbooks draw significant power (15-20W) [33]. The RADIANCE project is only allotted 15W of power at maximum and a Netbook would draw far too much due to unnecessary components such as a GPU, keyboard, and screen. Those components are not normally in use during system operation, but they take up space and power that could be used elsewhere. Most importantly, a Netbook would not fit inside the required space of a 3U cubesat. There are not any netbooks that would fit into the 10cm x 10cm cross sectional area. There are mini-PCs which are a small box with all key components of a computer contained into a small package, but these share the same power issues.

Table 9: Pros and Cons of Netbook Controller.

Pros	**Cons**
Powerful processing option	Expensive
Compatible with any software package	Requires too much power to run
Built in power	It will not fit inside the structure

Figure 16: Netbook used in systems applications [29]

4.2.2 Microcontroller

Initially the suggestion of the customer, a microcontroller consists of the core components available in a standard netbook in a smaller package. An important distinction should be made between microcontrollers and microprocessors. Microprocessors are often only the CPU (central processing unit) or ship that interfaces with all other components of the microcontroller [34].

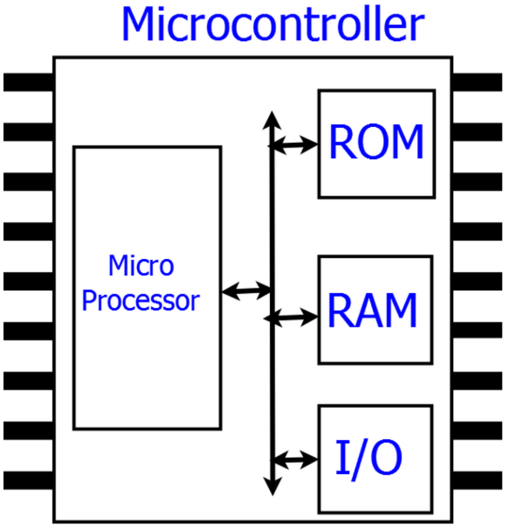

Figure 17: Illustration of the difference between microprocessors and microcontrollers [34].

Microcontrollers have only the necessary components to function as a computer and are designed to be run in headless mode (no display) on small systems without massive computational needs. Microcontrollers have a wide range of designs to fit specific needs of any project. NCAR envisioned using a Raspberry Pi Model A+ due to its low profile and their own familiarity with the microcontroller market. From past experience, microcontrollers can run into issues over long term use. This results from all memory (RAM - Random Access Memory) being exhausted as time goes on from multiple processes. This happens on all computers almost all require restart at some point. During the RADIANCE flight, a reset of the controller will not be possible. These issues are more frequent or lower end controllers and on systems with more daemons (programs that run in the background). These arise from more complex operating systems with many processes that will not be needed on the RADIANCE flight.

Table 10: Pros and Cons of Microcontroller.

Pros	**Cons**
Provides necessary processing power Compatible with almost all instrumentation options Inexpensive Very familiar	Not the fastest possible option Some have memory issues when operating for long periods

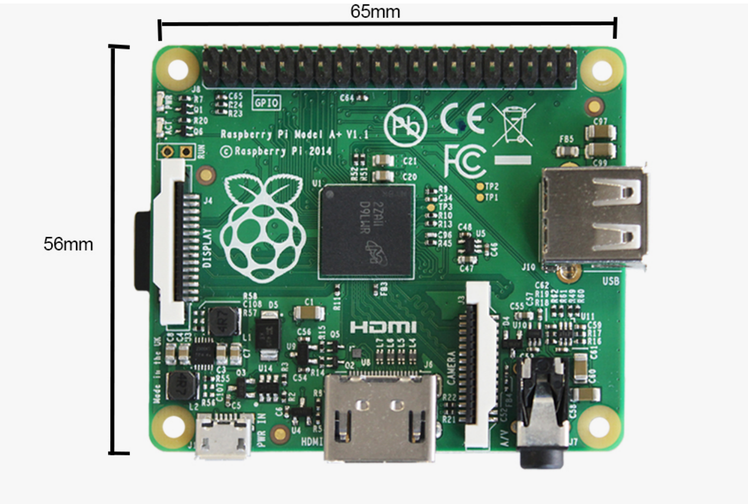

Figure 18: Raspberry Pi Model A+ [30].

4.2.3 FPGA

A FPGA board (Field-Programmable Gate Array) is a hardware programmable option for control. Instead of a CPU splitting resources between multiple processes, an FPGA can execute all processes in parallel [31]. This is very useful on robotic systems that require a large number of integrated systems, or projects that require many complex operations simultaneously. Because of their versatility and complexity, FPGAs can be difficult to work with and may pose a significant challenge to the team due to lack of experience and familiarity. Unlike other methods of processing available, FPGAs are hardware coded [32]. Boolean logic is used to code repeatable processes that can be run independently at incredibly fast speeds. Additionally, the exact power consumption varies with the processes coded into the board, which makes predicting the power usage difficult. However, FPGAs are very efficient, and so it is possible that power usage could be lower than a microcontroller, but the exact value would be impossible to determine before programming the controller [32].

Table 11: Pros and Cons of FPGA board.

Pros	**Cons**
Extremely fast processing Lower power consumption	Difficult to work with Will not know exact power consumption until programmed Expensive

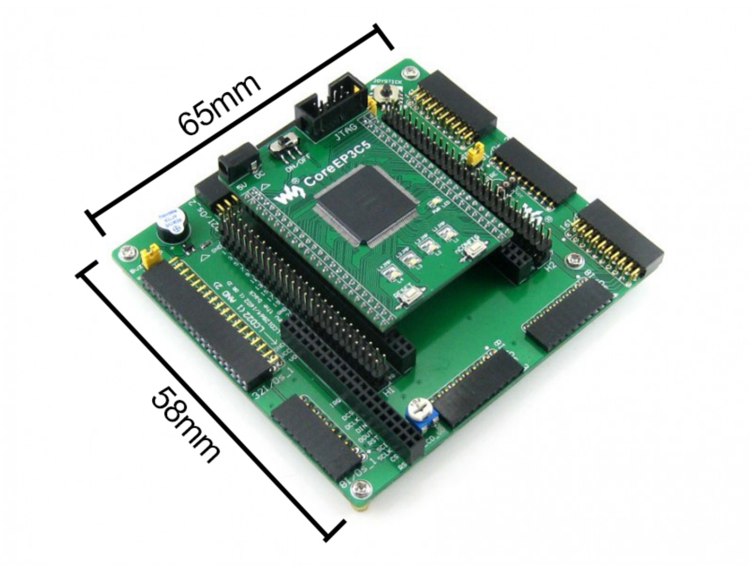

Figure 19: Example FPGA board [28].

4.2.4 FPGA & Microcontroller

The FPGA-microcontroller combination integrates the best features of FPGAs and microcontrollers into one device [31]. Certain processes that need to be done quickly and simultaneously are allocated to the FPGA component of the board while more variable processes can be handled on a more user-friendly microcontroller. These boards are often far more expensive due to their versatility and complexity. These are almost the most powerful portable option available (next to the Netbook), but because the FPGA still requires hardware coding, it still represents a significant challenge to the RADIANCE team.

Table 12: Pros and Cons of FPGA & Microcontroller combination.

Pros	**Cons**
Extremely fast processing	Very expensive
Can split between simple and complex processes	Difficult to work with

4.3 Power Source

In order for RADIANCE to be completely independent of the HiWind gondola the system must be capable of providing power to itself. The obvious choice for providing self power is the use of solar panels, for RTG's, and gas generators are not valid options for a cubesat that will have an volume of 3,000cm^3. Since solar power is the recommended choice from both HAO/NCAR and has been the main power source for most spacecraft and high altitude balloon payloads the type of solar panel that would be needed had to be determined. Three different grades of solar cells are available that could be used on the RADIANCE system, space-grade, industrial-grade, and consumer-grade. The key requirement when looking at solar power is that each cell or array of cells is different and has different characteristics, that being said a baseline power output is needed for a comparison of solar panels. The baseline power required was taken to be 15W, which is the power output that will be generated from the HiWind gondola. HiWind uses large solar panel arrays that will provide the entire gondola with power. The RADIANCE mission was given a guaranteed 15W power supply from these solar panels to power its system. However because the eventual goal is to build a cubesat that will be launched and flown on its own HAO/NCAR wished to have the RADIANCE mission provide its own independent power and only use the power from HiWind if necessary. HiWind will provide the backup power supply so the RADIANCE solar panels must provide at lease 15W of power to match this backup supply. Solar cells(or photovoltaic cells), have a unique material property in the layers in which they are built that allow photons to be turned into electrical power. This occurs on the atomic level when a photon passes through the different layers that make up a photovoltaic cell and at some point the photon is absorbed, but in the act of absorbing the photon the material gains energy, which then ejects an electron. This conversion from light to electricity is at the heart of how solar panels work. The complexities of the different layers and construction of the photovoltaic cell differs for each panel. However since all solar cells work in essentially the same way the details of the different types of panels was refined to look at each types performance. For this project the key parameters of importance are the efficiency of the solar cell, the amount of area required to generate 15W of power, and the amount of voltage and current each cells produces and draws [35].

4.3.1 Space Grade Solar Cells

The first type of solar cell that was looked at was a space grade solar cell that is typically used on small cubesats and other small satellites from Azurespace. They manufacture a large variety of solar solutions that can be applied to space applications. This was a good place to start seeing as the eventual plan for the RADIANCE system is to go onto a full space ready cubesat.

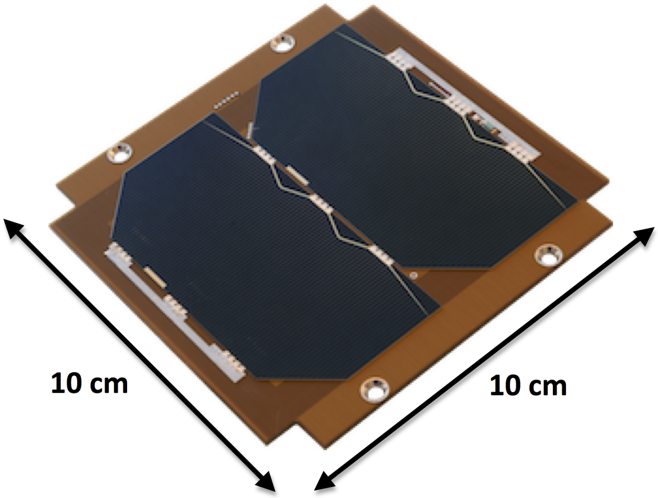

Figure 20: Example of a space-grade solar cell [36].

The following table lists the key features of the space-grade solar cells from Azurespace for an average per cell.

Table 13: Specifications for space-grade solar cells.

Specification	**Value**
Efficiency	40-46%
Nominal Voltage	2.35 V
Average Current	505 mA

Efficiency is really what defines the space-grade solar cells for they are typically between 35-40 percent efficient. They are also designed to handle a wide range of temperatures that they would be exposed to in the space environment. The following table gives a qualitative description for the pros and cons of using a space grade solar cell.

Table 14: Pros and cons of space-grade solar cells.

Pros	**Cons**
Proven on multiple spacecraft Small and light weight Highly efficient	Expensive Fragile and difficult to handle

As stated above the Azurespace solar cells have a proven history in space flight for powering small satellites such as cubesats. The cells tend to be lighter than other cells on the market for the do not have as many layers of protective coating for they are not expected to be exposed to weather; plus the mass of anything goes into space is reduced as much a feasibly possible. The downsides to using space-grade solar cells is that they are very expensive because of the fine micro films used in their construction to attain such high efficiency. Also due to the reduction of any unnecessary mass the cells are typically very fragile and need to be handled with extreme care.

4.3.2 Industrial Grade Solar Cells

The next step down from space flight ready solar cells are solar cells that can be bought for industrial purposes. These solar cells have moderate to high efficiency and are typically used to power things like homes and exterior devices that would be in constant exposure to sunlight during the daytime. The solar panels that these cells come on are normally large for they are meant to deliver large amounts of power, however the individual cells that make up these larger panels can be purchased separately or deconstructed from a larger panel to be used on a small system like RADIANCE.

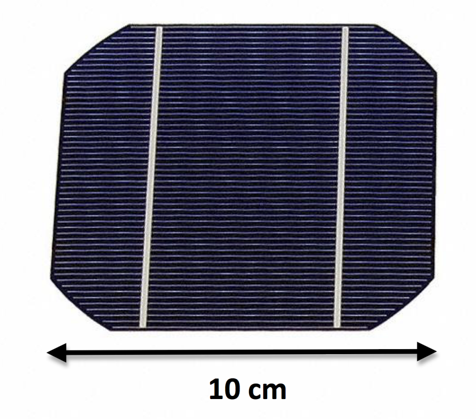

Figure 21: Example of a industrial-grade solar cell [37].

Properties of the industrial grade solar cells are similar to those of the space-grade solar cells, just with lower efficiency and not as compact. The following table demonstrates these averaged values looking at similar grade solar cells.

Table 15: Specifications for industrial-grade solar cells.

Specification	**Value**
Efficiency	20-30%
Nominal Voltage	5.5 V
Average Current	360 mA

The following table looks into the more qualitative overview of the advantages and disadvantages of the industrial solar cells:

Table 16: Pros and cons of industrial-grade solar cells.

Pros	**Cons**
Durable	Hard to integrate
Medium sized	Need to use all sides of cubesat

One of the most challenging things about using industrial grade solar cells is that they typically come in large arrays that would need to be disassembled in order to put connect them in a way to generate power for a small system such as RADIANCE. The advantage of using these cells is that they are low cost compared to the space-grade solar cells and much more durable.

4.3.3 Consumer Grade Solar Cells

The final grade of solar cell that was evaluated for feasibility on the RADIANCE system was consumer grade solar cells that can be purchased at any common site (i.e. Amazon.com). The advantage of of these cells is that they are very cheap compared to the other solar cells looked at for RADIANCE. These cells have very low efficiencies and are used for projects like small remote controlled powered devices.

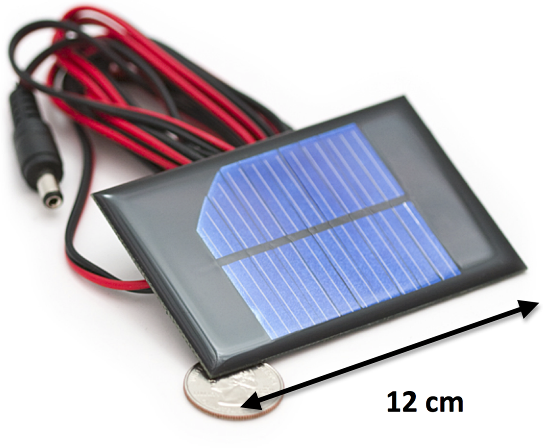

Figure 22: Example of a consumer-grade solar cell [38].

Typically these solar cells are small and provide low current draws. The voltage that each cell can generate is dependent on the size of the panel. For the panel reviewed it has the following properties.

Table 17: Specifications for consumer-grade solar cells.

Specification	**Value**
Efficiency	15-19%
Nominal Voltage	12 V
Average Current	0.58 A

There is typically a trade off of between voltage and current draw meaning that if you boost the voltage the current is typically dropped for the same area solar panel. The advantages and disadvantages of consumer grade solar panels is tabulated below:

Table 18: Pros and cons of consumer-grade solar cells.

Pros	**Cons**
Low cost Durable COTS hardware	Low Efficiency Large Surface Area

The best features of the consumer grade solar panels is the low-cost of the solar cells. they are typically very durable because they are meant for average consumer use in things like remote controlled cars. They can also be purchased almost anywhere, such as hobby, hardware, and general stores. he down sides are more substantial however. These solar cells are small and don't typically generate a lot of power so in order to reach the 15W minimum a large number of these cells would be required. Of course this means that more area would be required to generate that amount of power, and due to the low efficiency of the cells that area would likely go beyond that allowed by a 3U structure.

4.4 Batteries

Several different battery chemistries are under consideration in the design of the RADIANCE power system. The driving requirement of the power storage system is to provide power independently of the HiWind platform. To this end, batteries serve two purposes: to maintain power supply to RADIANCE if the the power generation system experiences interruptions and to buffer fluctuations from the power generation system. This meets functional requirement 5.3.

At a high level, there are two battery designs, primary (non-rechargeable) batteries, and secondary (rechargeable) batteries. Primary batteries have the advantage of being lightweight and inexpensive, but they have a low nominal cell voltage, and they experience significant voltage drops as the cell discharges. While primary batteries solve the design requirement 5.3 of powering RADIANCE when it is unable to generate its own power, it would also require a separate system to smooth the power generated by the solar panels.

Figure 23 gives a functional block diagram for rechargeable batteries and Figure 24 is a functional block diagram for non-rechargeable batteries. Both cases have the same functionality from the HiWind power source: the power is taken from an input from the platform (with the system fused such that RADIANCE does not overdraw power), then the voltage must be stepped down to a usable voltage for RADIANCE. With the independent power system, the decision to use primary or secondary batteries changes the necessary design. For the rechargeable case (Figure 23), the solar panels feed into the battery by way of an overcharge protection circuit. As long as the batteries are providing sufficient power to the power distribution board, the power switch will draw power from the batteries. In the case that there is insufficient power from the batteries, then the power switch will draw power from the HiWind platform. The non-rechargeable case has a similar functional process, however instead of the solar panels feeding into the batteries, the panels feed into capacitors to smooth the input power before being fed into the power switch. This power switch then will draw power from the batteries only if the solar panels don't provide enough power independently. If neither panels nor batteries are able to provide the necessary power, then the power switch will shift to power from HiWind.

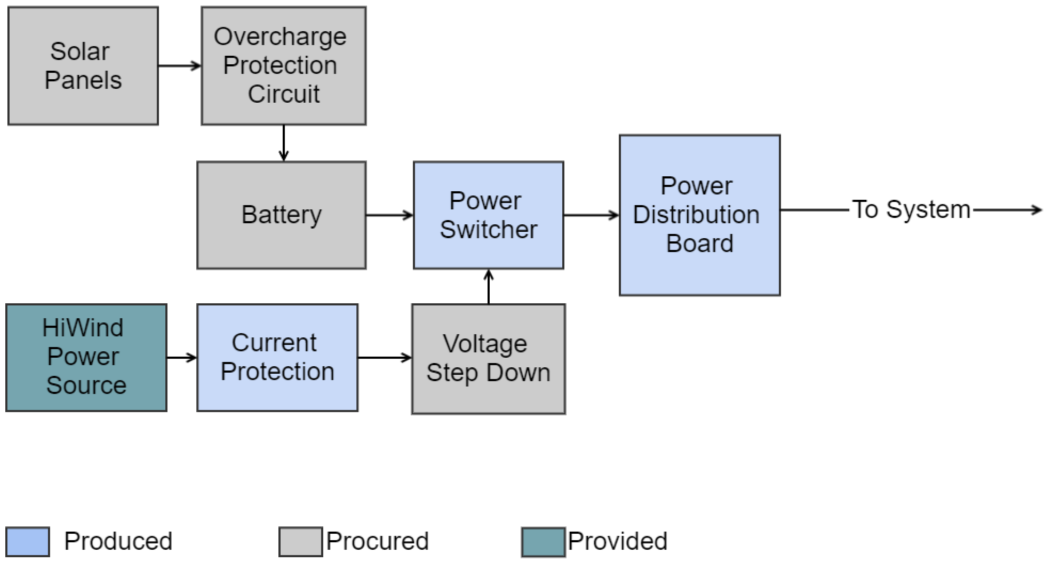

Figure 23: FBD of the power system using rechargeable batteries.

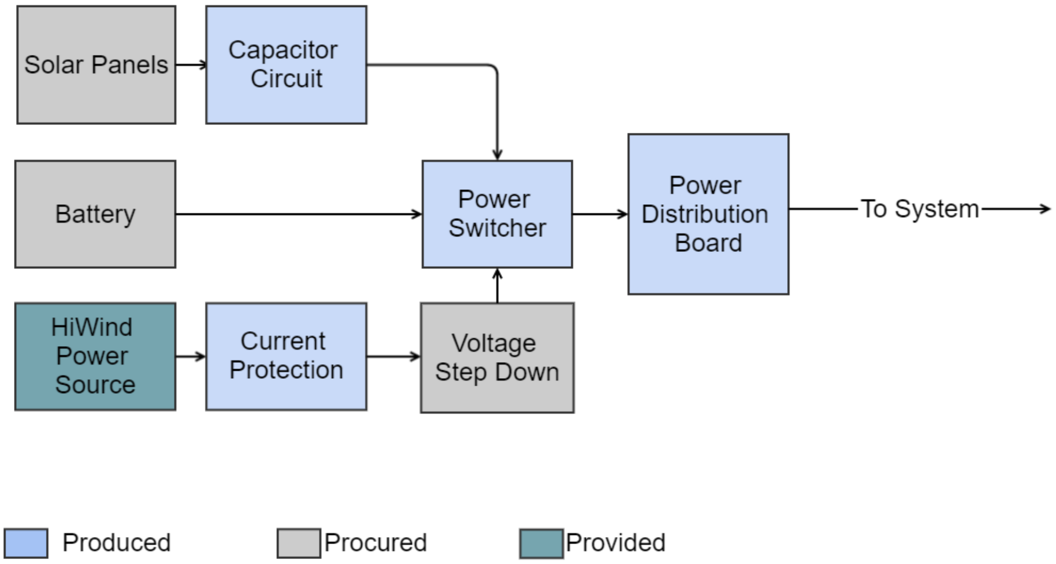

Figure 24: FBD of the power system with non-rechargeable batteries.

4.4.1 NiCd

The first battery option considered is the nickel cadmium (NiCd) battery. This battery type is a secondary (rechargeable) battery that is well understood, and has been in use since the 1950s. It has previous history in space based applications, making it an appealing option for near space conditions. While prepackaged multi-cell options exist for this battery, the most common off the shelf NiCd package contains a 1.2V cell. This presents a problem for generating the system's required voltage, as more batteries are required to generate the minimum voltage and power components such as the micro-controller need to operate. Two possible multi-cell design options to generate the minimal voltage necessary are shown in Figure 26 and Figure 27. In Figure 26, the batteries wired in parallel provide additional capacity to the system. Figure 27 shows a simpler option, trading a lower capacity for a simple, less space intensive circuit. Some selected properties of the NiCd battery are shown in Table 19 [60][61][64][65].

Figure 25: A standard 1.2V NiCd cell [53].

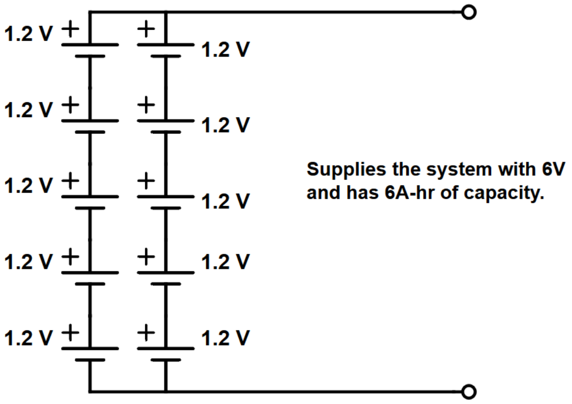

Figure 26: Schematic of the battery configuration to supply 6V at 1.2V per battery.

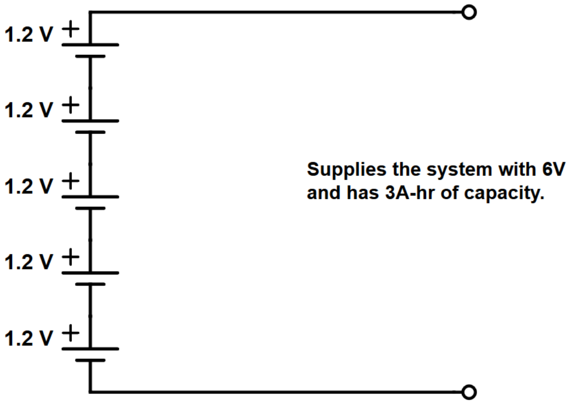

Figure 27: Schematic of a battery configuration to supply 6V and 3A-hr at 1.2V per battery.

Table 19: Table of selected NiCd battery properties [60][61][64][65].

Specification	**Value**
Energy Density	100 Wh/L
Nominal Voltage	1.2 V
Self Discharge (% per month)	10%
Operating Temperature	−40°C to 60°C

Some pros and cons of NiCd batteries are listed in Table 20. Some advantagous features of the NiCd battery are the wide temperature range, generally from −40° C to 60° C. As far as disadvantages, the battery has a memory effect of a non full discharge, meaning that if the battery isn't fully discharged, it is prone to not being able to discharge past said point on the next discharge cycles. The memory effect is a particular concern for this project, the batteries not being fully discharged is likely in the RADIANCE mission.

Table 20: Pros and cons of NiCd batteries.

Pros	**Cons**
Rechargeable	Low Nominal Cell Voltage
Wide Thermal Operating Range	Low Capacity
	Memory Effect

4.4.2 NiMh

Nickel metal hydride (NiMh) batteries are operationally very similar to NiCd batteries. The key differences is the higher energy density, which allows for a higher capacity in less space and weight. Fig. 28 shows an image of a multi-celled configuration of NiMh batteries, where several 1.2V cells have been wired together for a greater voltage and capacity, similar to the circuit diagram shown in Fig. 26 [60][61][65].

Figure 28: A multi-cell configuration of NiMh batteries [54].

Some properties of NiMh batteries are shown in Table 21. This table shows the trade off between NiCd and NiMh batteries, as the NiMh batteries have a much high energy density, but have a higher self discharge rate, and a smaller temperature range.

Table 21: Table of selected NiMh battery properties [60][61][64][65].

Specification	**Value**
Energy Density	400 Wh/L
Nominal Voltage	1.2 V
Self Discharge (% per month)	30%
Operating Temperature	−20°C to 60°C

Some pros and cons are listed in Table 22. Some notable details in this table are that NiMh, like NiCd's have a low nominal cell voltage of 1.2V, and the previously mentioned trade off of high energy density and high self discharge. NiMh batteries also have the advantage of being far more environmentally friendly, with less toxic materials than NiCd batteries.

Table 22: Pros and cons of NiMh batteries.

Pros	**Cons**
Rechargeable	Low Nominal Cell Voltage
High energy density	High self discharge
Non-toxic	

4.4.3 Lead Acid

The lead acid battery provides an appealing option from the voltage and capacity standpoint, as the lead acid batteries has an extremely large capacity and generally high voltage output, as a typical application of a lead acid battery is high capacity needs, such as for a car. A typical off the shelf lead acid battery is shown in Fig. 29 [60][61][63].

Figure 29: A lead acid battery pack [55].

Some properties of lead acid batteries are shown in Table 23. Some items of note are the low energy density compared to other rechargables on this list, as while the lead acid batteries are sold off the shelf at high voltages and capacities, the batteries are massive in size and weight.

Table 23: Table of selected lead acid battery properties [60][61][63].

Specification	**Value**
Energy Density	60-75 Wh/L
Nominal Voltage	2.1 V
Self Discharge (% per month)	3-20%
Operating Temperature	−20°C to 60°C

A pros and cons table is shown in Fig. 24. In addition to the size versus capacity trade off mentioned above, these batteries have the additional problem of be composed of lead and acid, which leads to difficulties disposing of the battery at the End of Life (EOF) of the system.

Table 24: Pros and cons of lead acid batteries.

Pros	**Cons**
Rechargeable	Heavy
High Capacity	Toxic
Resistant to Overcharging	Big

4.4.4 Lithium ion

The lithium-ion battery is a common choice in modern electronics and cubesat designs. For this project, Li-ion is appealing due to its high energy density, and moderately large operating temperature range. These properties are listed in Table 25. A picture of a lithium ion cell typical for hobbyist applications is shown in Fig. 30 [60][61][65].

Figure 30: A typical lithium ion cell [56].

Table 25: Table of selected lithium ion battery properties [60][61][65].

Specification	**Value**
Energy Density	420 Wh/L
Nominal Voltage	3.9 V
Self Discharge (% per month)	10%
Operating Temperature	−20°C to 60°C

Some pros and cons of lithium-ion batteries are listed in Table 26. The major problem with Li-ion batteries are the sensitivity to overcharging, which can kill or explode the battery cell. This creates a potential safety issue to ensure that RADIANCE does not catch fire during flight.

Table 26: Pros and cons of Lithium ion batteries.

Pros	**Cons**
Rechargeable Light weight History of use on Cubesats	Sensitive to overcharging Extra complexity in Circuit Design

4.4.5 Lithium Primary

As an alternative to rechargeable lithium batteries, lithium nonchargeable batteries exist with similar appealing properties as the lithium ion batteries, without the safety risks associated with overcharging lithium ion batteries. These properties are shown in Table 27. In general, non-rechargeable batteries have the advantage of a simpler circuit design to implement, as well as a cheaper off the shelf cost. The functional flow of a non-rechargeable battery circuit is shown in Fig. 24. An image of a common style of lithium primary batteries is shown in Fig. 31 [62].

Figure 31: A typical lithium primary battery [57].

Table 27: Table of selected lithium primary battery properties [62].

Specification	**Value**
Energy Density	300-710 Wh/L
Nominal Voltage	3 V
Self Discharge (% per month)	1%
Operating Temperature	−55°C to 85°C

Some advantages and disadvantages of lithium batteries are shown in Fig. 28. Notably, lithium primary batteries have a high energy density, meaning that the cells are small. However, lithium primary batteries have the problems typical of non-rechargeable batteries, namely that they have a low discharge current, and will rapidly experience a voltage drop as the battery is discharged.

Table 28: Pros and cons of Lithium primary batteries.

Pros	**Cons**
Cheap	Non-rechargeable
Light weight	Low discharge current
High Energy Density	Voltage drop after discharge

4.4.6 Alkaline

Alkaline batteries are another option of non-rechargeable batteries. Alkalines are the most common off the shelf battery, and are the typical batteries seen in grocery stores for consumer electronics. These cells have a slightly higher nominal cell voltage than other non-rechargeable batteries looked at in this report, so a potential multi-celled circuit would have to contain less batteries in the cell to get the same total voltage and capacity to the system. This configuration is shown in Fig. 32 A single cell alkaline battery is shown in Fig. 33 [66].

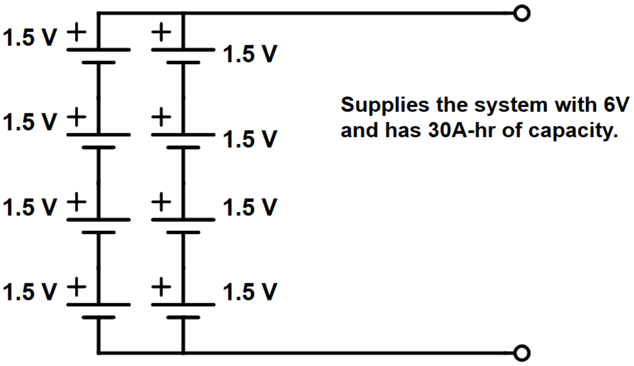

Figure 32: Schematic of battery configuration supplying 6V and 30A-hr at 1.5V per battery.

Some properties of alkaline batteries are shown in Table 29. Notably, the battery has extremely low self discharge, and mid to high energy density.

Figure 33: Typical alkaline battery cells [58].

Table 29: Table of selected alkaline primary battery properties [66].

Specification	**Value**
Energy Density	250-434 Wh/L
Nominal Voltage	1.5 V
Self Discharge (% per month)	0.17%
Operating Temperature	0°C to 65°C

Some advantages and disadvantages of alkaline batteries are shown in Table 30. Both advantages and disadvantages are similar to other non-rechargeable batteries. Some advantages of them include being cheap and lightweight, and some problems with them being the low discharge current and high voltage drop during discharge.

Table 30: Pros and cons of alkaline batteries.

Pros	**Cons**
Cheap	Non-rechargeable
Light weight	Low discharge current
High Energy Density	High Voltage drop during discharge

4.4.7 Li-Po

Lithium polymer batteries are a newer form of rechargeable battery that are able to provide a small and lightweight form. A typical Li-Po cell is shown in Fig. 34. These batteries are known for their high energy density, and are typically used in application where space and weight are critical. Unfortunatly, Li-Po battery cells have been known to explode if misused. Some properties of the Li-Po battery are shown in Table 31 [60][61].

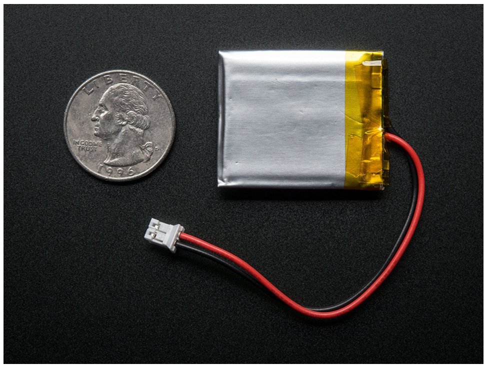

Figure 34: A single LiPo battery cell [59].

Table 31: Table of selected Li-Po battery properties [60][61].

Specification	**Value**
Energy Density	250-730 Wh/L
Nominal Voltage	3.7 V
Self Discharge (% per month)	10%
Operating Temperature	20°C to 60°C

Some advantages and disadvantages of Li-Po batteries are listed in Table 32. Some notable features of the Li-Po battery is its typically high price, and it has a risk of explosion if misused. Some advantages of the Li-Po battery is its light weight and high nominal voltage, leading to less cells needed, and therefore less space used.

Table 32: Pros and cons of Li-Po batteries.

Pros	**Cons**
High nominal voltage Light weight High Energy Density	Risk of exploding Expensive

4.5 Storage Medium

The storage device for RADIANCE will provide a location to store instrument, envirnomental, and housekeeping sensor data for the system. Three types of data storage will be considered: mechanical hard drives, solid state drives, and flash storage.

4.5.1 Mechanical Hard Drive

A mechanical hard drive uses a spinning disk and magnetic head to store data. They come in two form factors, 3.5 inch and 2.5 inch shown in Figure 35. The 3.5 inch form factor measures 146mm in length by 101.6mm in width, and is either 19mm or 25.4mm in height depending on the manufacturer and capacity. The 2.5 inch form factor measures 100mm in length by 70mm in width, and is between 5mm and 19mmm in height depending again on manufacturer and capacity. The most common 2.5 form factor drive is 9.5mm in height. Both 2.5 inch and 3.5 inch form factor drives interface with SATA, causing connectivity issues with the selected processing device. Pros and cons of mechanical hard drives are shown in Table 33 [39][40][41][42][43][44].

Figure 35: 2.5 inch and 3.5 inch form factor hard disk drives [45].

Table 33: Pros and cons of mechanical hard drives.

Pros	**Cons**
Cheap	High power usage
Large storage capacity	Large
	Heavy

Both pros are expanded upon here. These drives come in a capacity from 120GB to 6TB depending on the storage needs. Depending on how much storage is needed, there will be a drive for the capacity needed. Because these drives are so common, a modest 1TB capacity drive costs $50, which would allow for money to be spent on other components as necessary. Each of the cons is also explained here. There is a linear increase in power usage as the storage capacity increases. 500GB drives typically use 2-3 Watts while idling and 5-6 Watts while writing data. As the drive size increases toward 6TB power usage increases to 5-6 Watts while idling and 10 Watts while reading and writing data. This is more than can reasonably be provided as explained above. Drives in the 3.5 inch form factor have two dimensions exceeding the maximum size of of the cubesat, and are thus not usable in this project. Drives in a 2.5 inch form factor have a volume of 70 cm^3 which is larger than some of the other options. Due to the metal platters, hard drives have a significant mass. Mass increases approximately linearly with capacity, from 0.43 kg for a 500 GB drive to 0.72 kg for a 6TB drive [39][40][41][42][43][44].

4.5.2 Solid State Drive

A solid state drive uses flash memory chips to store data in the forms of 1s and 0s. They typically come in 2.5 inch form factors and M.2 interface. The M.2 interface is shown in Figure 36. 2.5 inch dimensions are the same as above. M.2 form factor measures from 30mm to 110mm in length, 12mm to 30mm in width, and 1.5mm in height. The most common form factor is 80mm in length and 22mm in width. None of the microcrontrollers for this project have the capability to use the M.2 interface, so only basic information for these drives was researched. The pros and cons of the SSD are shown in Table 34 [42][43][44].

Figure 36: 2.5 inch drive and M.2 interface drive [46].

Table 34: Pros and cons of solid state hard drives.

Pros	**Cons**
Large storage capacity Low power usage Lightweight	Expensive

Solid state drives come in a capacity from 120GB to 4TB. Depending on the storage need, any drive could be procured to be used for this project. While idling, these drives consume microwatts of power, and while reading and writing these drives use about 3 Watts of power. These drives also have a mass of approximately 55g. SSDs are less common, but are becoming increasingly more common and as such a 500GB SSD costs approximately $150. This offers a large storage capacity for a relatively inexpensive price, but is 6x the cost per GB over the mechanical hard drive [42][43][44].

4.5.3 Flash Storage

For this project, flash storage is defined as a storage device which uses flash memory chips, but is not an SSD. Both SSDs and USB devices use flash memory, but the interface with the computer is different. A Solid State drive is typically inside the computer, whereas a USB or SD card are outside of the computer. USB and SD cards also use less power because they are limited by the port on the computer they are attached to. As such, this section focuses USB and SD Cards. USB and SD cards are shown in Figure 37. These have a wide array of uses for portable storage across an array of devices from smart-phones to digital cameras. USB flash drives do not have a standardized length or width measurement, and each manufacturer of these drives add various components to the exterior of each device. SD cards are standardized and have a length of 32mm and a width of 22mm. The pros and cons of flash memory are shown in Table 35 [48][49].

Figure 37: USB flash drive and SD Card.[47]

Table 35: Pros and cons of flash memory.

Pros	**Cons**
Very low power usage	Low storage capacity
Very small	Expensive
Very lightweight	

USB and SD are limited in power by what the port can provide. USB can only provide a maximum of 1.5 amps, but typically operate at less than 500mA. They also operate at an average of 5 volts or less. This is a maximum power draw of 2.5 W. USB memory sticks typically measure 1.5cm wide by 3cm long by 1cm in height. SD cards are standardized to the dimensions above. These have the smallest footprint of any of the storage devices considered. They also have the lowest mass at approximately 30g. Flash drives and SD cards are limited to 512 GB due to teh physical size of the package. The cost per gigabyte of storage is much higher than the other storage methods. A 256GB flash drive costs approximately $70. This is approximately 5.6x the cost per GB of mechanical hard drives, but is slightly cheaper than SSDs [48][49].

4.6 Attitude Determination

Attitude control for RADIANCE will be provided by the HiWind gondola, which is guaranteed to provide accurate pointing to within one degree of the sun. As RADIANCE will be sun-pointing, HAO/NCAR wants to verify this one degree accuracy by determining the angle between the instrument boresight and the sun vector to within 1 arcminute.

In addition to the hardware and methods for determining the off-sun angle, RADIANCE will also have environmental sensors that will roughly determine its "absolute attitude": that is, in which direction the system is pointed relative to the magnetic south pole and its elevation above the local horizontal. This is in accordance with the requirement that RADIANCE take and store environmental data.

4.6.1 Photodiodes

A photodiode is a semiconductor device that generates a potential difference when exposed to light. Most commercial photodiodes output a range of currents according to the ideal curve given by Equation 1, where θ is the incidence angle on the photodiode [16].

$$I = I_{max} \cos\theta \tag{1}$$

If we assume that the spectrometer boresight is within 90 degrees of the sun (HiWind should keep it within 1 degree of the sun), four photodiodes placed 45 degrees off of the spectrometer boresight will be sufficient to fully define the sun vector relative to the spectrometer boresight [20]. One of the biggest advantages of photodiodes is their price: a simple photodiode only costs a few dollars [17].

Table 36: Pros and cons of photodiodes.

Pros	**Cons**
Very low power usage	Interference from Earth albedo
Small and lightweight	Need to develop algorithm from scratch
Very inexpensive	

Figure 38: A typical photodiode [17].

4.6.2 Gyroscopes/Inertial Measurement Unit (IMU)

Another option for attitude determination is using gyroscopes or an inertial measurement unit (IMU). An IMU consists of three gyroscopes for full three-axis angular velocity determination, and three accelerometers to measure linear acceleration in all three axes. IMUs have an extensive heritage on both atmospheric and space missions since high-end models can be extremely accurate. However, determining angular position from gyroscope measurements requires integrating angular velocity, which becomes inaccurate over long time ranges and requires another form of attitude determination to calibrate against. As RADIANCE will be flying for two weeks, this effectively makes gyroscopes a non-option. A cheap IMU is approximately \$50, while more expensive models can cost thousands of dollars.

Table 37: Pros and cons of gyroscopes/IMU.

Pros	Cons
Extensive heritage	Extreme inaccuracy over long time ranges
Simplicity of installation and use	More expensive
	Large and heavy

Figure 39: A typical inertial measurement unit [18].

4.6.3 Coarse Sun Sensors

Coarse sun sensors are pre-built photodiode arrays used for determining the position of the sun in body coordinates, which would fulfill the requirement of measuring the off-sun angle. Coarse sun sensors are used on many space missions as well as for solar panel tracking mechanisms on the ground due to their relatively low price and simplicity. However, coarse sun sensors tend to be much more expensive than assembling a custom photodiode array, especially for the higher-end models that are usually rated for a space environment [19]. These space-grade coarse sun sensors cost thousands of dollars, while cheaper and less sophisticated models can be under $1000.

Table 38: Pros and cons of coarse sun sensors.

Pros	Cons
Low power usage	Very expensive
Extensive heritage	Larger and heavier than photodiodes
Very durable	

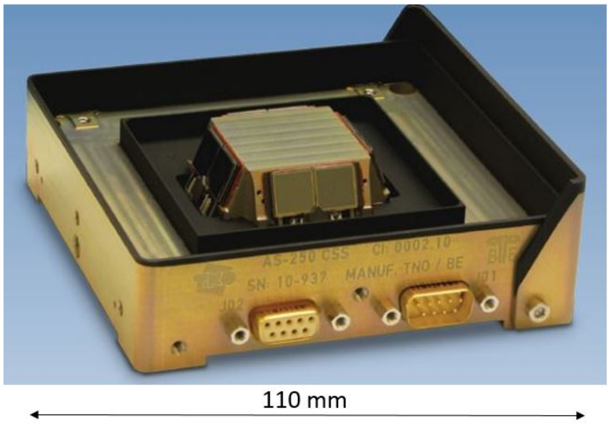

Figure 40: A typical coarse sun sensor array [19].

4.6.4 Camera

Another option for measuring the off-sun angle is processing the images captured by the required camera with a neutral density filter. With a known angular distance per pixel, the angle between the camera boresight and the sun can be determined through image processing. However, this is beyond the computing power of most microcontrollers and would be far more complex than using photodiodes.

Table 39: Pros and cons of using the camera.

Pros	Cons
No need for additional hardware	High required processing power
Inexpensive	Very complex image processing algorithm

4.7 Structure

The structure of the RADIANCE payload is one of the most integral parts of the design in that it will hold all of the subsystems and keep the entire system together. The design of the structure needs to be robust enough to survive a rough crash landing when the HiWind gondola lands, and flexible enough to allow changes to the subsystems as the final design becomes more complete. The structure must be able to easily integrate with HiWind so that it can be easily installed and removed before and after flight. Without currently knowing what the exact interface between HiWind and RADIANCE will be from the customer the path that must be taken in structure design must be able to accommodate later changes to the design such that it will interface correctly. Several designs for a structure could be eliminated using common knowledge and other systems that have flown for other missions with a variety of purposes. Since a 3U design will be used to build the RADIANCE payload one idea that was considered for the structure was to take three 1U cubesat structures and attach them together to complete a 3U system that is required for the RADIANCE system. In principle this seems like a good idea, except that the design has several flaws. The first of these flaws is that it adds extra complexity to the design that is unnecessary. The challenges that are involved with taking three separate sub-structures to one large main structure creates more parts and interfaces which add to the likelihood of failure. The design also adds no practical advantage in a system that will likely fill all three U's worth of space. For these reasons this design was not considered for manufacturing. The requirements have lead to two fundamental designs that fit the 3U structure and allow for flexibility with the specifics of the design once parts and subsystems are finalized.

4.7.1 Interior Structure

The first of these two designs is a very typically seen 3U cubesat configuration where there is some interior structure with exterior face plates that add structure and support. The advantage of an interior structure is that it adds a framework for all the other components of the structure to be mounted to while providing the added advantage of more support for external loading, like crashing. The design would likely incorporate a framework that is made of bars or struts that internal components like the thermal control unit, spectrometer, and others could be mounted to. It would also have plates on all the exterior surfaces to make up added support to increase the overall durability of the structure. These plates would be bolted, or screwed to the sides of the interior framework to allow easy access to the interior components and subsystems.

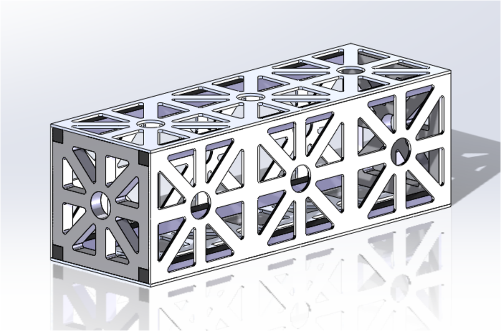

Figure 41: Concept of an interior structure framework.

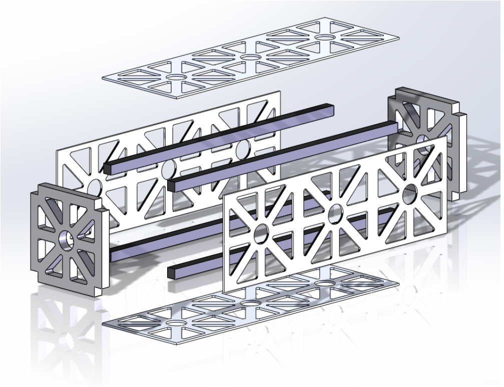

Figure 42: Exploded view of an interior structure concept.

Some of the advantages of this design are that it is a common design used in similar space-flown cubesat designs. In terms of ease of manufacturing the design yields to simplicity of machining cuts and tapping into the rods to create threads for the exterior plates to be mounted. In Figures 41 and 42 there are cutouts in the side-plates; this is a conceptual design and not the final configuration but the advantage is that there is flexibility to the weight, also the panels can be used to easily mount insulation to help with the thermal system through the ascent and descent stages of the mission. Perhaps the biggest advantage of the design however is that it is easy to access the interior to make changes to the interior subsystems, or access the storage device for post processing without disassembling the entire structure. The biggest disadvantage to this design is that if an interior structure is used it reduces the amount of interior volume that can be used to place components and subsystems. Another disadvantage is that if an interior framework is used with exterior mounted plates it adds to the complexity of manufacturing and assembling the structure, due to the fact that there will be more parts and interfaces between surfaces.

4.7.2 Exterior Structure

Another considered design option is building the structure completely out of plates on the exterior. This design has also been flown on many cubesat missions for a variety of reasons such as, light weight, structurally durably, maximizing interior payload space, and others. In the scope of this project this design would allow for the maximum amount of space on the interior of the structure which would allow a lot of flexibility in the location of items like the camera, spectrometer, and batteries. This design would likely incorporate some form of interlocking plates along the 10cm by 30cm sides that would then bolt or screw into two 10cm by 10cm end plates.

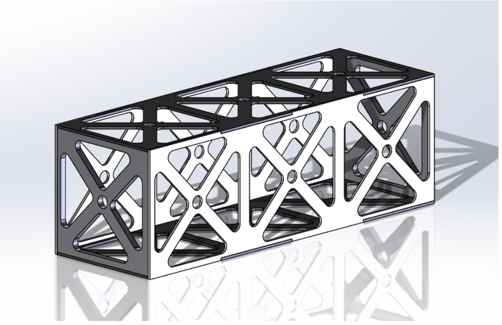

Figure 43: Concept of an exterior structure framework.

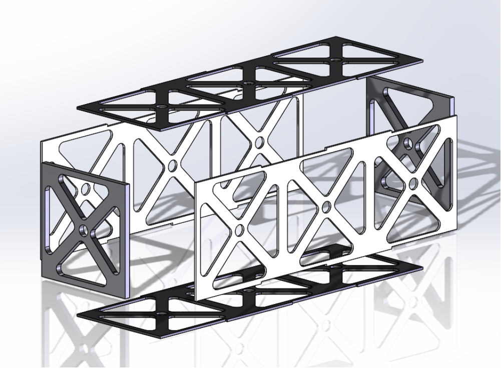

Figure 44: Exploded view of an exterior structure concept.

The second design is another concept of structures used in cubesats that have flown in space, so the design has some heritage from other missions that needed an similar system. This design maximizes the amount of interior volume usable for subsystems and components, while maintaining durability. The interfaces between the components are simple and require minimal hardware like bolt/screws to hold them together. Some disadvantages are that it is easier to mess up the interface between side plates during manufacturing due to the tight tolerances required to make the design structurally sound. The biggest disadvantage is that when making changes to the interior or subsystems, the majority of the structure has to be taken apart to access the interior. This adds unnecessary complexity to the process of making internal changes.

4.8 Materials

The structure will be built primarily of one material, so the following considerations were made when looking at the types of materials that the structure should be built out of. With price being such a huge factor that was the first thing that was looked at in terms of selecting materials. Thermal properties, and strength were the second most important items looked at for the structure will experience a huge range of thermal exposure ranging from $-60°$C to $20°$C, and needs to survive the force of impact with the ground during landing.

4.8.1 Metals

The first and most well known material that was evaluated was different types of metals, in particular Aluminum. Aluminum has a vast history in space applications was it was the first place we start to look for materials to build the structure out of. The following table of material properties is and average of many different types of Aluminum ranging from Al 6061-T6, 5052-H32, 7075-T6.

Table 40: Average table of property values Aluminum [50].

Property	Average Value
Ultimate Tensile Strength	370 MPa
Modulus of Elasticity	70.3 GPa
Shear Modulus	26.2 GPa
Thermal Conductivity	145 $\frac{\text{W}}{\text{m-K}}$

Table 41: Pros and cons of using metals.

Pros	**Cons**
Strong and Rigid	Heavy
Inexpensive	High Thermal conductivity
Proven in Space	

As shown in Table 41, the biggest potential advantage of using metals in the design of the structure of the system is that aluminum has a vast heritage of space flown missions. This is advantageous to the RADIANCE mission because the eventual plan is to build a cubesat that can be flown in the space environment. The strength of aluminum and its relatively low cost typically outweigh the disadvantage of the material being heavy compared to composites.

4.8.2 Composites

Composites are a quickly expanding field in the aerospace industry for their high strength and light weight, so it made sense to look into building the structure of the system out of composites. Looking into composites yielded an immense variety in available types of materials to choose from, so in order to narrow down the search the focus was on carbon composites. The key properties to look at were the tensile strength, modulus of elasticity, and thermal conductivity.

Table 42: Average table of property values Carbon composite T300 [51].

Property	**Average Value**
Tensile Strength	1.689 GPa
Modulus of Elasticity	137 GPa
Thermal Conductivity	$0.025 \frac{\text{Cal}}{\text{cm}\cdot\text{s}\cdot{}^\circ\text{C}}$

Due to the vast amount of composites that are available for building materials in space applications the carbon composite sheeting was used and the following table of advantages and disadvantages breaks down the data in Table 42.

Table 43: Pros and cons of using composite materials.

Pros	**Cons**
Strong	Expensive
Proven in Space	Difficult to manufacture
Many Options	

One of the biggest down sides to the use of composites in structure construction is that it is typically difficult to manufacture without the proper equipment. For the carbon composite used in this analysis it would require being fabricating using an epoxy and carbon fiber fabric to create a hard lightweight layer of material. This would then be used to create the entire structure. Unfortunately there are a lot of unknowns into how this process would work which counter-balances the advantages of the extreme strength, and use in space.

4.8.3 Plastics

The final material that was considered for building the structure of the system out of was plastic. Typically plastic has a very poor record in space applications due to the fact that in a vacuum the material out-gasses releasing harmful materials into the area around the spacecraft that could harm or degrade the systems or instruments. Out-gassing, however is not a problem at the 40 km altitude that the HiWind balloon will cruise at so plastics can be considered as a viable means of building the structure. The primary method of plastic manufacturing is injection molding, which is far out of the budget for RADIANCE mission, however advances in 3D printing and laser fabrication allow other methods of plastic manufacturing. The key properties of plastics that are important to the RADIANCE mission are the tensile strength, modulus of elasticity, flexural strength, and coefficient of thermal expansion. The material that was focused on for the purposes of manufacturing was 3D printed ABS plastic (acrylonitrile butadiene styrene; a common material in 3D printing). This was because the properties of the ABS were the closest to what we would need in order for the structure to be sturdy enough and reliable enough fly in cold temperatures and survive impact with the ground.

Table 44: Average table of property values for ABS 3D printed material [52].

Property	**Average Value**
Tensile Strength	55 MPa
Modulus of Elasticity	2.4 GPa
Flexural Strength	65 Gpa
Coefficient of Thermal Expansion	$8.82^{5}\ \frac{\text{mm}}{\text{mm}\cdot{}^{\circ}\text{C}}$

The values in Table 44 are the average between ABS printed using a polyjet printer and a FDM printer. Both printers build the model in layers, but the FDM uses a spool of plastic that it then melts to lay out each layer, while the polyjet printer uses two different build materials in a liquid state that prints each layer at a time curing it as it goes using a UV lamp. The following table lists the advantages and disadvantages of using 3D printed structure for the RADIANCE system.

Table 45: Pros and cons of using plastics.

Pros	**Cons**
Lightweight	Brittle at low temperatures
Flexible design options	Moderately expensive
Many Options	Not typically used in space application

3D printing has been changing the field of manufacturing in all fields of industry and aerospace is no exception. The biggest advantage of using 3D printing over conventional manufacturing techniques is its ability to allow extreme customization in the design of structures. Unlike machining and CNC a 3D printed structure can have elaborate internal framework that other manufacturing methods won't be able to achieve. In the scope of the RADIANCE project this would allow flexibility and customization to internal component layout which would allow the team to maximize the internal area usage. The biggest downside of 3D printed plastics is the fact that at cold temperatures the plastic becomes very brittle and prone to breaking. A 3D printed plastic is already more brittle than an injection molded part because the plastic is laid out and cured in layers creating natural flaws in the material which make it more prone to shear. After looking at the pressure and atmospheric models it was determined that in the medium vacuum, which will be the cruise altitude for the balloon, out gassing will likely not be a problem.

4.9 Thermal Control

Due to the extremely dynamic environmental swings through ascent and descent, some form of thermal control system must be in place to prevent thermal shock to the instruments on RADIANCE. There are three main categories of thermal control to be considered: active control which allows for variable heating of the system, passive control which provides a constant amount of heating or cooling, and thermal insulation which slows temperature shifts in the system. It should be noted that these categories are not mutually exclusive. In many cases, all three categories are used in conjunction with one another [67].

4.9.1 Active Thermal Control

If implemented, active thermal control will help assist in keeping the instruments working the dynamic sections of the flight as the pressure decreases and the ambient temperature swings wildly. During ascent the convective and radiative cooling will not be constant and at some points may be higher than the system can handle without active heating. Strategically placed heaters may help keep the system warm through ascent and descent.

4.9.1.1 Peltier Devices Peltier devices are arrays of thermocouples which can drive heat through them when a current is applied. They can drive heat in either direction depending on the direction of current flowing through them and can move more heat than they use. The biggest problem with Peltier devices is that they need relatively constant current to work properly, pulsed current will not work effectively, and alternating current will heat stress them to the point of failure relatively quickly [68].

Table 46: Pros and Cons of Peltier Devices.

Pros	**Cons**
Heating and cooling	Requires heat sink
Can move more heat than energy used	Subject to cyclic stressing
Capable of cooling below ambient temperature	Requires extra driver circuitry

4.9.1.2 Resistive Heating Resistive heaters are heating elements that can easily be put in parallel with existing electric systems. They don't require any additional drivers, though they can be driven on separate circuits with just about any form of current. They can also be sized to be able to handle several watts of heating without any stress to the heating element.

Table 47: Pros and Cons of Resistive Heating.

Pros	**Cons**
Extremely easy to implement	Point sources of heat
Can provide as much or little heat as desired	Requires moderate FOS on power rating
Very Inexpensive	

4.9.2 Passive Thermal Control

If implemented, passive thermal control will hold the instruments at or near the nominal operating temperature during cruise. The actual need for these is yet to be determined and will depend on the other components that are chosen.

4.9.2.1 Radiators and Solar Heaters Radiators are the mechanically simplest way to disperse or absorb heat for a system when it is in a vacuum. They consist of a heat line leading to a metallic plate with an emissive coating. There is a wide array of coatings that can be selected to either emit heat or absorb it.

Table 48: Pros and Cons of radiators and solar heaters.

Pros	**Cons**
Easily analyzed	Requires heat path
Does not require additional power draw	Cannot change heat flux
No moving/electrical parts	Requires additional Hardware

4.9.2.2 Heat Draw from Solar Panels One slightly more exotic way to get heat is to pull it off the solar panels. They are known to get extremely hot and often have radiative coatings on the back to help them cool down. This method would draw any additional heat needed to keep the system warm from the solar panels which would help cool the solar panels at the same time.

Table 49: Pros and Cons of Drawing Heat from Solar Panels.

Pros	**Cons**
Does not require additional panels	Requires heat sink line
Increases solar panel efficiency	More difficult to deploy (In path to space)
No additional electrical parts	Harder to analyze

4.9.3 Thermal Insulation

If implemented, thermal insulation will aide in both sections of the flight and will slow temperature shifts of the instruments. It may be necessary to prevent heat stressing of the components in the system. It may also help to keep the heat in the system during ascent and descent to keep the instruments working and taking data on the planned schedule.

4.9.3.1 Silica Aerogel Silica aerogel is known as one of the lightest solid substances ever created. It is about 99% open space and is known as a fantastic conductive insulator. Aerogel is extremely expensive but used extensively in satellite applications due to its thermal properties.

Table 50: Pros and Cons of Silica Aerogel Insulation.

Pros	**Cons**
Extremely low density	Very delicate
Very high thermal resistivity	Expensive

4.9.3.2 Fiberglass Fiberglass is an average household insulator. Many people know it as the pink "cotton candy" in their attic. It can be in loose fiber form or in a loosely felted sheet known as a batt. Fiberglass unfortunately presents a potential health and safety risk if used. It is well known that fiberglass is an irritant and can be harmful if it gets into the lungs [69].

Table 51: Pros and Cons of Fiberglass Insulation.

Pros	**Cons**
Very inexpensive	Difficult to purchase in small quantities
Lightweight	Needs special coating to contain fibers
Easy to manipulate into any desired shape	Little test data for vacuum environment

4.9.3.3 Mineral Wool

Mineral wool is a high temperature version of fiberglass insulation. It is primarily used to insulate furnaces and chimneys. Unfortunately mineral wool has similar health issues like fiberglass, however it is slightly safer [69].

Table 52: Pros and Cons of Mineral Wool Insulation.

Pros	**Cons**
Lightweight	Designed for high temperatures
Easy to manipulate into any space	Needs special coating to contain fibers
	Little test data for vacuum environment

4.9.3.4 Polyurethane Foam Panels

Polyurethane foam panels are high density foam panels that are designed to be low profile with high resistance to heat transfer. These foam panels are often used in homes to insulate crawl spaces and basements from the cold ground. They are sold in large boards and often in large packs of those boards.

Table 53: Pros and Cons of Polyurethane Foam Panel Insulation.

Pros	**Cons**
Lightweight	Difficult to get in small quantities
Easy to manipulate	
Fiber Free	

4.9.3.5 Polystyrene Foam Panels

Polystyrene foam panels are similar to polyurethane panels but are made from a cheaper form of plastic and is much less dense. It has similar uses to the polyurethane foam but is cheaper and more flammable. It can also be found in almost all packing applications due to its ability to absorb shock.

Table 54: Pros and Cons of Polystyrene Foam Panels.

Pros	**Cons**
Very lightweight	Tends to produce and hold static charge
Fiber Free	Messy during manipulation (foam beads)
Very Inexpensive	

4.9.3.6 Cardboard

Corrugated cardboard sheets are extremely lightweight, inexpensive and due the structure are good insulators. Several layers of cardboard can be built up to produce a thick insulating layer. Cardboard can be found just about anywhere and is the simplest possible insulation in this case.

Table 55: Pros and Cons of Cardboard Insulation.

Pros	**Cons**
Extremely inexpensive	Easy to damage
Very easy to manipulate	Susceptible to humidity

4.9.3.7 Vacuum Panels

Vacuum panels are a new technology that have a high density, high strength foam in a vacuum bag that have ultra-high resistance to heat transfer, and are very lightweight. The biggest problem with vacuum panels is that they cannot be punctured or modified in any way or they will lose their vacuum and lose their effectiveness [70].

Table 56: Pros and Cons of Vacuum Panel.

Pros	Cons
Extremely high conductive resistance	Cannot be modified whatsoever
Very lightweight	Very expensive
Low profile	Can't get in small pannels

4.9.3.8 Metalized Kapton "Space Blanket" Space blankets aren't designed for conductive insulation, they are a radiative heat insulator and are used extensively on satellites. This option could be used in conjunction with another option to resist both radiative and conductive heat losses [71].

Table 57: Pros and Cons of Space Blankets.

Pros	Cons
Very Lightweight	Does not provide conductive resistance
Easy to add to any surface	
Can act as a static barrier	

5 Trade Study Process and Results

5.1 Spectrometer

Table 58: Explanation of spectrometer scores and normalization.

Value	Price	Power Reqs	Wavelength Range	Detector Elements	Detector Pixel Depth	Mass
1	>\$4000	>400mA at +5VDC	Range covers none of the required range	<1000 elements	<10 μm	400-500 g
2	\$3000-4000	300-400mA at +5VDC	Small portion of the required range	1000-2000 elements	10-20 μm	300-400 g
3	\$2000-3000	200-300mA at +5VDC	Covers half of the required range	2000-3000 elements	20-30 μm	200-300 g
4	\$1000-2000	100-200mA at +5VDC	Covers vast majority of the required range	3000-4000 elements	30-40 μm	100-200 g
5	<\$1000	<100mA at +5VDC	Covers required range	>4000 elements	>40 μm	<100 g

Table 58 lists the various scores given for the particular value. The following describe the weights for each value:

Price (35%): Price is the most important characteristic because the average spectrometer price is a significant portion of the total project budget. This means that there are fewer options for other components like microcontrollers and the power system.

Power Requirements (20%): Power required will greatly determine power system complexity and cost. Batteries and solar panels become more expensive and more difficult to design for as power consumed increases. If HiWind gondola is used and the spectrometer requires more power than the HiWind gondola can provide the spectrometer will not be feasible.

Wavelength Range (20%): Wavelength is important because it defines the limits of the science the customer can use. Additionally, larger wavelength ranges are advantageous because they allow more margin for spectrometer configuration. For example, a spectrometer configuration could sacrifice wavelength range to increase spectral resolution.

Detector Elements (15%) and Detector Pixel Depth(5%): Spectral resolution depends on a number of factors including slit width, grating size, and wavelength range. These can be chosen to suit the needs of a specific project. However, spectral resolution also depends on the quality of the detector. Detector elements and detector pixel depth directly affect spectral resolution so they are important quantities for measuring the accuracy of a spectrometer. These quantities are also easily compared between spectrometers with different configurations.

Mass (5%): While our system has no strict mass requirement the future of the system will value low mass.

Characteristics like size were considered for selection for baseline design but are considered threshold criteria — the only requirement is that they fall above or below a certain value. Once over this value, minimizing or maximizing them isn't as important as price or other characteristics.

Table 59: Trade study between selected spectrometers.

Criteria (ranked by weight)		**Ocean Optics USB2000+**		**Ocean Optics USB4000**		**B&W Tek SpectraRad Xpress**		**Avantes Mini 2048**	
Price	0.35	2	0.70	2	0.70	3	1.05	3	1.05
Power Requirements	0.20	3	0.60	3	0.60	2	0.40	3	0.60
Wavelength Range	0.20	5	1.00	5	1.00	4	0.80	5	1.00
Detector Elements	0.15	3	0.45	4	0.60	3	0.45	3	0.45
Pixel width	0.05	4	0.20	5	0.25	4	0.20	4	0.20
Mass	0.05	4	0.20	4	0.20	3	0.15	4	0.20
Totals	1.00		**3.15**		**3.35**		**3.05**		**3.50**

5.2 Processor

When selecting a processor for the project, there were seven parameters that were both common among all choices, and would provide insight on making the best choice.

Price (5%): In many other categories, price has been a major design driver due to the limited budget provided. However in the case of the controller, each option is such a small percentage of the budget that it is not a major cause of concern. Microcontrollers can range from $30-100 and in either case the budget should be flexible enough to accommodate this. FPGA boards are slightly more expensive although the low end does match well to the microcontroller high end. Netbooks are quite expensive comparatively but there are smaller ones that are within the low $100 range.

Processing Speed (5%): The reason processing speed is worth so little when traditionally it would be a large driver on controllers, is because of the intensity of the processes being done. The RADIANCE mission is primarily concerned with taking data, not processing or any sort of control which will be taken care of by Hi-Wind. FPGA boards are able to do calculations instantly however the lack of expensive calculations makes this unnecessary.

Parallel Processing (10%): The ability to do multiple processes at once far outweighs the need to do them quickly. There will be many measurements taken during the flight often at the same time interval. The FPGA excels here because this is the exact category they are designed for. Previously this section would have been narrowed down to memory (RAM), which gives a metric for how a microcontroller would handle parallel operations, but the FPGA circumvents that entirely.

Power Usage (30%): The power budget for the entire RADIANCE mission is only 15W. The controller will draw a significant percentage of this power. Therefore the power usage of the controller is a major selection driver. The logic behind the selections of each system have to do with available knowledge. The netbook uses far too much power, and it is known that it will take too much power giving it the lowest score. The FPGA almost certainly will consume less power than the microcontroller, however the exact power drawn will not be known until the entire board is already programmed. At that point in time, it will be too late in the project to alter the design should it prove to be too much. It is an unknown that can't be planned for, and that uncertainty is problamatic even if the end result would be better. Therefore the microcontroller is the best option because the power consumption is low, and it is a known varriable.

Size (10%): This is a fairly simple parameter. The cubesat only has a set area to place all components in and the size is the major reason the netbook is not a viable option. A netbook simply will not fit. All other options are roughly the same size and cannot be altered significantly.

Compatibility (20%): This is a measure of what options each controller gives. There are many components that run off of GPIO (General Purpose Input/Output) such as most COTS (commercial off the shelf) temperature/environmental sensors. Microcontrollers and FPGA boards have a number of GPIO ports to attach more than enough components for this project, however a netbook does not. There are ways around this, but they do add complexity to the design. A netbook does have the ability to interface with more complex components. For example the spectrometer will most likely require its own software/driver package to be installed in order to work with it. This would work fine on almost any OS, but not any OS can run on a microcontroller and certainly not an FPGA. The metric for each system is difficult to decide because each system has its advantages and disadvantages. The microcontroller overall has the most options when interfacing with other equipment and the importance of the spectrometer integration places the netbook higher than the FPGA.

Familiarity (20%): When dealing with such important and versatile equipment, the former experience plays a large role. The most common pitfall with FPGA boards is the inexperience using them. They are not coded in a traditional format using HDL (hardware description language). The difficulty in coding is why FPGAs are notoriously hard to work with and the major reason they will not be used on this project with no clear reason to use them over other options. Alternatively there has been a large amount of experience with both microcontrollers and netbooks.

Table 60: Trade study of types of controllers available on this project.

Criteria (ranked by weight)		**Microcontroller**		**FPGA**		**FPGA + Microcontroller**		**Netbook**	
Power Usage	0.30	4	1.20	2	0.60	2	0.60	1	0.30
Compatibility	0.20	5	1.00	4	0.80	4	0.80	3	0.60
Familiarity	0.20	5	1.00	1	0.20	1	0.20	5	1.00
Parallel Processing	0.10	3	0.30	4	0.40	5	0.50	3	0.30
Size	0.10	5	0.50	5	0.50	5	0.50	1	0.10
Price	0.05	5	0.25	3	0.15	2	0.10	2	0.05
Processing Speed	0.05	3	0.15	4	0.20	5	0.25	5	0.25
Totals	1.00		**4.40**		**2.85**		**2.95**		**2.60**

5.3 Power Source

In order to achieve the top tier requirements RADIANCE must be able to supply its own power. In order to accomplish this solar panels will be used. The backup power supply that will be provided to RADIANCE from the HiWind gondola is 15W, which means that RADIANCE will need to supply at least that much in order to use the provided power only as a backup system to the primary source of power. The big trade offs with solar panels is that in order to generate large amounts of power (on the order of 15W) a large amount of area is required, or else very efficient solar cells are required. As one would expect, as the efficiency of the solar cell increases, so does the price, and since price is a huge design driver for the RADIANCE project, it was given the heaviest weight in the trade study at 40%. The RADIANCE mission will see large temperature changes as the gondola ascends and descends through the atmosphere, meaning that the solar panels need to survive under those conditions. Considering that the solar panels would be deployed for the entire mission it would be tricky to heat of cool the panel. That being said the weight assigned to thermal operation was

20%. The power output per area of the panel determines how much total area is required to generate the amount of power needed. Since RADIANCE will integrate with the HiWind gondola with a restriction of a maximum area of 70cm x 70cm for solar cells, power output per square centimeter is a constraining design criteria and thus given a weight of 20%. Finally the efficiency of the solar panel was considered in the trade study. Efficiency denotes how much incoming light or photons are converted into usable power. Naturally the higher the efficiency the better the cell. Since efficiency ties into both size and price, the efficiency of solar cells was given a weight of 15%. With all the weights of the criteria established the following trade study was conducted on the three different grades of solar cells available for purchase.

Table 61: Trade study for power source on solar cell quality.

Criteria (ranked by weight)		**Space Grade Solar Cells**		**Industrial Grade Solar Cells**		**Consumer Grade Solar Cells**	
Price	0.40	1	0.40	4	1.60	5	2.00
Thermal Operation	0.20	5	1.00	3	0.60	3	0.60
Power output per cm^2	0.20	5	1.00	3	0.60	1	0.20
Efficiency	0.15	4	0.60	3	0.45	2	0.30
Totals	**1.00**		**3.00**		**3.25**		**3.10**

The Following table denotes why each of the grades of solar cells scored they way they did in the trade study. This gives a solid quantitative value on how each criteria is scored allowing for a more complete analysis of each grade of cell.

Table 62: Explanation of solar panel scores and normalization.

Value	**Price**	**Power Output** (cm^2)	**Efficiency** (%)	**Thermal Operation** (°C)
1	> 1000	< 3200	0-10	<-40
2	500-1000	3200-2600	10-20	-50 to -40
3	100-500	2600-2000	20-30	-50 to -60
4	50-100	2000-1200	30-40	-60 to -70
5	< 50	< 1200	40-50	< -70

As can be seen from Table 61 the industrial grade solar cells scored the best in terms of raw numbers, however it is beneficial to see if the deciding weights and values make sense to use that choice for the baseline design. The heaviest weight was cost due to the fact that there are other expensive components that are more key to the success of the RADIANCE mission which really ruled out the space-grade solar cells because they would likely be too expensive for the team to afford. This leaves the consumer grade solar cells; looking at the hard restriction of an area of 70cm x 70cm the consumer grade solar cells start to look like they may end up taking more than the allotted design area eliminating them as a design choice. This left just the industrial grade solar cell, which is what the trade study said was the best, hereby confirming the results.

5.4 Power Storage

There is a wide range of battery options available off the shelf. For this mission, the fundamental trade off is between non-rechargeable and rechargeable (or primary and secondary batteries respectively). However, this is impossible to do without a better understanding of the types of batteries available for purchase. The trade study shown in Table 63 compares 7 different types of battery, with 5 rechargeable and 2 non-rechargeable battery types. The factors considered were the size, price, capacity, weight, safety, thermal requirements, and the power deliverable of each battery. Size was considered the primary driver of the trade study, as space is at a premium in a 3U cubesat sized project. Price and power deliverable were considered the next two highest drivers in design decisions. Price becomes an important driver as the focus of this mission is to take data, and not to provide an independent power system. Therefore, it would be unreasonable to dedicate a large portion of the project's budget to an independent power system. The next factor considered was the weight of the battery. While weight is not a critical aspect of this project, the lead acid battery, weighing in at approximately nine pounds, makes the weight criteria an important balance to other desirable battery features. The next criteria is safety, which can be a concern in two regards: one, lithium polymer and lithium ion batteries are capable of exploding if misused, and two, many batteries use toxic materials, creating problems at the end of life of the system. The next two criteria are equally weighted, as while battery chemistry has an impact on the these numerical values, they are more capable of being designed around than factors such as price and size. The thermal requirements for instance are capable of being met through the use of a thermal control system, though the design of these systems are highly dependent on each other, as active thermal control will draw power to keep the batteries operating. As far as capacity, the independent power system will have to power the system when solar power will be unreliable, particularly during ascent and decent. At worst case, the system will have to survive entirely on battery power during the 1 hour ascent, making a high capacity important to keep the system functioning.

Table 63: Trade study of types of batteries available on this project.

Criteria (ranked by weight)		**NiCd**		**NiMh**		**Lead Acid**		**Li-ion**		**Li Primary**		**Akaline**		**Li-Po**	
Size	0.25	2	0.50	2	0.50	1	0.25	4	1.00	3	0.75	3	0.75	4	1.00
Price	0.20	4	0.80	3	0.60	4	0.80	2	0.40	2	0.40	5	1.00	1	0.20
Power Deliverable	0.20	2	0.40	2	0.40	5	1.00	5	1.00	1	0.20	2	0.40	5	0.80
Weight	0.15	3	0.45	4	0.60	1	0.15	5	0.75	5	0.75	3	0.45	4	0.60
Saftey	0.10	4	0.40	4	0.40	3	0.30	3	0.30	4	0.40	5	0.50	1	0.10
Thermal Reqs.	0.05	4	0.20	3	0.15	3	0.15	1	0.05	5	0.25	3	0.15	2	0.10
Capacity	0.05	1	0.05	4	0.20	3	0.15	1	0.05	5	0.25	2	0.10	1	0.05
Totals	1.00		**2.80**		**2.85**		**2.80**		**3.55**		**3.00**		**3.35**		**2.85**

The score for each category is defined numerically in Table 64.

Table 64: Explanation of battery scores and normalization.

Value	**Size**	**Price**	**Capacity**	**Weight**	**Safety**	**Thermal Requirements (Minimum Operational Temperature)**	**Power Deliverable**
1	> 1000 cm^3	> \$150	<10 A-hr	> 4lbs	Risk of explosion	> 0 °C	< 1 A
2	600 - 1000 cm^3	\$100 - \$150	10 - 13 A-hr	3-4 lbs	Risk of fire	-15 to 0 °C	1 - 2 A
3	400-600 cm^3	\$50 - \$100	13-16 A-hr	2-3 lbs	Heavy use of toxic materials	-30 to -15 °C	2-3 A
4	200-400 cm^3	\$25 - \$50	16-20 A-hr	1.3 - 2 lbs	Some toxic material use	-45 to -30 °C	3-4 A
5	< 200 cm^3	< \$25	>20 A-hr	<1.3 lbs	Minimal toxic material use	< -45 °C	>4 A

5.5 Storage Medium

Five categories determine which storage medium will work best for this project. Capacity determines the amount of data that can be taken during the mission. Back of the napkin calculations determined that the minimum data taken during the flight was 20GB. This does not include high resolution photos of the sun. By increasing the storage capacity, the number and resolution of photos can be increased. The amount of power that can be used is directly related to every other electrical component on-board the satellite. As such, power consumption must be minimized to maximize the output from the other instruments on-board. Minimizing price is also important, but not as important in the design process. The maximum cost for storage should not exceed \$300, which is significantly less than the spectrometer, but still significant to the overall budget. The size is less important because each of the storage devices considered has a total volume of less than 70 cm^3. If necessary, they can be attached to the side of the spacecraft with Velcro. The final factor analized is the operating temperature. If the operating temperature is low enough, the thermal system does not need to work as hard in order for the data to be able to be stored. The lower the operational temperature, the higher ranking the component receives. A breakdown of how each component schore is shown in Table 65.

Table 65: Options for data storage medium.

Criteria (ranked by weight)		**Mechanical Hard Drive**		**Solid State Drive**		**Flash Memory**	
Capacity	0.30	5	1.50	5	1.50	4	1.20
Power Requirement	0.30	1	0.30	4	1.20	5	1.50
Price	0.20	5	1.00	4	0.80	4	0.80
Size	0.10	2	0.20	4	0.40	5	0.50
Operating Temperature	0.10	4	0.40	4	0.40	5	0.50
Totals	1.00		**3.40**		**4.30**		**4.40**

Each category score is described in Table 66.

Table 66: Explanation of storage medium scores and normalization.

Value	**Capacity**	**Power** [W]	**Price**	**Size** [cm^3]	**Temperature** [^{o}C]
1	$<$ 120 GB	$>$ 5	$>$ \$500	$>$ 350	$>$ 30
2	120 GB - 249 GB	4-4.99	\$400 - \$499	250-349	20-29
3	250 GB - 499 GB	3-3.99	\$300 - \$399	150-249	10-19
4	500 GB - 1 TB	2-2.99	\$200 - \$299	50-149	0-9
5	$>$ 1 TB	$<$ 2	$<$ \$200	$<$ 50	$<$ 0

5.6 Attitude Determination Hardware

Due to the high cost of the spectrometer, the price of other components is critical in developing a baseline design. The various attitude determination hardware design options have a very wide range of prices, from less than \$10 to greater than \$1000, so price was weighted the heaviest in the trade study. Next was the accuracy: since 1 arcminute accuracy is a design requirement, the achievable accuracy for each hardware option was also weighted heavily.

The next consideration was the complexity of implementation. A coarse sun sensor would be exceptionally simple: CSS's typically output either the angle off the sun or a small current that can be directly mapped to an angle using a cosine relationship provided by the vendor. On the other hand, processing the camera images to determine the location of the center of the solar disc would be difficult due to both the complexity of image processing and the processing power limitations. Size is another important characteristic due to the small size of the RADIANCE package, but since most of the attitude determination hardware options will be mounted outside of the main structure it was not weighted as heavily. Finally, the power requirements of the hardware options were given the lowest weight due to the fact that all of the options are low-power.

Also note that the camera option was given high scores for price and size: this is because RADIANCE will have a camera anyways, so using it for attitude determination would not require an additional purchase or additional space to be made to install the hardware.

Table 67: Options for attitude determination hardware.

Criteria (ranked by weight)		**Photodiodes**		**Gyros/IMU**		**Coarse Sun Sensors**		**Camera**	
Price	0.40	5	2.00	4	1.60	1	0.40	5	2.00
Accuracy	0.3	3	0.90	1	0.30	5	1.50	3	0.90
Complexity	0.15	3	0.45	2	0.30	5	0.75	1	0.15
Size	0.10	5	0.50	2	0.20	3	0.30	5	0.50
Power Reqs.	0.05	5	0.25	2	0.10	5	0.25	3	0.15
Totals	1.00		**4.10**		**2.50**		**3.20**		**3.70**

5.7 Structural

The structure of the RADIANCE system is paramount to the design as it will contain all subsystem assemblies, components, and be the connection to the HiWind gondola. The first thing to consider when developing a structure is what material will the structure be made out of. This section will detail a trade study comparison on three different types of materials: metal, composites, and 3D printed plastic. The main design driver of the structure is how much it will cost, which is why the price of each component in terms of a 12in x 24in sheet was given a weight of 35%. Durability was the next big design driver since it will determine the best approximate analysis of whether the material can survive a crash landing. In order to determine this, the tensile strength of each material was used and given a weight of 25% for the trade study. The ease of manufacture of the material is the next most important aspect of the material, as it will determine how easy it is to machine, cut, print, and assemble into a form that would make up the structure. This criteria was given a weight of 10%. The next criteria looked at was density, and to a greater extent weight. Because the exact volume, size, shape of the structure is not known, the comparison of each material's density will determine whether it is a good lightweight choice for the design. However because the design is not heavily restricted by weight, the density criteria was given a low weight of only 5%. Thermodynamics play a huge role in the RADIANCE mission and thermal conductivity of material will either make it easier or harder to transfer heat through the material. It is predicted that the low temperatures will be a problem, so a material that doesn't conduct heat well can be used as an insulator. However due to the large amounts of unknowns about the thermal model at this point, the thermal conductivity of a material was given a low weight of only 5%. The final criteria looked at was familiarity with the material. This means how much knowledge does the team have when it comes to working with each material and manufacturing each material. Because it is important, but not critical, the team's familiarity with each material was also given a weight of 5%.

Table 68: Trade study of different materials for the RADIANCE structure.

Criteria (ranked by weight)		**Metals**		**Composites**		**Plastics**	
Price	0.35	4	1.4	2	0.70	3	1.05
Durability	0.25	4	1.0	5	1.25	1	0.25
Manufacturability	0.10	5	0.50	1	0.10	4	0.40
Density	0.05	1	0.05	3	0.15	3	0.15
Thermal Conductivity	0.05	2	0.10	3	0.15	4	0.20
Familiarity	0.05	4	0.20	1	0.05	5	0.25
Totals	1.00		**3.25**		**2.40**		**2.30**

The following table breaks down how why each material received the score it did in the trade study to help the team get a better more quantitative picture when completing a final analysis on the trade study results.

Table 69: Explanation of structure scores and normalization.

Value	**Price** $	**Durability** (MPa)	**Ease of Manufacturing**	**Density** g/cm^3	**Thermal Conductivity** W/m/K	**Familiarity**
1	> 100	< 50	Need to procure equipment	> 5	> 150	No experience with material
2	100 to 50	50 to 100	Limited access to equipment	5 to 2.5	150 to 100	Knowledge of material
3	50 to 20	100 to 200	Access to equipment	2.5 to 1.5	100 to 75	Used material before
4	20 to 10	200 to 500	Easy access to equipment	1.5 to 1	75 to 50	Very experienced with material
5	< 10	> 500	Readily available equipment and techniques	< 1	< 50	Expert with material

As can be seen in Table 68, the clear winner is metals, or more specifically aluminum. This is backed by cubesat heritage, as many cubesat and similar projects use an aluminum structure. Aluminum has a proven track record in space ready missions, meaning that it is a versatile, strong material that can handle space environments. While plastics are easy to manufacture, there are too many unknowns in how 3D printed plastics behave at high altitude, as well as a lack of information on thermal shock at cold temperatures. In addition, plastics do not have comparable tensile strength to that of aluminum. Composites are stronger, but are also more expensive and harder to manufacture, leaving the team with only one viable option.

5.8 Thermal Control

Thermal control is critical to the survival and success of the other components in the RADIANCE mission. Active control and insulation will likely be employed while passive control will be a backup to control any major offsets found in the thermal modeling of the system. The two trade studies for thermal control are for the active control and the thermal insulation. Neither of these studies guarantee that the method of thermal control will be used, but rather explores which should be used if they are needed.

5.8.1 Active Control

The active control trade study takes into account six different criteria: price, minimum working power draw, ease of use, flexibility of use, ease of access, and vacuum rating. Price is important for the whole system, but from researching the different types of non-mechanical active heating, both major options have a reasonable price range, making price a secondary factor for consideration. The second criteria, minimum working power draw, was selected as the most important factor. Due to the limited power budget, it is imperative that the thermal system be able to squeeze every last drop of power out that it can, which may mean working on less that a Watt of power. Some devices may not produce the desired amount of work if they don't receive enough power and therefore would not be useful in those low power situations. Ease of use discusses how easy it is to put the device into the system on a physical level. The easier it is to pop the component into the system, the better. If it requires additional drivers, that will add mass, computation power, and use more power. Flexibility of use discusses the capabilities of the device. Peltier devices are able to push and pull heat in a system at varying levels, resistors are able to heat a system at variable levels, and something like an RTG may heat a system, but it would be incapable of changing the heat output. Ease of access is not a top priority, but does need to be considered. If the component is incredibly difficult to procure, or requires special licencing and training, it might not be worth the time and effort to use. If, however, the component is readily available at any average store, it would be better to select that component over the one that would take more effort. The final consideration is the vacuum rating. Many components have trouble in vacuum environments for various reasons, so it is important to be sure that they are at least vacuum capable and preferably have been used in vacuum environments in the past.

Table 70: Trade study of different active thermal control methods for RADIANCE.

Criteria (ranked by weight)		**Peltier Device**		**Resistive Heaters**	
Min Power Draw	0.30	4	1.20	5	1.50
Price	0.20	2	0.40	4	0.80
Ease of Use	0.15	3	0.45	5	0.75
Flexibility of use	0.15	5	0.75	3	0.45
Ease of Access	0.15	3	0.30	5	0.50
Vacuum Rating	0.10	5	0.50	5	0.50
Totals	1.00		**3.60**		**4.50**

Table 71: Explanation of active thermal control scores and normalization.

Value	Minimum Power Draw	Price	Ease of Use	Flexibility of Use	Ease of Access	Vacuum Rating
1	<2W	>$50/device	Requires special equipment	Fixed Heating	Not Accessable	Not Vacuum Capable
2	>2W	<$50/device	Requires specific drivers		Requires special licencing	
3	>1W	<$10/device	Cannot recieve pulsed power	Variable Heating	Difficult to find	Vacuum Capable
4	>.5W	<$3/device	Can be driven easily		Can find nearby	
5	≈ 0W	<$1/device	Plug and Play	Variable Heating and Cooling	Can find anywhere	Proven in Vacuum Environment

5.8.2 Thermal Insulation

Thermal insulation will assist in keeping a desirable temperature for the electronics during ascent, descent and cruise. It will also help produce a higher temperature gradient if a radiator is found to be needed, and trap more heat if a solar heater is needed. There are 6 criteria for the trade studies that are very similar to those for the active thermal control: price, RSI, density, workability, ease of access, and vacuum rating. Ease of access and vacuum rating are exactly the same as with the active components. Price is rated slightly lower because most of the insulation will be inexpensive enough and will be purchased in low enough quantities that it should be inconsequential (with the exception of the aerogel insulation). RSI is a metric measurement of the conductive resistivity of a material per inch of thickness of the material. The higher the value, the more resistive it is to conductive heat transfer. RSI is the most important metric to be considered because it will determine the minimum depth of insulation necessary. If the RSI is too low, the insulation layer will need to be thicker to keep the system at the same temperature. The volume is severely limited in RADIANCE so the thinner the insulation can be, the better. Density is the next metric that is not vitally important for the balloon flight, but should be considered when thinking about the path to space where every gram counts. Workability is a rather important metric because if the insulation cannot be altered from its purchased state without loosing its insulating properties, it is useless to the system. The insulation chosen should be workable to the extent that it can create a shape slightly more complex than a box so that the odd shapes of the components can be insulated adequately.

Table 72: Trade study of different materials for thermal insulation of RADIANCE. (Part 1)

Criteria (ranked by weight)		**Silica Aerogel**		**Fiberglass**		**Mineral Wool**		**Polyurethane Foam Panels**	
RSI	0.35	4	1.40	2.5	0.88	2	0.70	4	1.40
Workability	0.20	3	0.6	4	0.80	4	0.80	4	0.80
Price	0.15	1	0.15	4	0.60	4	0.60	2	0.30
Density	0.10	5	0.50	4	0.40	1	0.10	3	0.30
Ease of access	0.10	3	0.30	5	0.50	4	0.40	3	0.30
Vacuum Rating	0.10	5	0.50	3	0.30	3	0.30	3	0.30
Totals	1.00		**3.45**		**3.48**		**2.90**		**3.40**

Table 73: Trade study of different materials for thermal insulation of RADIANCE. (Part 2)

Criteria (ranked by weight)		**Polystyrene Foam Panels**		**Cardboard**		**Vacuum Panels**		**Space Blankets**	
RSI	0.35	3	1.05	2	0.70	5	1.75	0	0.00
Workability	0.20	3	0.6	4	0.80	1	0.20	4	0.80
Price	0.15	2	0.30	5	0.75	1	0.15	4	0.60
Density	0.10	3	0.30	4	0.40	2	0.20	5	0.50
Ease of access	0.10	4	0.40	5	0.50	1	0.10	3	0.30
Vacuum Rating	0.10	3	0.30	3	0.30	3	0.30	3	0.50
Totals	1.00		**2.95**		**3.45**		**2.70**		**2.70**

Table 74: Explanation of thermal insulation scores and normalization.

Value	**RSI**	**Workability**	**Price**	**Density**	**Ease of Access**	**Vacuum Rating**
1	<.6	Not Workable	$>\$10/\mathrm{ft}^2$	$>4\mathrm{g/cm}^3$	Not Accessible	Not Vacuum Capable
2	>.6	Difficult to work	$<\$10/\mathrm{ft}^2$	$<4\mathrm{g/cm}^3$	Requires special licencing	
3	>.8	Workable	$<\$6/\mathrm{ft}^2$	$<2\mathrm{g/cm}^3$	Difficult to find	Vacuum Capable
4	>1	Has minimal limitations	$<\$3/\mathrm{ft}^2$	$<1\mathrm{g/cm}^3$	Can find nearby	
5	>2	Easily workable	$<\$1/\mathrm{ft}^2$	$<.5\mathrm{g/cm}^3$	Can find anywhere	Proven in Vacuum Environment

6 Selection of Baseline Design

6.1 Spectrometer

The Avantes Avaspec-Mini 2048 has been selected for the baseline design. While many commercial spectrometers fulfill the wavelength range and resolution requirements, the Avaspec-Mini 2048 is relatively low-cost and comes in a small form factor.

6.2 Processor

The controller that will be used for this project is a microcontroller. They are cheap, easy to work with, provide many integration options, and can handle low intensity processes such as data acquisition. If this project required more intense parallel calculations an FPGA might have been required. A netbook uses unnecessary power and cannot fit within the cross sectional area of a 3U cubesat.

6.3 Power Source

The best solution for the power requirements needed to meet the 15W minimum power output are the industrial-grade solar cells. They provide the most cost effective per unit area cells that would generate the needed amount of power. Though these solar cells may be tricky to wire they are the only ones that would generate enough power within the budget.

6.4 Batteries

While many appealing battery options exist, the lithium-ion battery provides the best all round performance. The trade study found that the top two options were the lithium ion and alkaline battery. Lithium ion batteries are rechargeable, which has the advantage over non-rechargeable batteries in that they would need a lower capacity to maintain power for the duration of the flight. Lithium ion batteries also have the advantage of heritage on cubesat designs, which when combined with the trade study score, makes them a reasonable choice for this project.

6.5 Storage Medium

A mechanical hard drive is not usable for this project as they require too much power. Solid state drives and flash drives are statistically tied for their role in this project, however the cost per gigabyte of a flash drive is slightly cheaper than the solid state drive. Flash drives also use less power than a solid state drive. As such, the baseline design calls for the use of a flash drive as the storage medium.

6.6 Attitude Determination

RADIANCE shall use an array of four photodiodes arranged on the sun-facing face of the 3U structure. The photodiodes will be angled 45 degrees from the spectrometer boresight (body X axis of the full structure) such that the sun will always have a non-zero incidence angle on at least two photodiodes, provided the sun vector is within 90 degrees of the spectrometer boresight. This arrangement will allow for determination of the off-sun angle with an accuracy of approximately 1 arcminute, per the customer's requirements.

In addition to the off-sun angle determination required by the customer, RADIANCE shall include magnetometers and accelerometers as part of the environmental sensor package. These sensors will allow for definition of the magnetic field and linear acceleration of the HiWind gondola in three dimensions.

6.7 Structure

The baseline design for the structure is to use an internal structure with exterior mounted side plates. This design offers the best flexibility with interior layout while adding extra support to the overall system. This configuration makes access to the interior components much easier than a solely exterior framework. The design has a proven history of space flight missions that needed to seal the interior subsystems, much like RADIANCE will need to do in order to accommodate the drastic thermal changes on ascent and descent.

6.8 Materials

The structure of the RADIANCE system will be made out of aluminum. Aluminum is the most widely used material in small satellite construction, is relatively low cost, and is very strong. All these features will allow the RADIANCE system to survive a flight around the antarctic at 40 km. There are too many unknowns with how plastics will perform, and the challenges of manufacturing composites do not make it a more advantageous option for the design.

6.9 Thermal Control

The selections for thermal control have not been determined in full yet. If implemented, the insulator will either be Polyurethane foam panels or cardboard. While fiberglass and aerogel scored very high, they are not feasible for the scope of this project. Aerogel is incredibly expensive, on the order of $50 per cubic inch, and fiberglass poses additional health concerns and the fibers will be difficult to keep contained. While they didn't score very high in the trade study, space blankets may also be employed depending on radiative insulation needs of the system.

The heating element decided upon if it is to be implemented is the resistive heater that can be easily placed in parallel with any existing circuit. This was selected due to both the extremely low price of the method of heating, as well as the ability to put heaters exactly where they are needed without taking up excessive additional volume. The peltier devices would be a great way to achieve the same result, but the amount of resources that would need to go into controlling them is too great.

No selection has been made for whether or not to use a radiator or a solar heater because the system has not been analyzed to the extent necessary to know which, if any will be necessary.

6.10 Baseline Design Choice

All components of the system were evaluated through trade studies to determine the best method of approach for the baseline design. The trade studies incorporated both quantitative analysis and qualitative analysis. As a result the baseline design will include the Avantes Avaspec-Mini 2048 spectrometer selected mainly due to its price and size. The design will include industrial grade solar cells with a Lithium ion battery backup supply, be controlled by a microcontroller, data will be stored on a flash drive, attitude will be determined by photodiodes, magnetometers, and accelerometers, and the structure will be made from aluminum configured as an internal structure with external side-plates. Exact thermal choices have yet to be determined as they require more in depth analysis involving configuration, future budget constraints, and thermal requirements of specific hardware.

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