RADIANCE

Research at high **A**ltitude on **D**istributed **I**rradiance **A**board an i**N**expensive **C**ubesat **E**xperiment

Preliminary Design Review

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Team Members: Russell Bjella, Katelyn Dudley, David Varley, Lance Walton

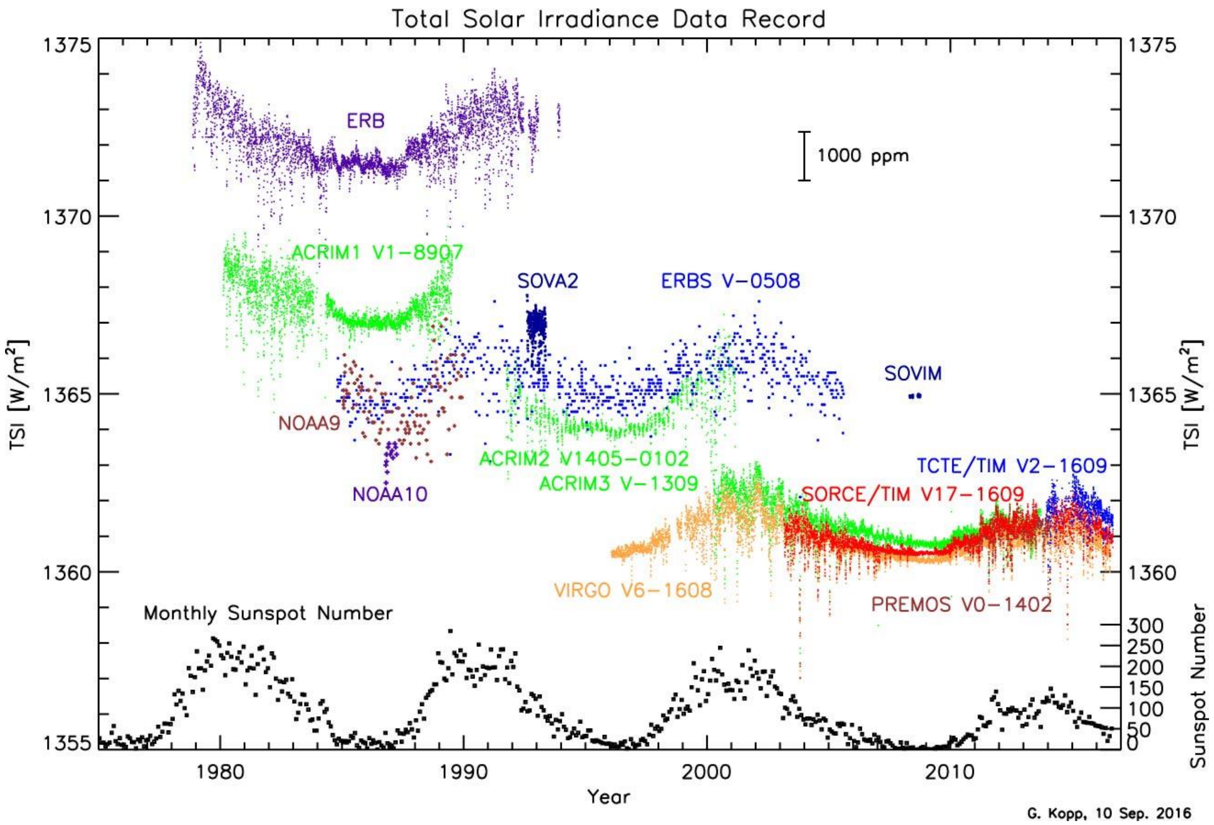
Project Overview

Customer

High Altitude Observatory

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

Project Motivation



Are these variations real?
How does it inform climate science?

- Solar irradiance data is plentiful, but…
  - The record has gaps
  - Datasets vary between different instruments
  - Full-scale space missions are costly
  - Full-scale space missions are time-consuming

Mission Statement

RADIANCE is a 3U CubeSat-style payload that will collect solar irradiance data, images, and ambient atmospheric data during a 2-week circumpolar high-altitude balloon flight.

The mission will launch from Antarctica between November 2017 and February 2018.

Project Statement

RADIANCE will design, build, test, and deliver a 3U CubeSat-style payload to collect solar irradiance data, images, and ambient atmospheric data on a high-altitude balloon flight in Winter 2017/2018.

The HiWind Gondola

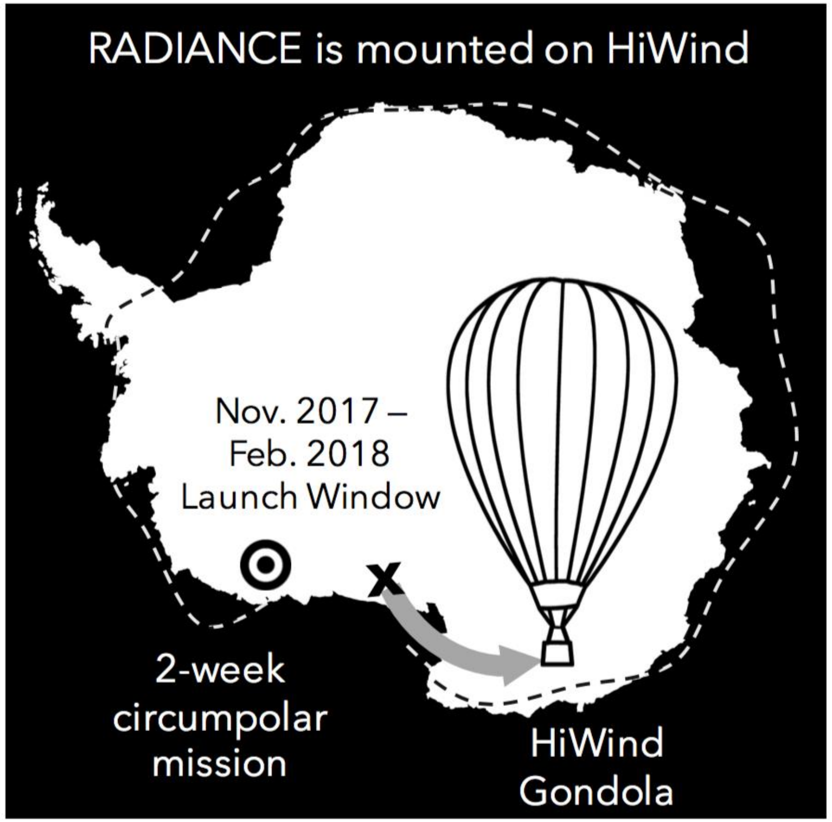
Project Objectives

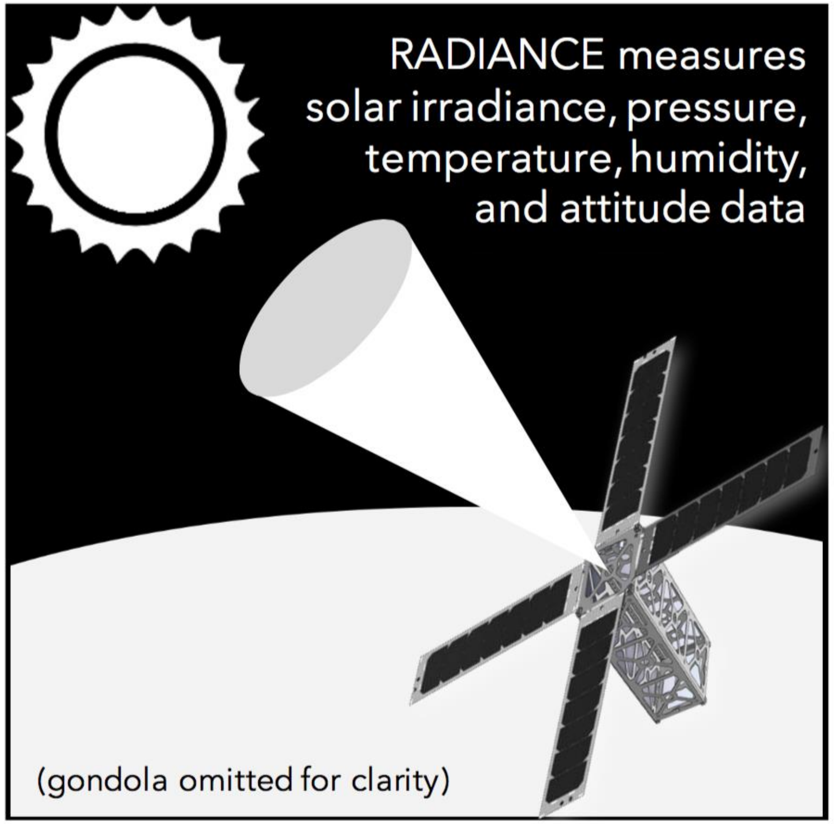
RADIANCE shall…

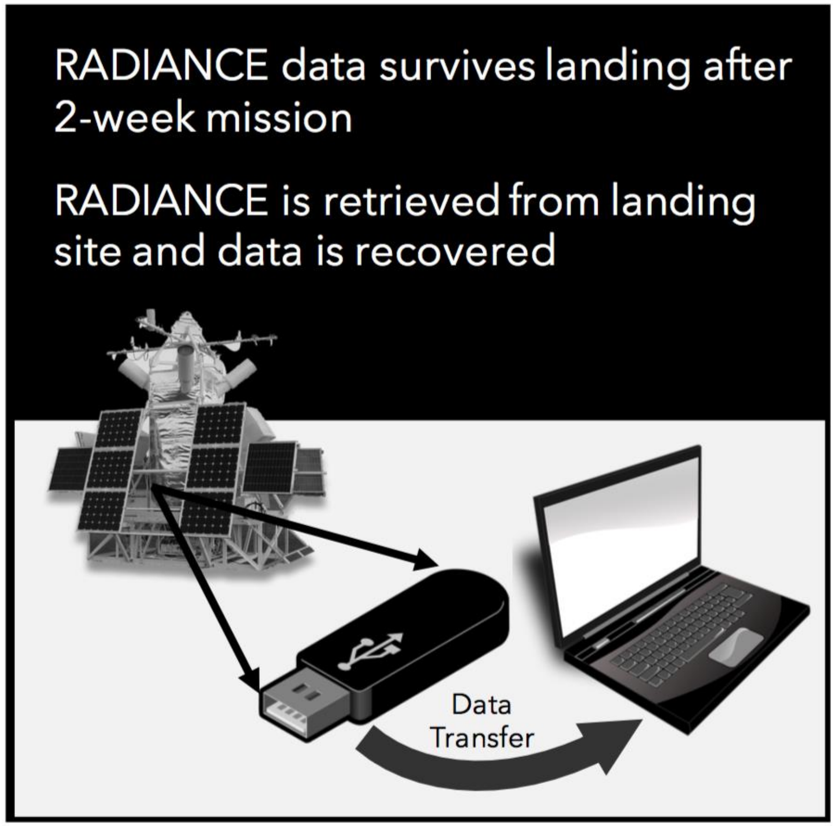
1. Take solar irradiance measurements.
2. Survive the environmental conditions of a high-altitude balloon flight up to 40 km.
3. Return data.
4. Determine its attitude.
5. Interface with the HiWind Gondola.
6. Capture images of the Sun in the visible spectrum.

The project deliverables shall include a Path-to-Space report.

Concept of Operations

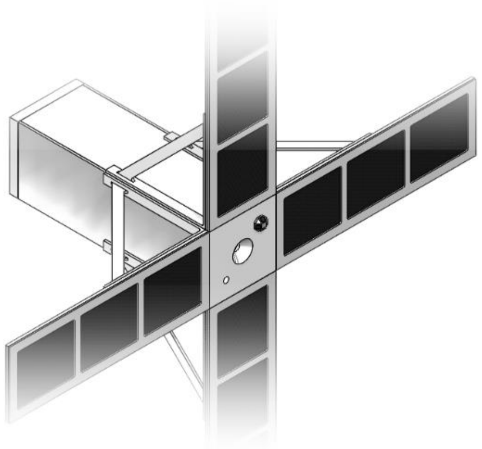






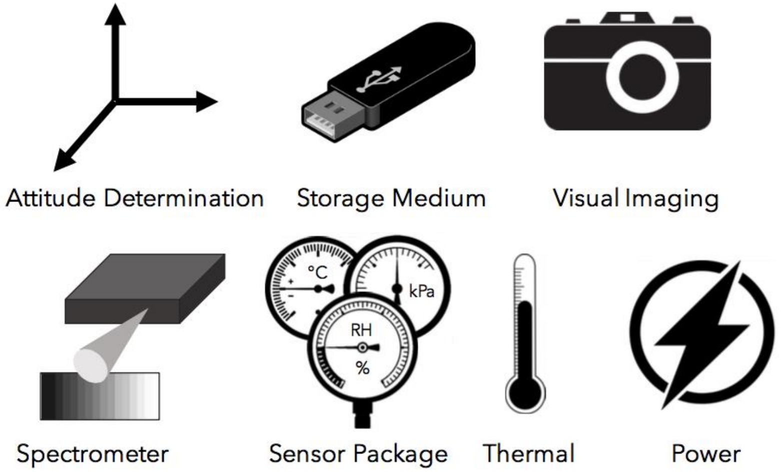
Power Up

Using external power source equivalent to 13 W of expected solar power



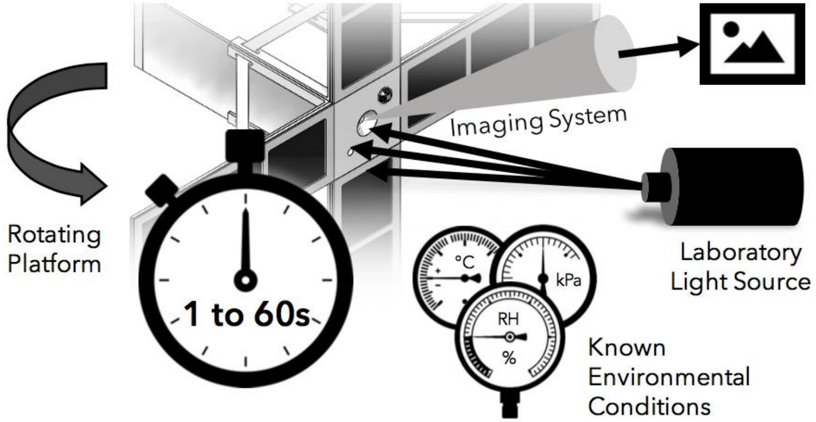
System Check-Out

All systems run through health-and-safety checks to establish functionality before becoming operational



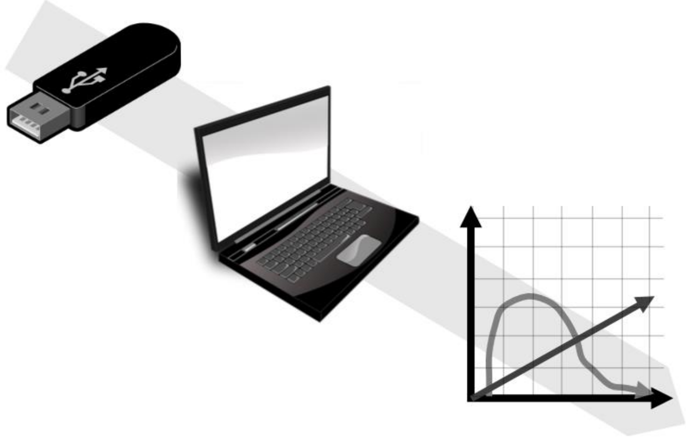
Take Data

Record data from sensors, imaging system, spectrometer, and attitude determination system every 1-60 seconds for the duration of the test



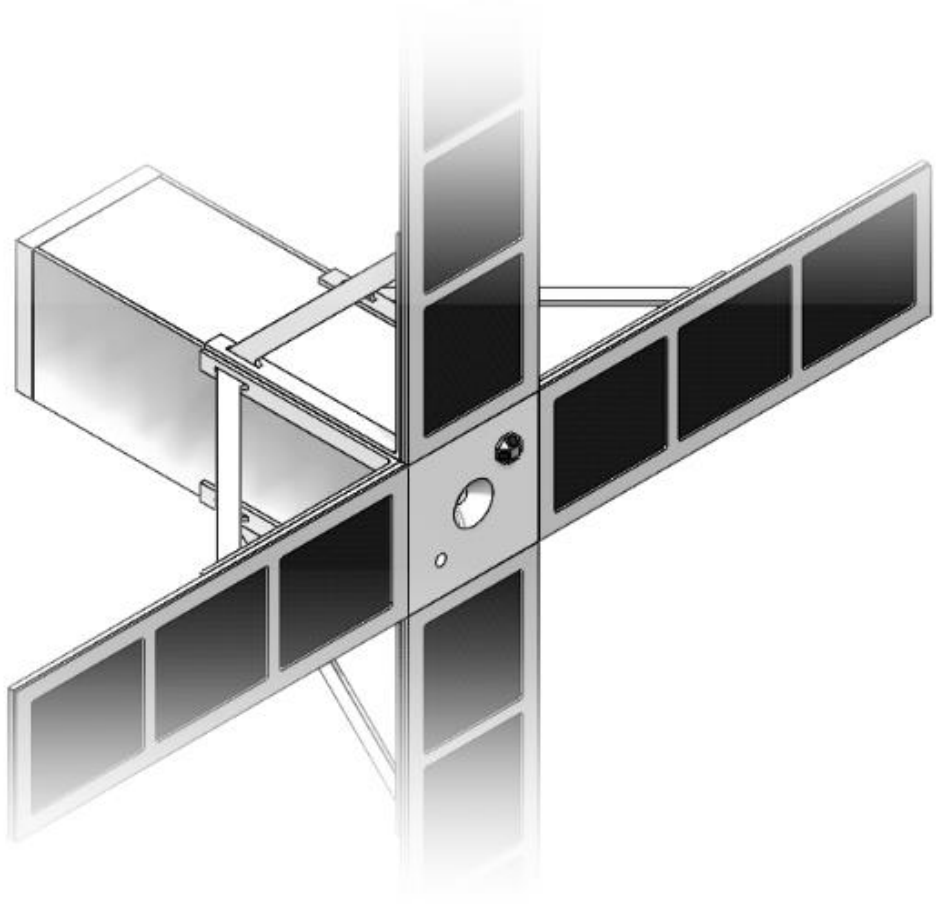
Power Down & Retrieve Data

Operations finish, and data is retrieved from the storage medium for comparison with predicted models

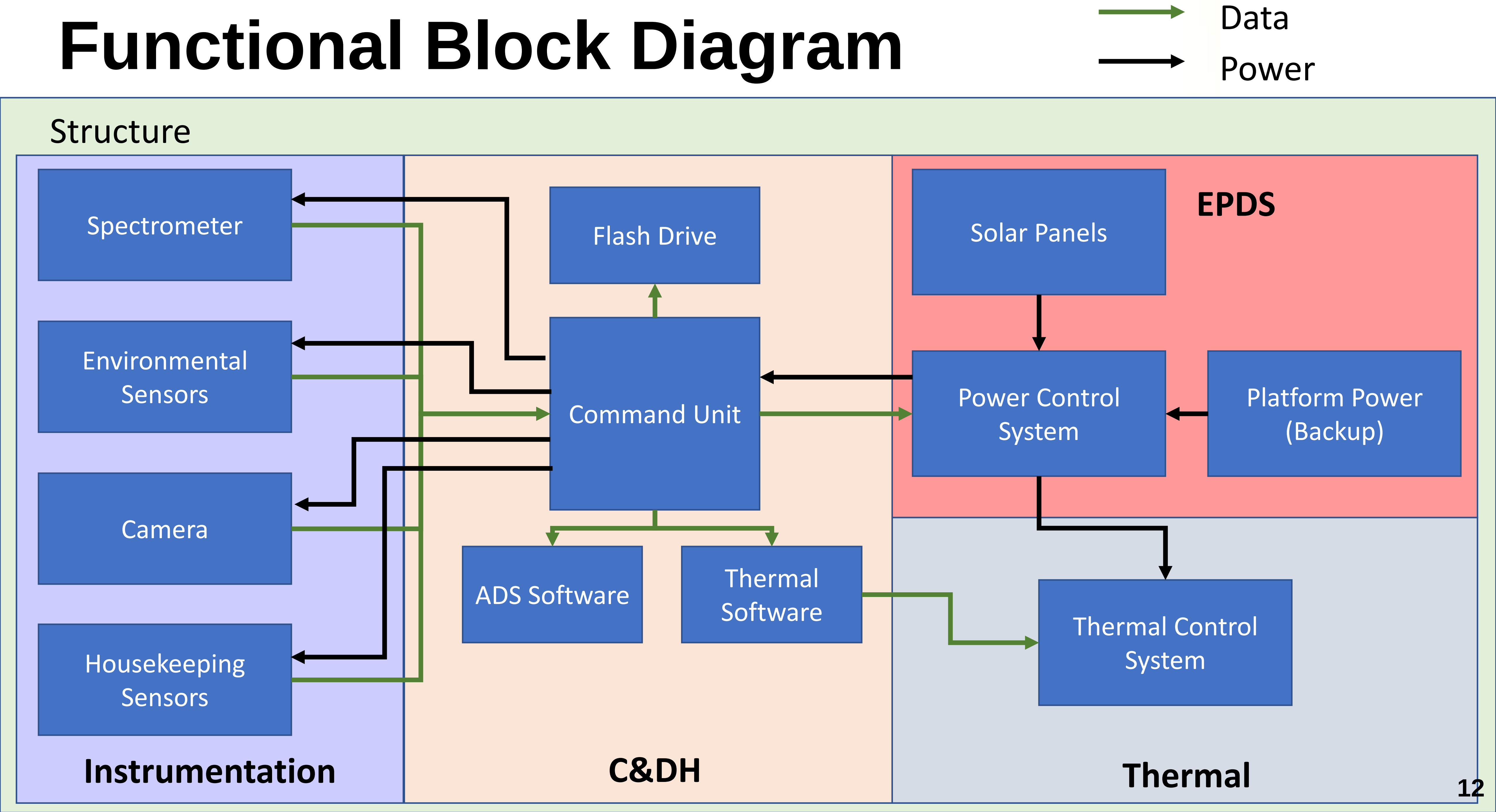


Power Up

Using external power source equivalent to 13 W of expected solar power



Functional Block Diagram

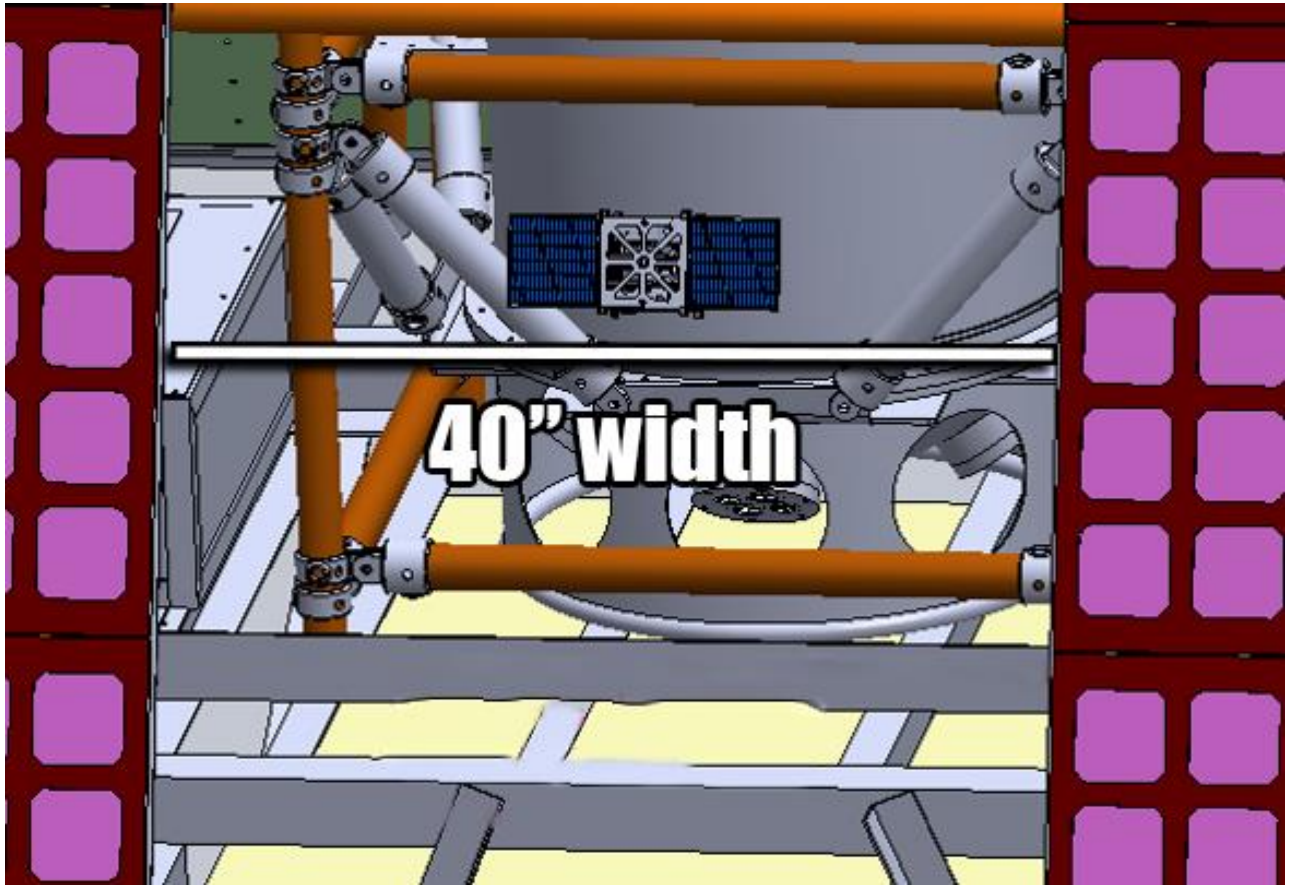


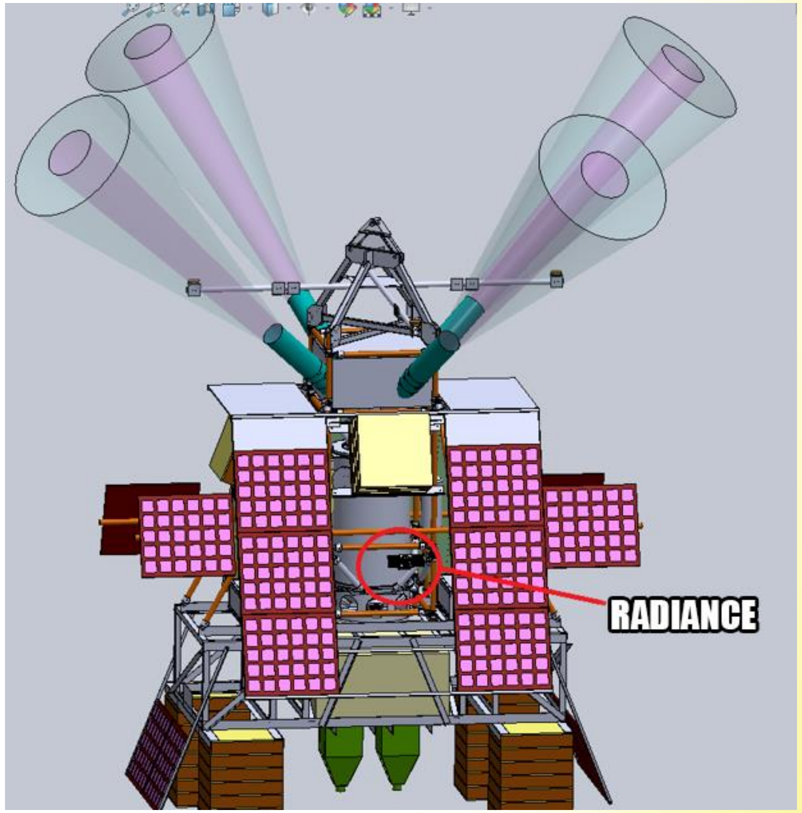
Baseline Design Overview

Baseline Design Topics

- **Structural**
  - Integration with HiWind
  - Structure
  - Materials
- **Thermal**
  - Thermal Control
- **EPDS**
  - Power Generation
  - Battery
- **C&DH**
  - Microcontroller
  - Software
  - Data Storage
- **Instrumentation**
  - Spectrometer
  - Camera and Lens
  - Environmental Sensors
  - Attitude Determination
  - Housekeeping Sensors

Integration with HiWind





Integration with HiWind

General Interfacing

- HiWind has not been fully designed yet
- Sun Facing Side
- ± 1° pointing accuracy

Power

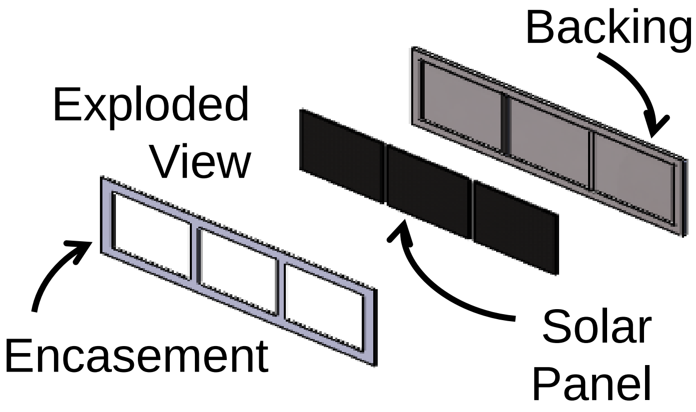
- 24 – 28 V
- 15 W

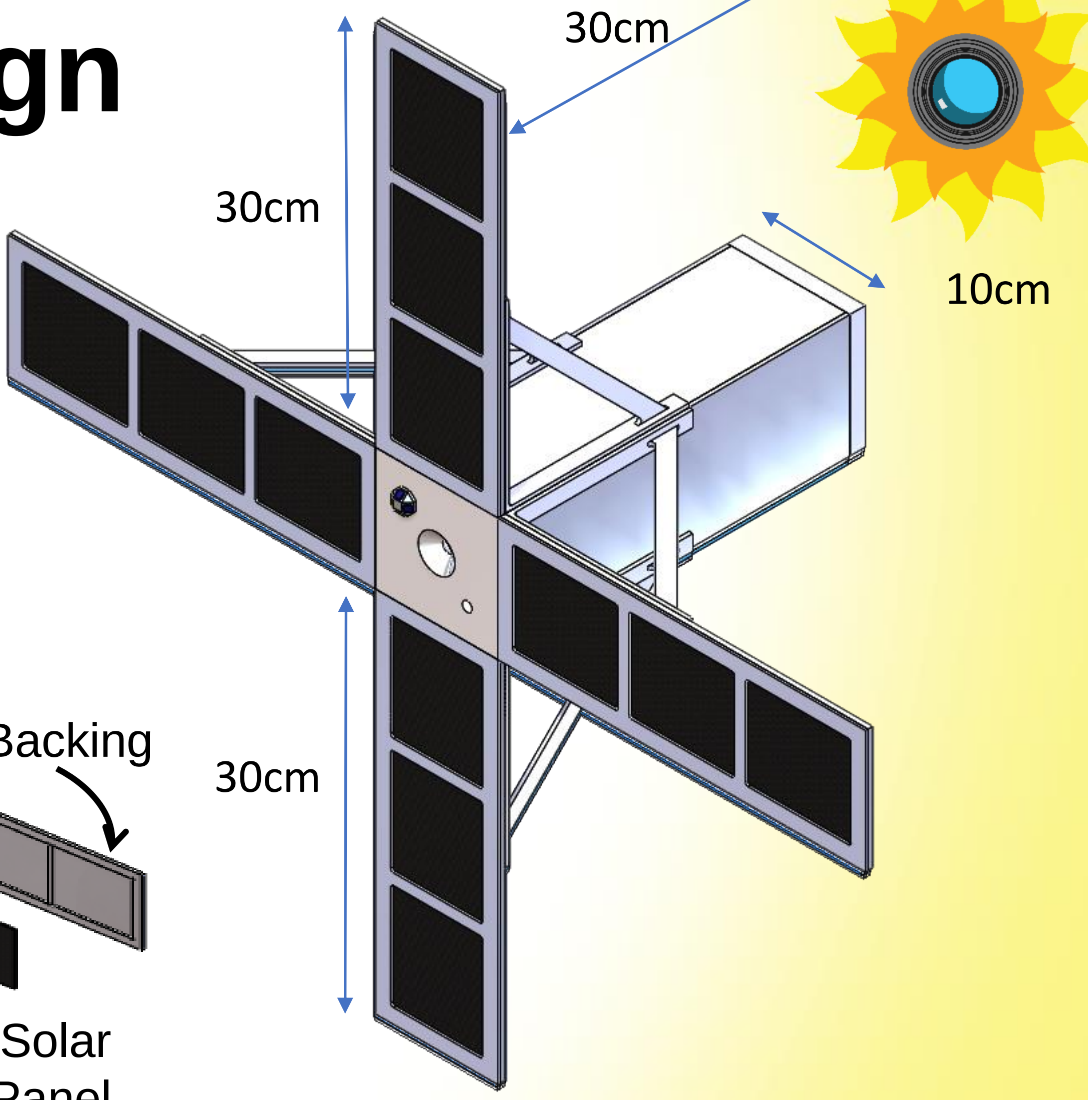
Structure

- RADIANCE Must fit in 70 x 70 x 30 cm volume
- Easily removable storage device

Structure Baseline Design

- Front and Back interface plates
- Interior support struts
- External mounted solid plates
- Layered solar panel frame
- Support brackets for mount solar panels
- Made from Aluminum 6061-T6

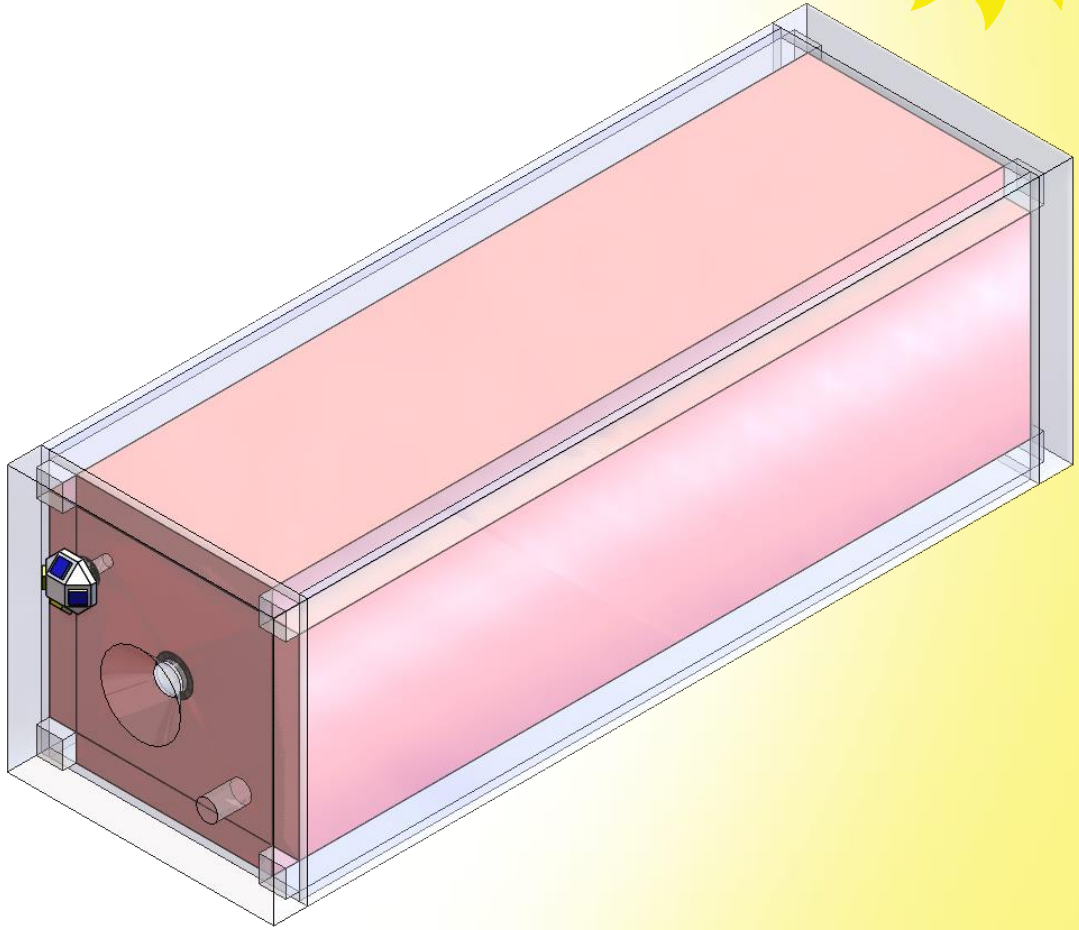




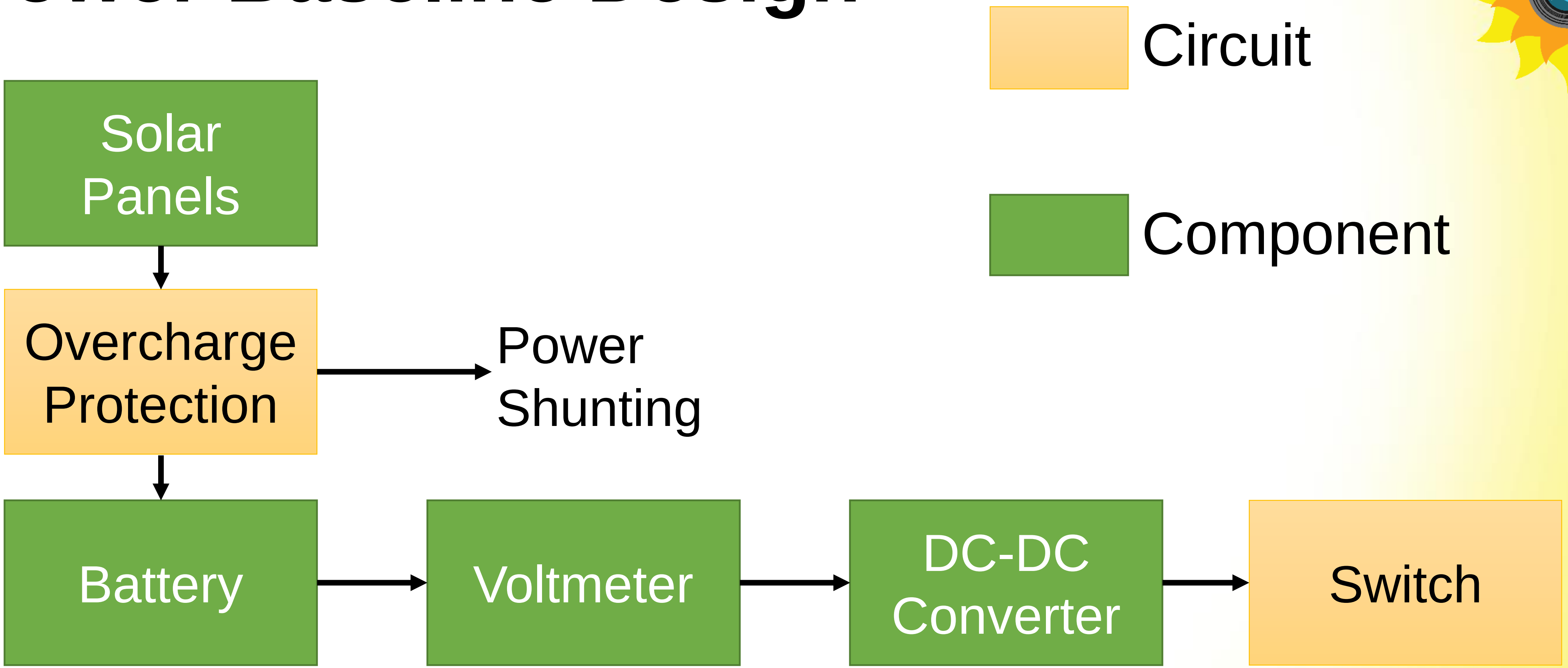
Thermal Control Baseline Design

- Active Thermal Control
  - Resistive heaters
  - Affixed to internal structures

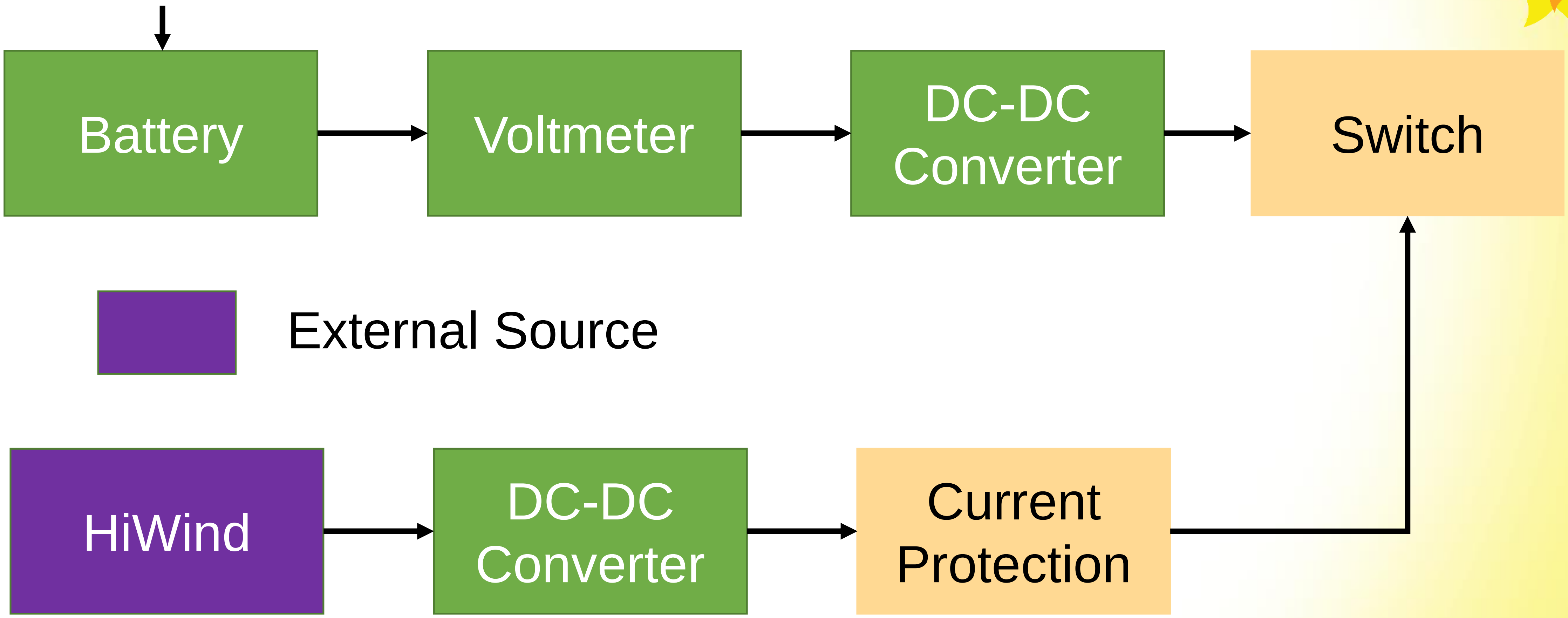
- Passive Thermal Controls
  - 1cm Polyurethane foam liner insulation



Power Baseline Design

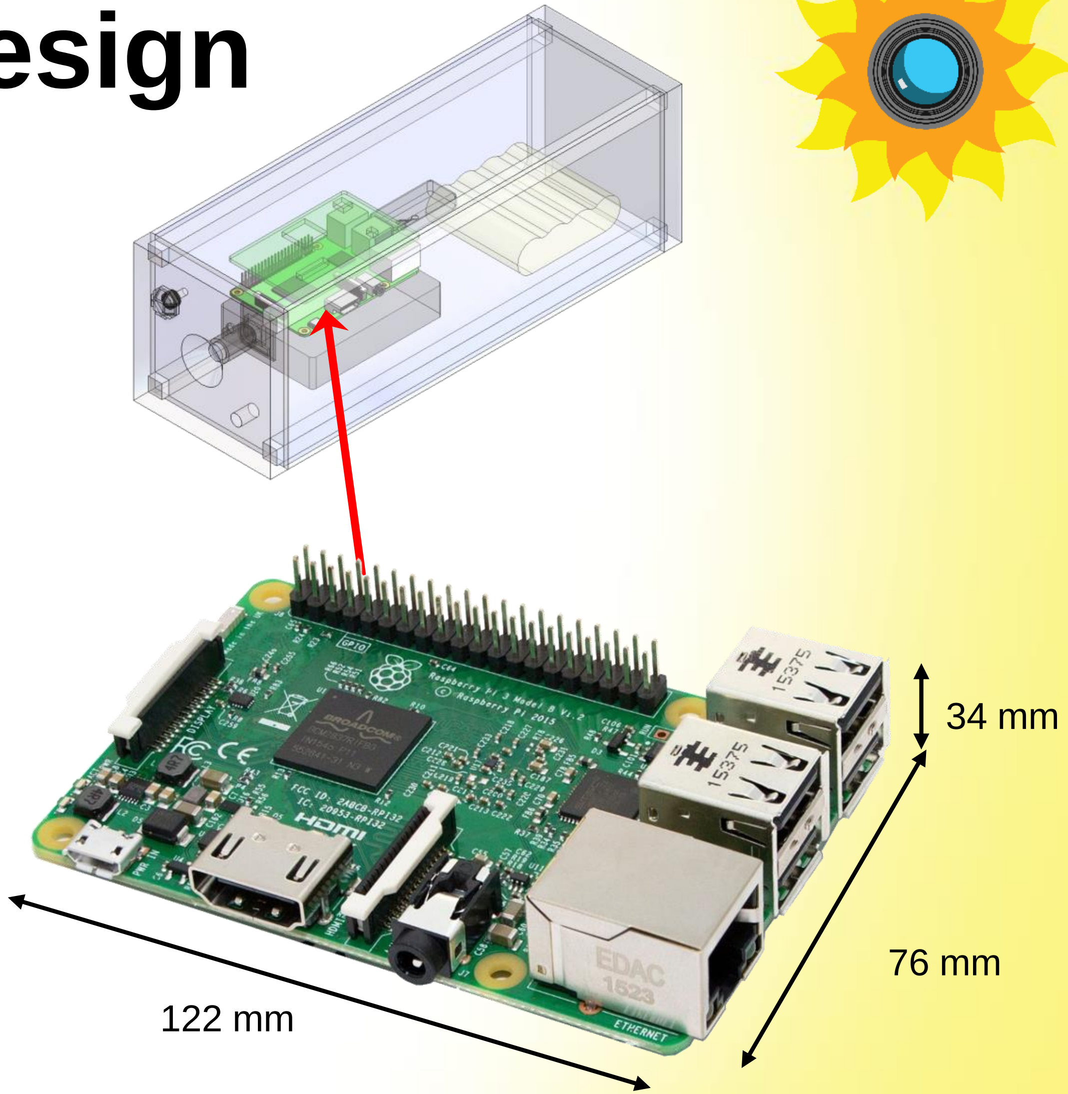


Power Baseline Design

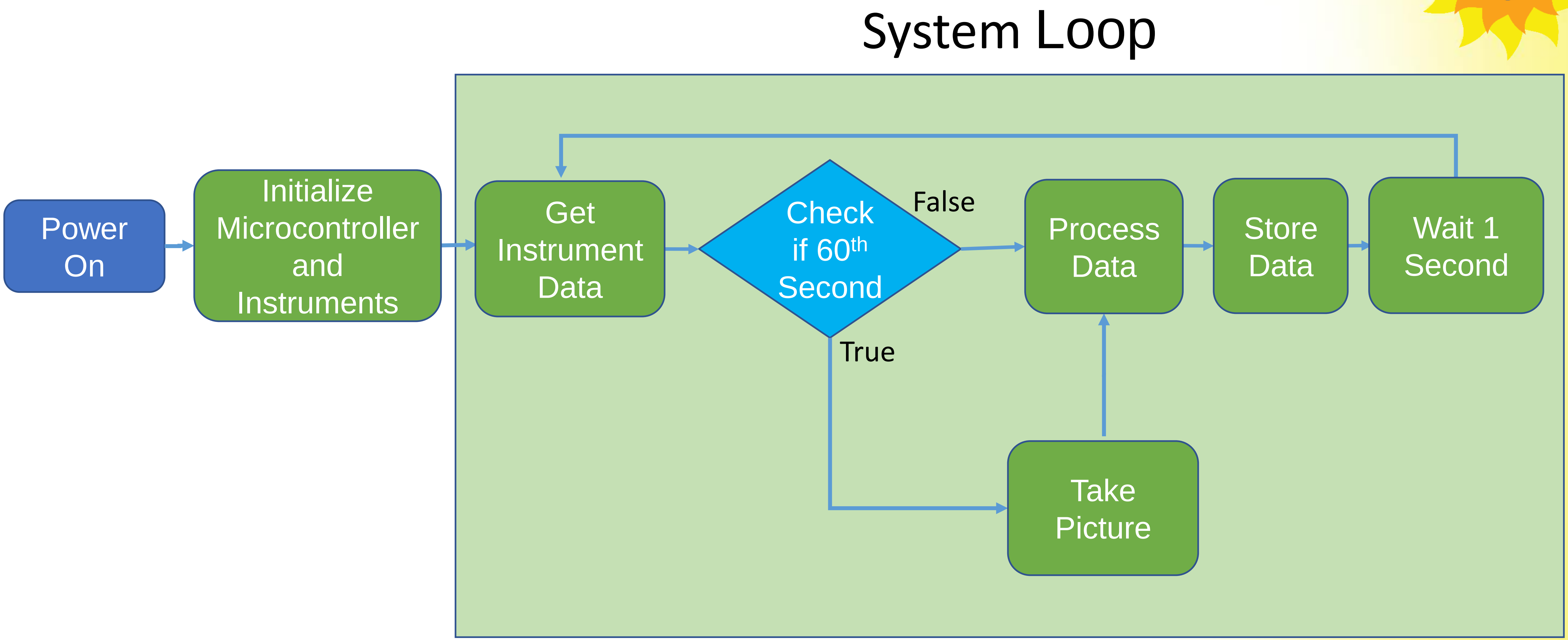


Microcontroller Baseline Design

Raspberry Pi Model 3 B	
CPU	1.2 GHz quad-core
Interface	4 USB, 40 GPIO
OS Storage	1 microSD Slot
OS	Raspbian



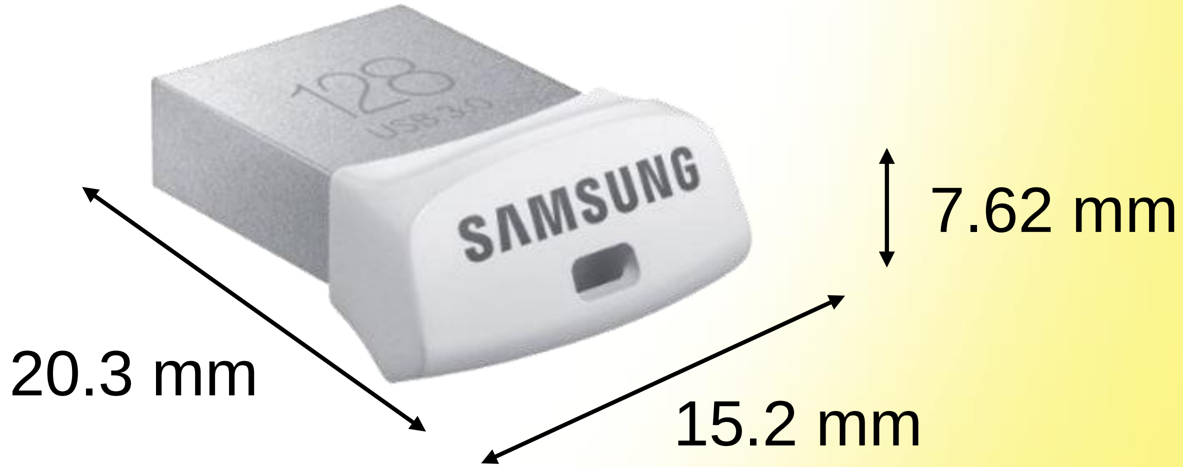
Software Flow



Data Storage Baseline Design

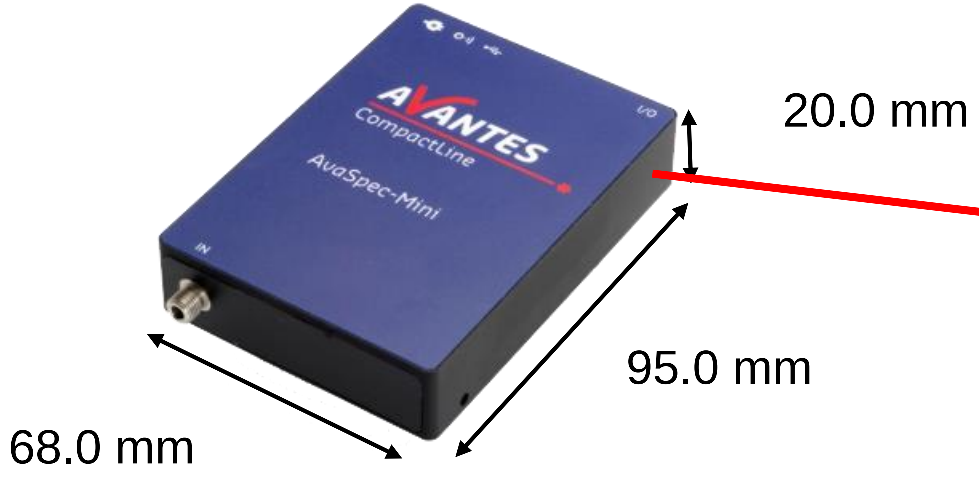
Samsung MUF-128BB/AM 128GB* Flash Drive	
Transfer Speed	130 MB/s
Storage Capacity	119 GB

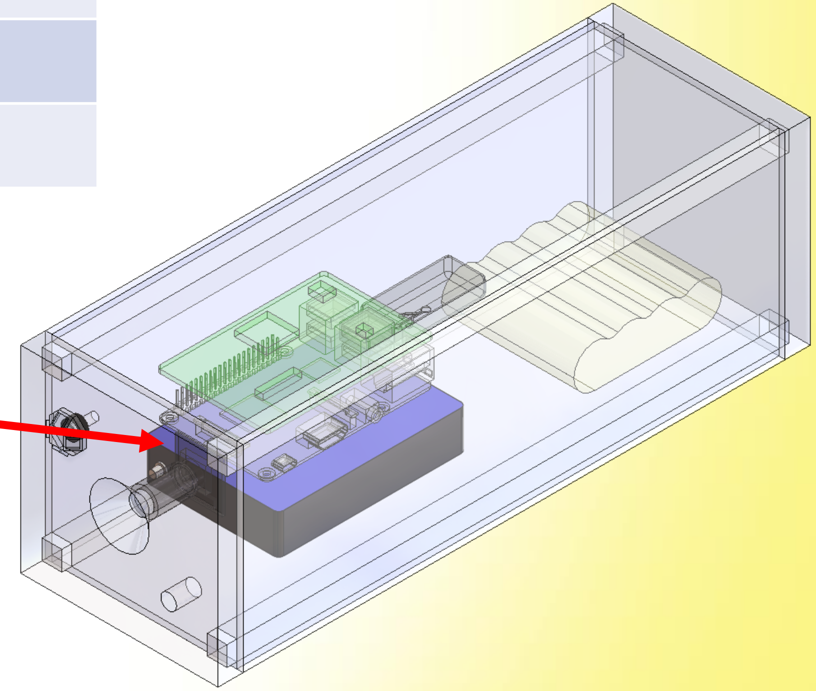
- Additional Notes:
  - Shock Resistant



Spectrometer Baseline Design

Avantes AvaSpec-Mini 2048L-UVI25	
Optics	200-1100nm, 1.4 nm resolution
Grating	300 lines/mm
Slit Size	25µm
Price	$2946.25

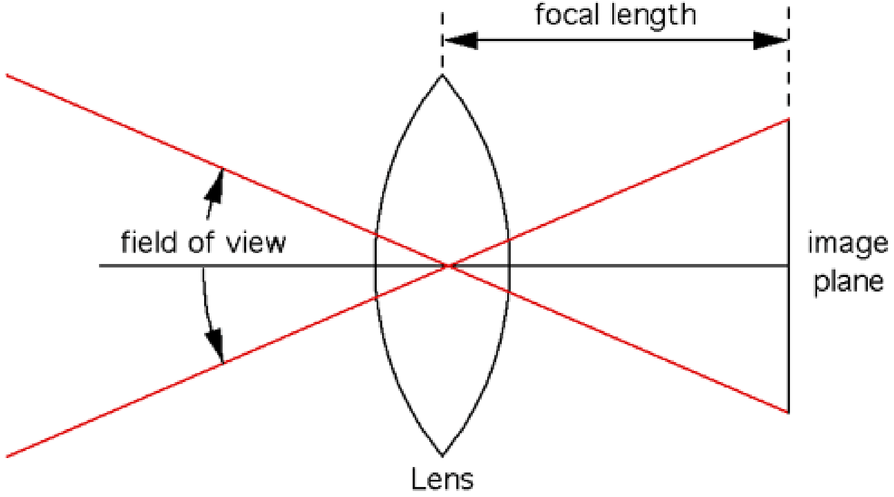


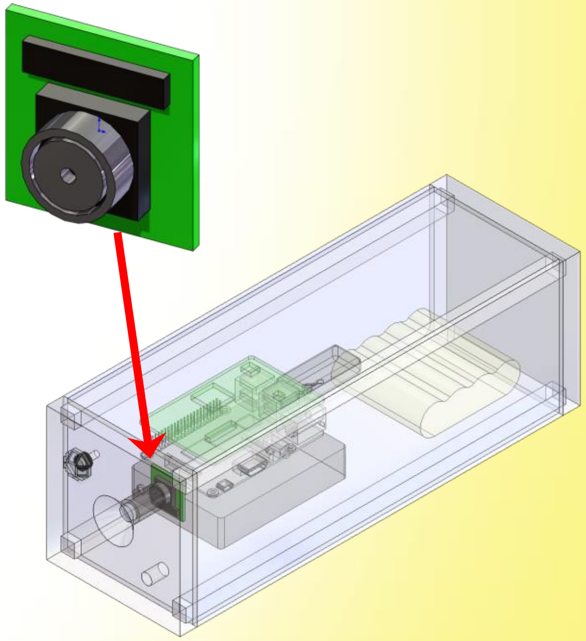


Camera and Lens Baseline Design

- Raspberry Pi Camera Module V2
  - Remove provided lens
  - Replace with separate lens

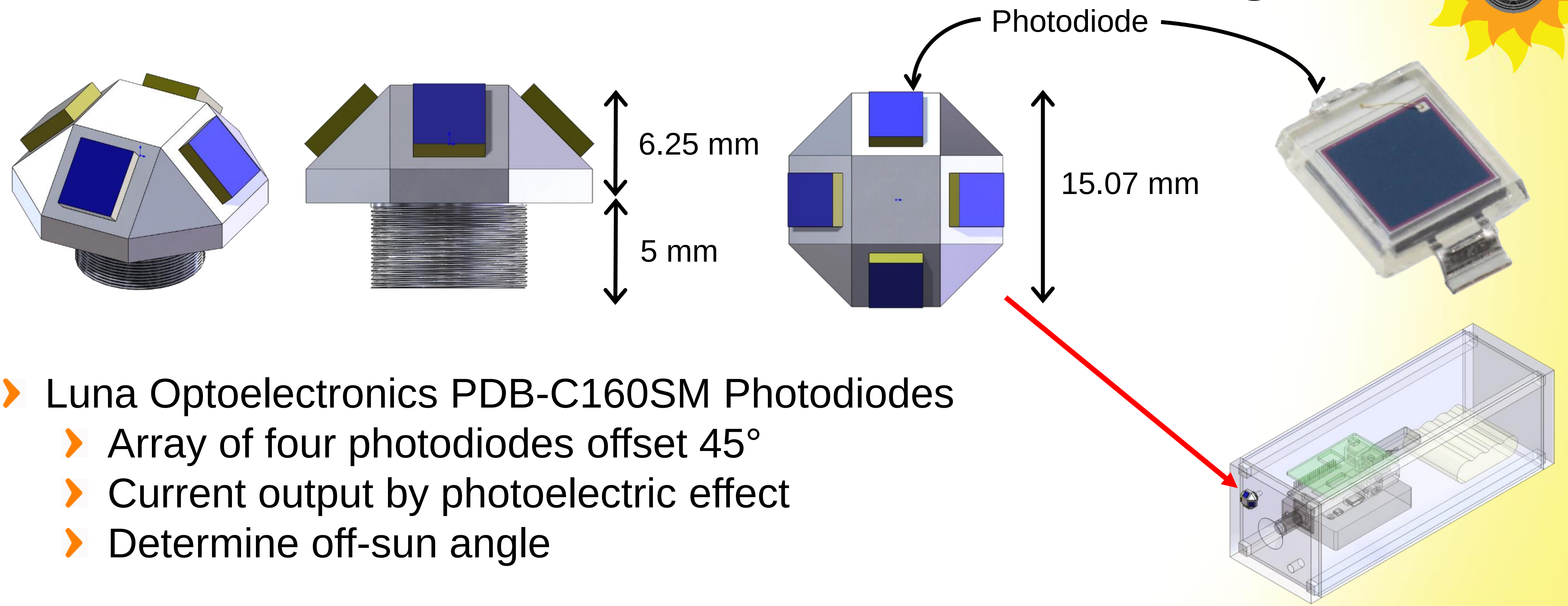
Lens	
Tube Dimensions	1 cm diameter 3 cm length
Focal Length	30 mm
Modifications	Neutral density filter





→ Design results in 5.16° FOV

Attitude Determination Baseline Design



- Luna Optoelectronics PDB-C160SM Photodiodes
  - Array of four photodiodes offset 45°
  - Current output by photoelectric effect
  - Determine off-sun angle

Identification of Critical Project Elements

Critical Project Elements

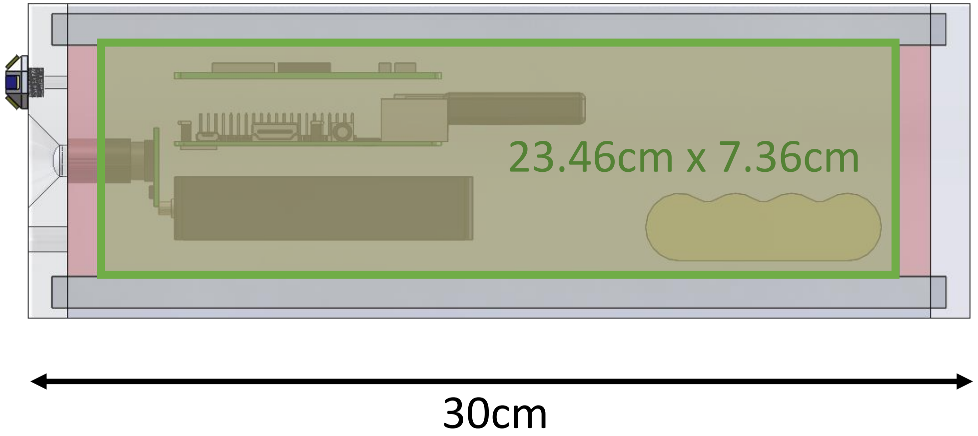
- Structural
  - Integration with HiWind
  - Structure
  - Materials
- Thermal
  - Thermal Control
- EPDS
  - Power Generation
  - Battery
- C&DH
  - Microcontroller
  - Software
  - Data Storage
- Instrumentation
  - Spectrometer
  - Camera and Lens
  - Environmental Sensors
  - Attitude Determination
  - Housekeeping Sensors

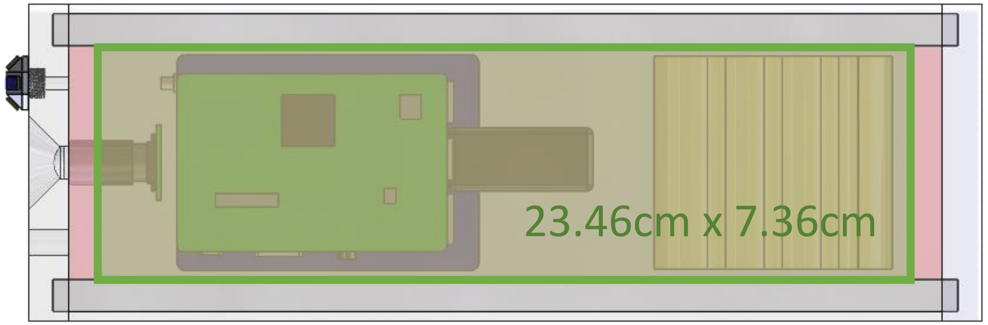
Subsystem Feasibility Analysis

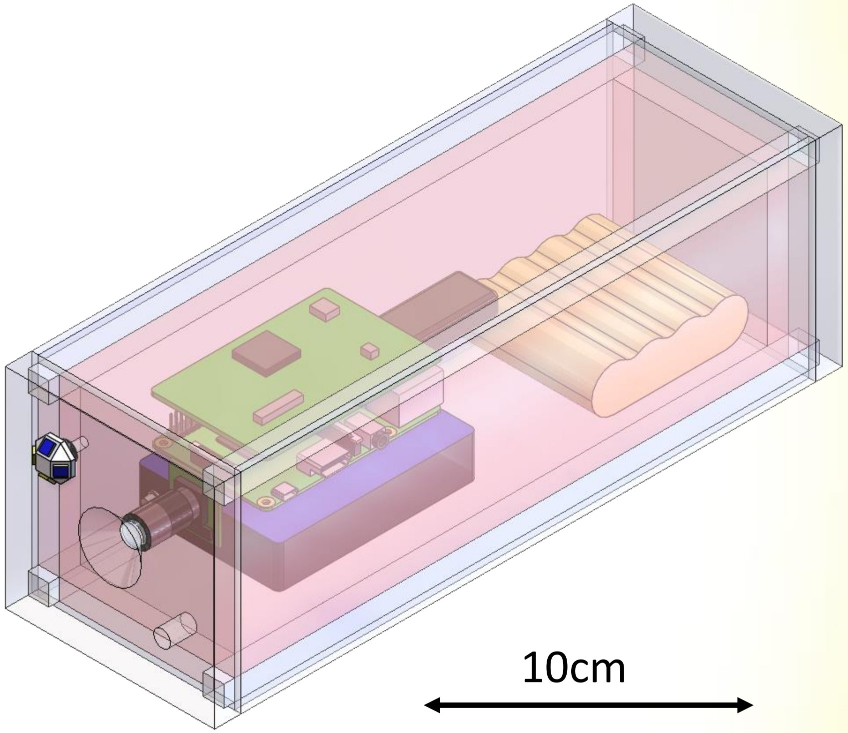
Structure Feasibility

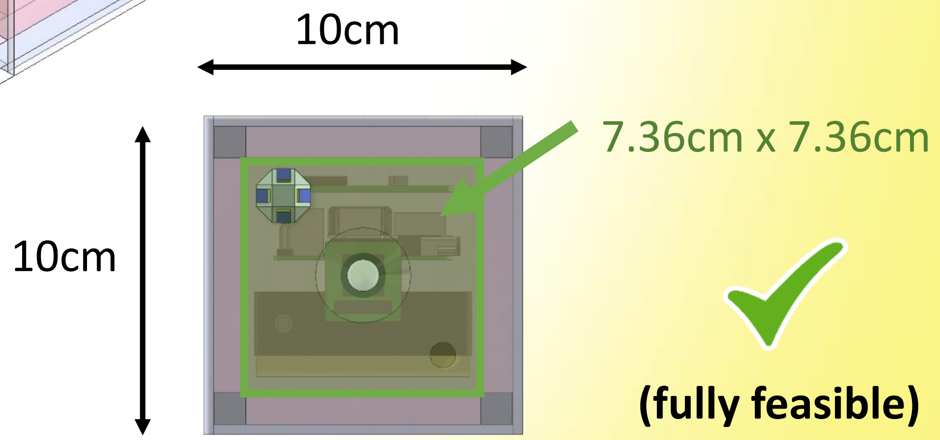
Requirement	Description
5.1	The system (excluding the solar panels) shall have dimensions of 30 cm x 10 cm x 10 cm.
5.2	The system (including the solar panels) shall not exceed dimensions of 70 cm x 70 cm x 30 cm (height, width, and depth respectively).

Structure Feasibility









Structure Feasibility

Component	Volume (cm^3)
Aluminum Structure	697.1
Polyurethane Insulation	913.9
Spectrometer	129.2
Camera	3.41
Raspberry Pi	15.4
Power Board	10.8
Battery	97.1
Flash Drive	9.6
Total System	1876.51

Total Available Volume:
3000 cm^3

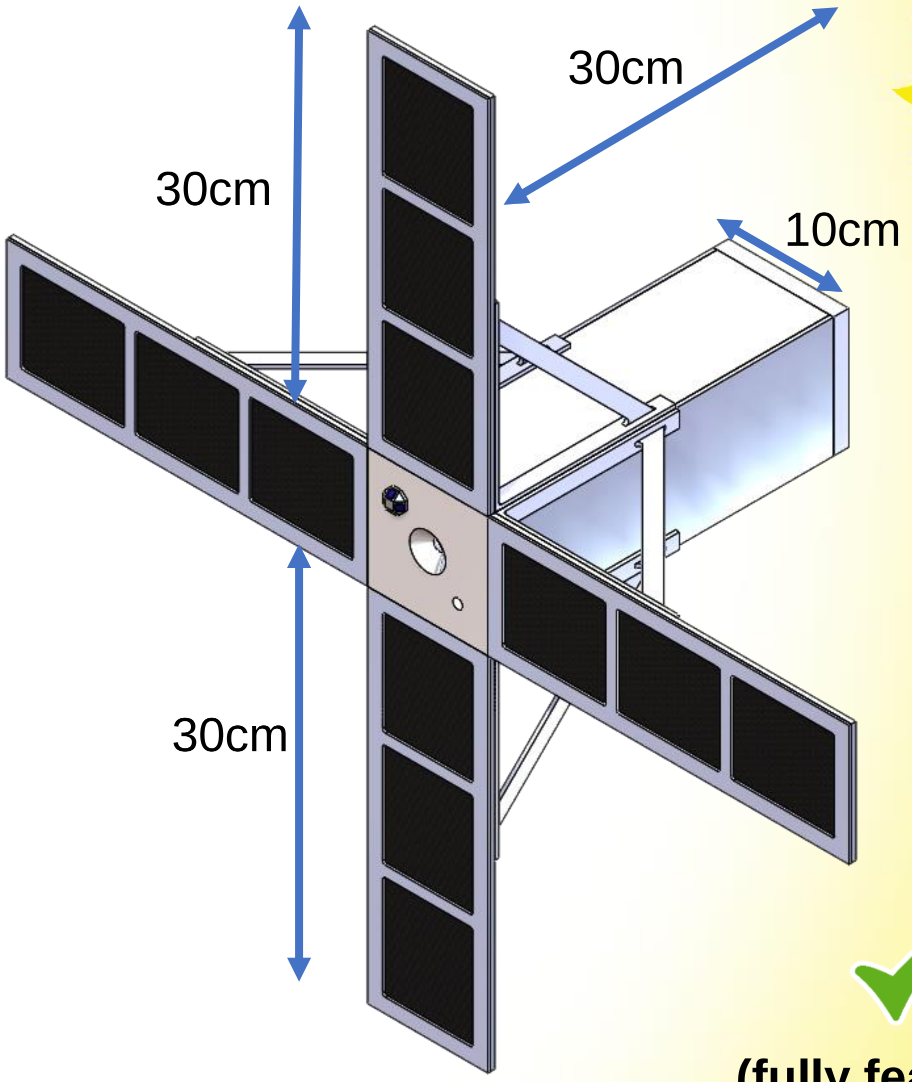
Cables, Sensors, Heaters, etc.:
450 cm^3 ~15%

Remaining Interior Volume:
673.49 cm^3 — 22.45% left

(fully feasible) ✓

Structural Feasibility

Entire structure must fit within a 70cm x 70cm x 30cm envelope



(fully feasible)

Structural Feasibility

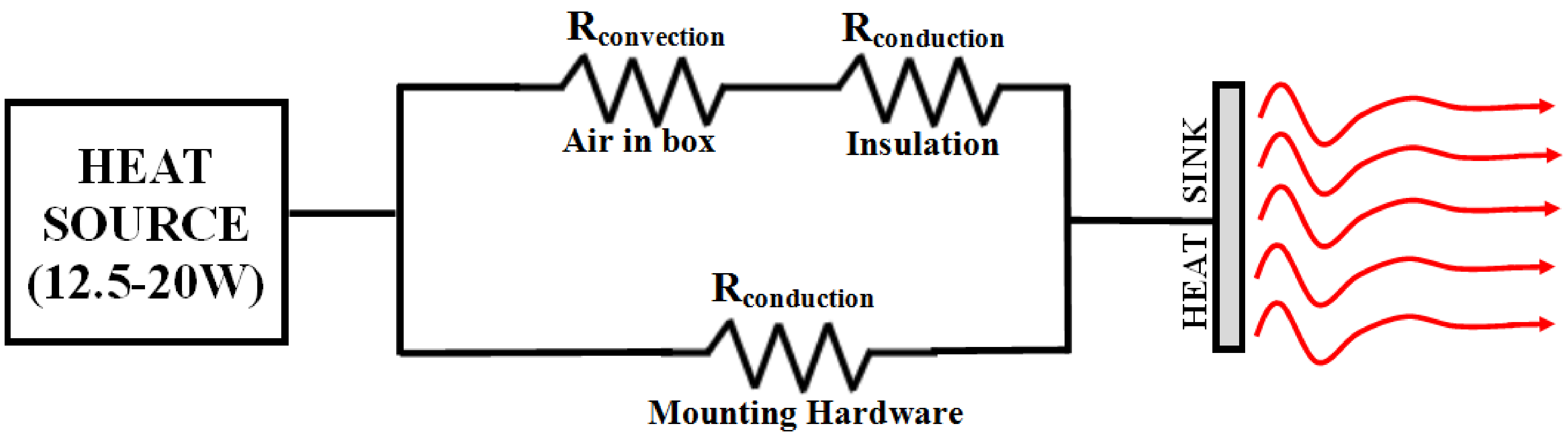
Requirement	Description	Design	Feasibility
5.1	The system (excluding the solar panels) shall have dimensions of 10 x 10 x 30 cm.	Structure is designed such that all internal components fit in the 10 x 10 x 30 cm.	✓
5.2	The system (including the solar panels) shall not exceed dimensions of 70 x 70 x 30 cm (height, width, and depth respectively).	Structure is designed to be exactly 70 x 70 x 30 cm (customer included margin in requirement)	✓

Thermal Requirements

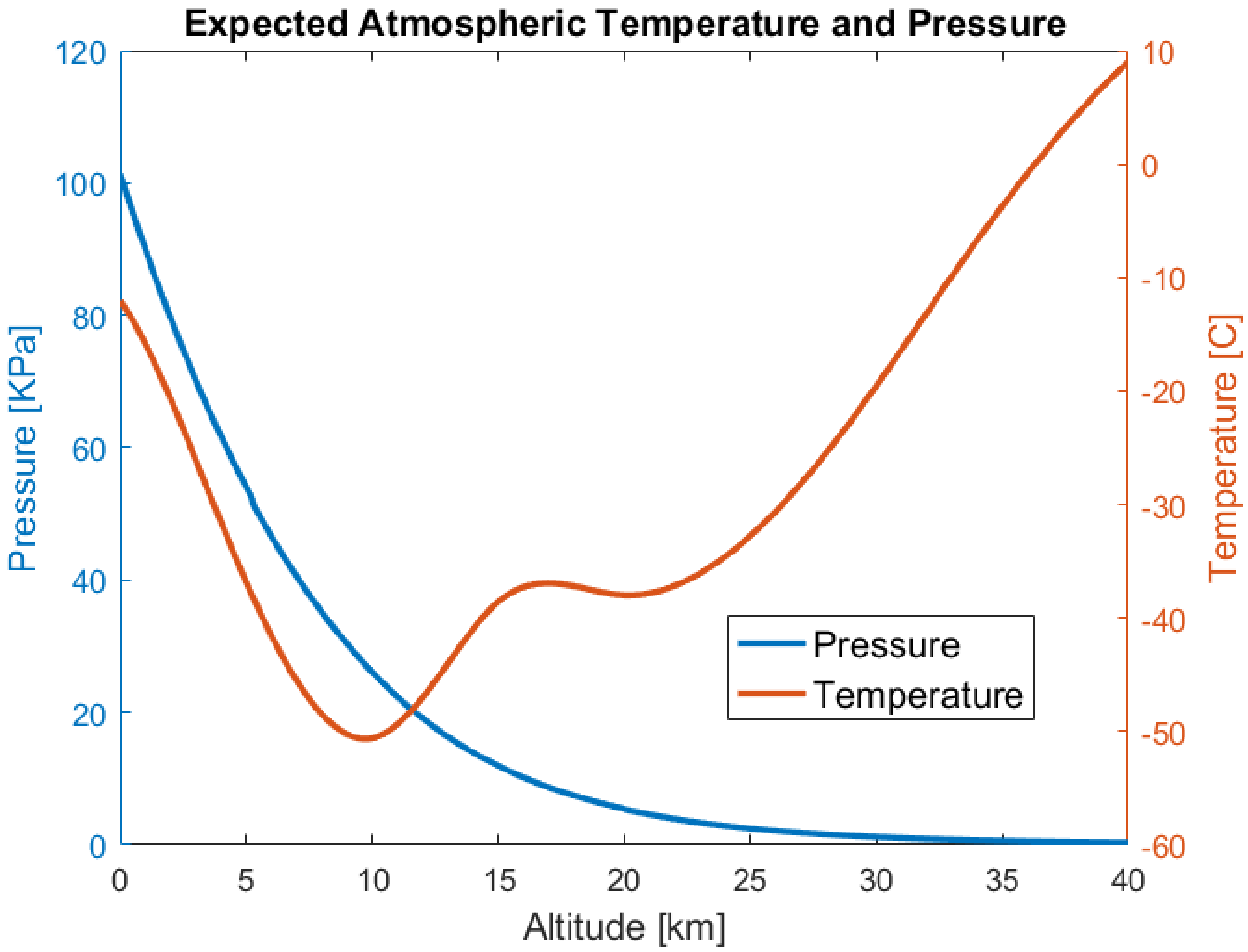
Requirement	Description
2.1	During ascent and descent, the system shall survive temperatures from -60°C to 10°C
2.2	During cruise, the system shall operate at temperatures from 0°C to 20°C

Thermal Design Model

- 1D Thermal model
- Heat Source → Resistors → Heat Sink → Atmosphere

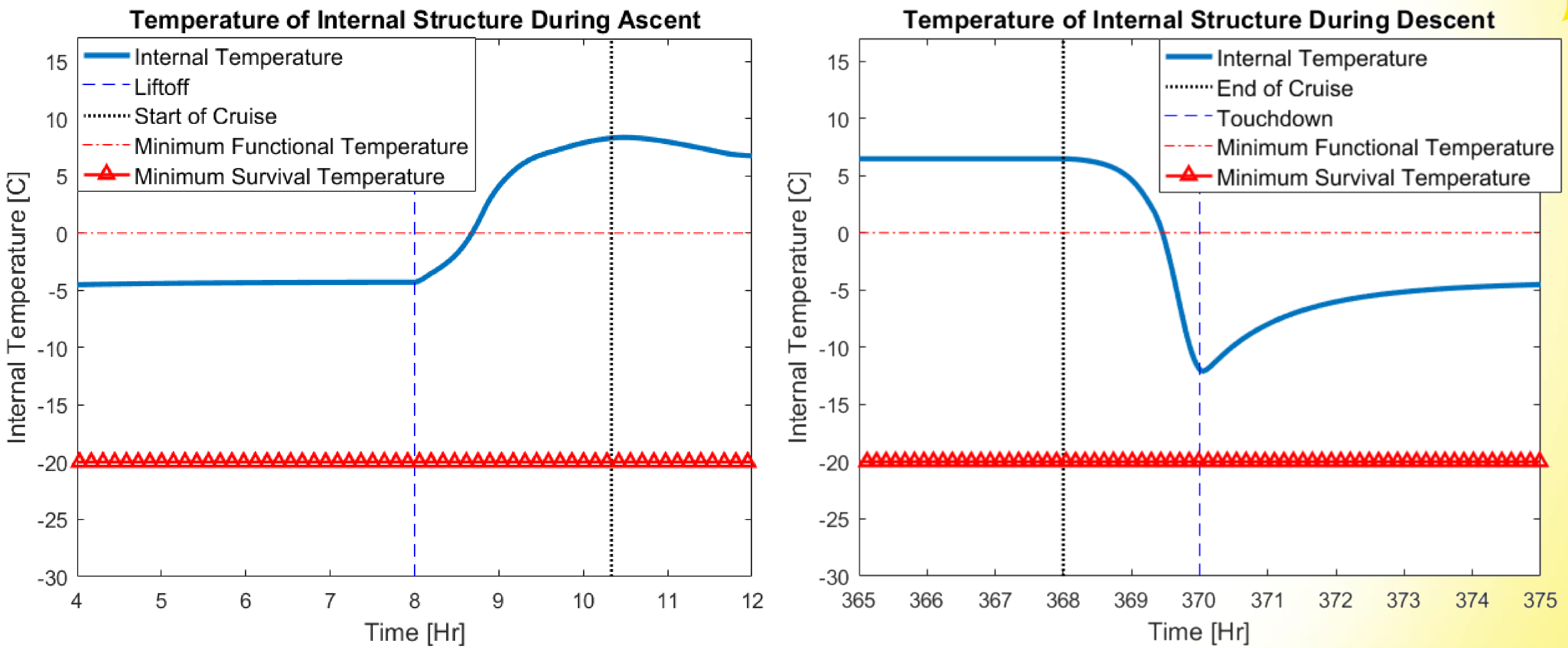


Atmospheric Model



- Temperature model chosen representative of flight data
- Pressure model is standard atmosphere

Ascent/Descent Thermal Profiles



Thermal Feasibility

Requirement	Description	Design	Feasibility
2.1	During ascent and descent, the system shall survive temperatures from -60°C to 10°C	The internal structure will not drop below -13°C during ascent and descent	✓
2.2	During cruise, the system shall operate at temperatures from 0°C to 20°C	The internal structure will maintain 6°C during cruise	✓

Microcontroller Requirements

Requirement	Description	Motivation
3.1.1	Science data shall be recorded at a rate of one measurement per minute.	Customer requirement; science data includes irradiance data and environmental data
3.1.2	Measurements from all science instruments shall be recorded and stored in < 1 sec.	Customer Requirement. Measurements taken at the same time can be reliably compared and correlated.
3.1.3	Camera images shall be recorded at a rate of one image per minute.	Customer Requirement. Provides context for the spectrometer data.

Microcontroller Feasibility

- All measurements must be recorded in < 1sec.
- Worst case scenario
  - with camera

Segment	Time(s)
Measurement	0.52
Processing	0.01
Storage	0.083
Total	0.613 (< 1sec)

(fully feasible)

Microcontroller Feasibility

Requirement	Description	Feasibility
3.1.1	Science data shall be recorded at a rate of one measurement per minute.	✓
3.1.2	Measurements from all science instruments shall be recorded and stored in < 1 sec.	✓
3.1.3	Camera images shall be recorded at a rate of one image per minute.	✓

Data Storage Feasibility

Requirement	Description
3.1.1	Science data shall be recorded at a rate of one measurement per minute.
3.1.2	Measurements from all science instruments shall be recorded and stored in < 1 sec.
3.1.3	Camera images shall be recorded at a rate of one image per minute.
3.2	Storage medium shall survive conditions of flight, including landing.

Data Storage Feasibility

Component	Quantity	Measurement Size	Frequency	Total Over Flight
Spectrometer	1	4 kB	1 Hz	4.6 GB
Camera	1	2.5 MB	1/minute	49.2 GB
ENV Sensors	3	4 byte	1 Hz	13.8 MB
Attitude	5	4 byte	1 Hz	23.1 MB
HK Sensors	11	4 byte	1 Hz	50.8 MB

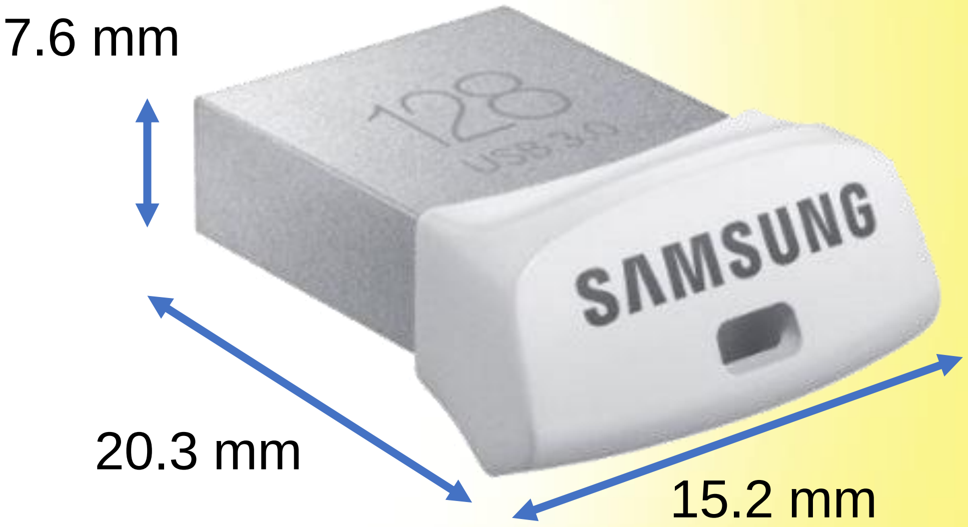
Total storage required: 54.1 GB
Write speed required: 2564.1 kB/s (peak)

Total storage available: 119.2 GB
Write speed available: 8090 kB/s

(Fully feasible)

Data Storage Feasibility

- Cruise conditions: 0° to 20°
  - Operating temperature 0° to 60°
- Ascent/descent conditions: -60° to 10°
  - Survival temperature -10° to 70°
- Expecting high G landing
  - Can withstand up to 1500 Gs



Samsung MUF-128BB/AM

Data Storage Feasibility

Requirement	Description	Feasibility
3.1.1	Science data shall be recorded at a rate of 1 measurement per minute.	✓
3.1.2	Measurements from all science instruments shall be recorded and stored in < 1 sec.	✓
3.1.3	Camera images shall be recorded at a rate of 1 image per minute.	✓
3.2	Storage medium shall survive conditions of flight, including landing.	✓

Instrumentation Feasibility

Requirement	Description
1.1	Solar irradiance measurements shall be taken by a spectrometer
1.1.1	The spectrometer shall measure spectra from 250 nm to 1000 nm
4.1	The off-sun angle shall be determined to ± 1 arcminute.
4.2	Attitude data shall be recorded in parallel with other environmental and housekeeping measurements at a rate of 1 Hz.
6.2	The field of view of the camera shall be 5° (±1°)

Spectrometer Feasibility

System	Criteria	Design	Feasibility
Optics	250nm-1000nm range	200-1100 nm range, 1.4 nm resolution	✓
Power	< 3W	1.25 W	✓
Interface	Ability to work with Raspberry Pi	USB2.0, Qt4 library on Raspbian	✓
Size	No dimension > 10 cm	6.8 x 9.5 x 2 cm	✓
Price	< $4000	$2947	✓

Status Summary

Interface Summary: Power Budget

Subsystem	Power Consumption
Instrumentation	2.3 W
C&DH	6 W
Thermal	11.7 W
Total	20 W ✗ **Above 15 W of HiWind power**

Design Options Considered

- Direct Heating at Temperature Critical Components
- Use Both HiWind and Independent Power
- Increased Insulation

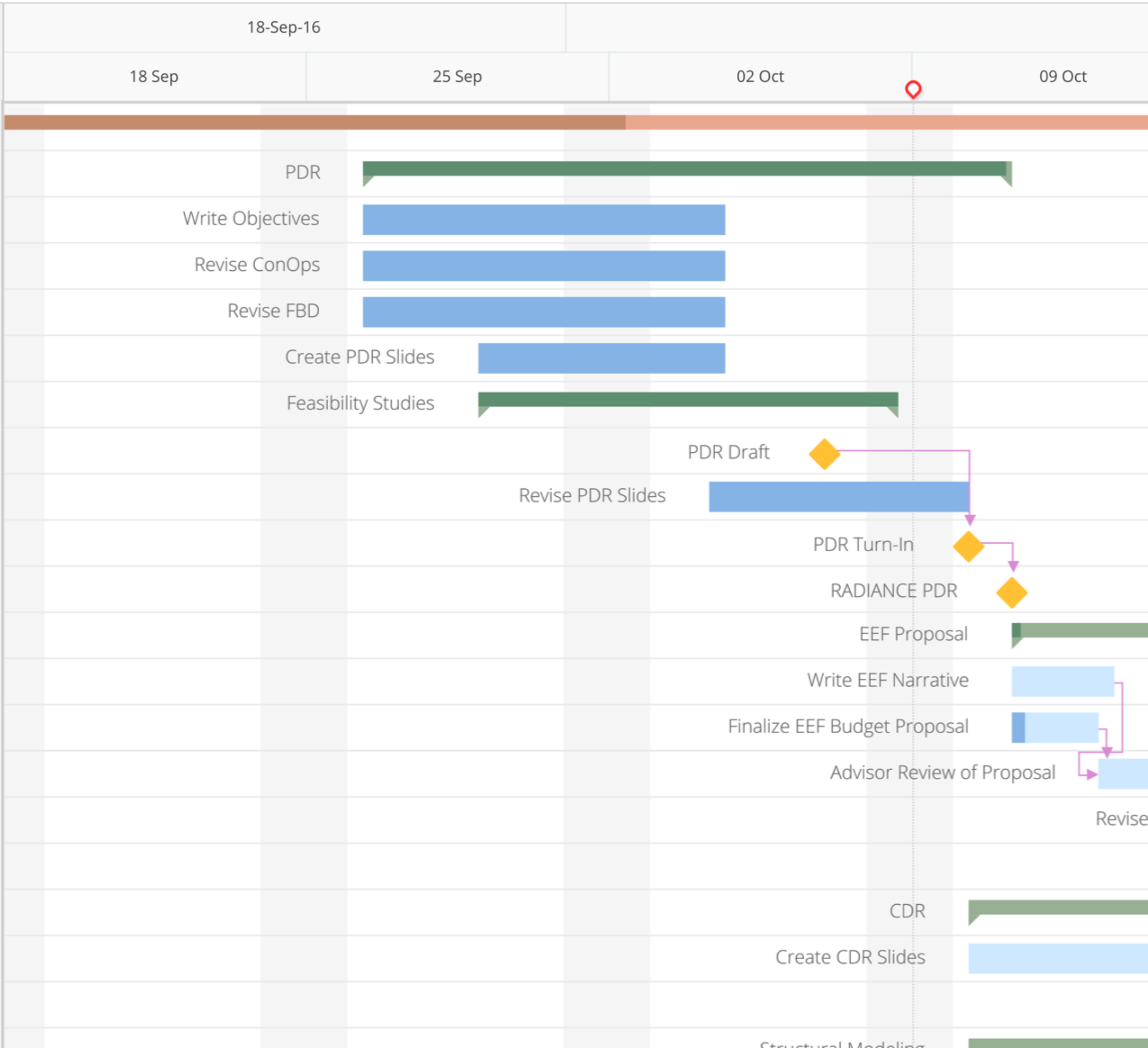
Interface Summary: Mass Budget

Subsystem	Mass
Instrumentation	0.177 kg
C&DH	0.047 kg
Power	0.479 kg
Thermal	0.042 kg
Structure	2.0 kg
Total	2.745 kg ✓ **Less Than a Lead Brick!**

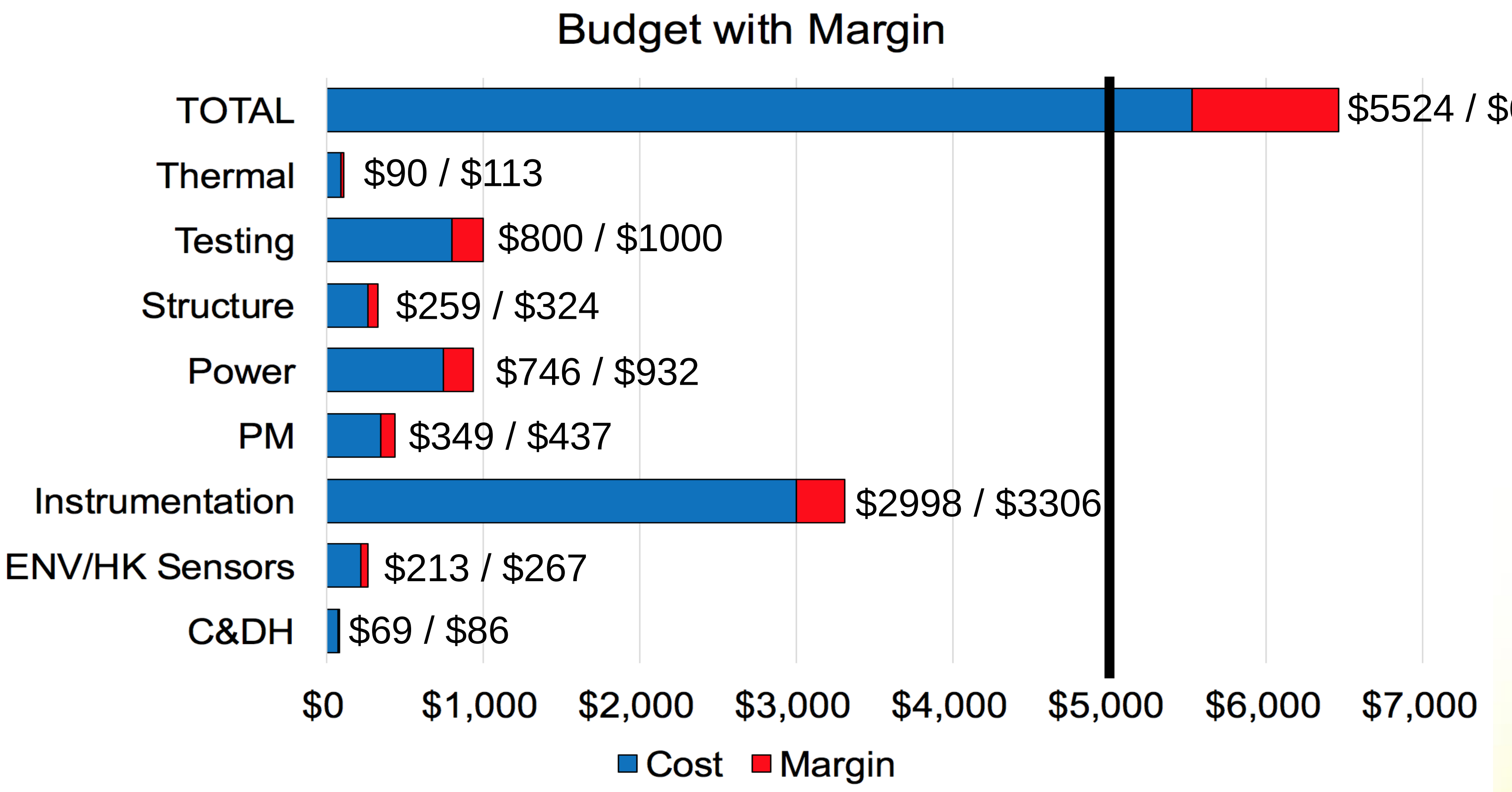
Feasibility and Next Steps

	Functional Requirement	Feasibility Shown	Next Steps
FR 1	The system shall take solar irradiance measurements	Spectrometer	Communicate with Vendor to Acquire Test Unit
FR 2	The system shall survive the environmental conditions of a high-altitude balloon flight up to 40 km	Thermal	CAD Model and ANSYS Model
FR 3	The system shall return data	C&DH	Mock Data Testing
FR 4	The system shall determine its attitude	Attitude	Circuit Design, Attitude Algorithm
FR 5	The system shall interface with the HiWind gondola	Structures, Power	Structure Design, Power Design
FR 6	The system shall capture images of the sun in the visible spectrum	Camera	Optics Modeling, Mock Data Testing

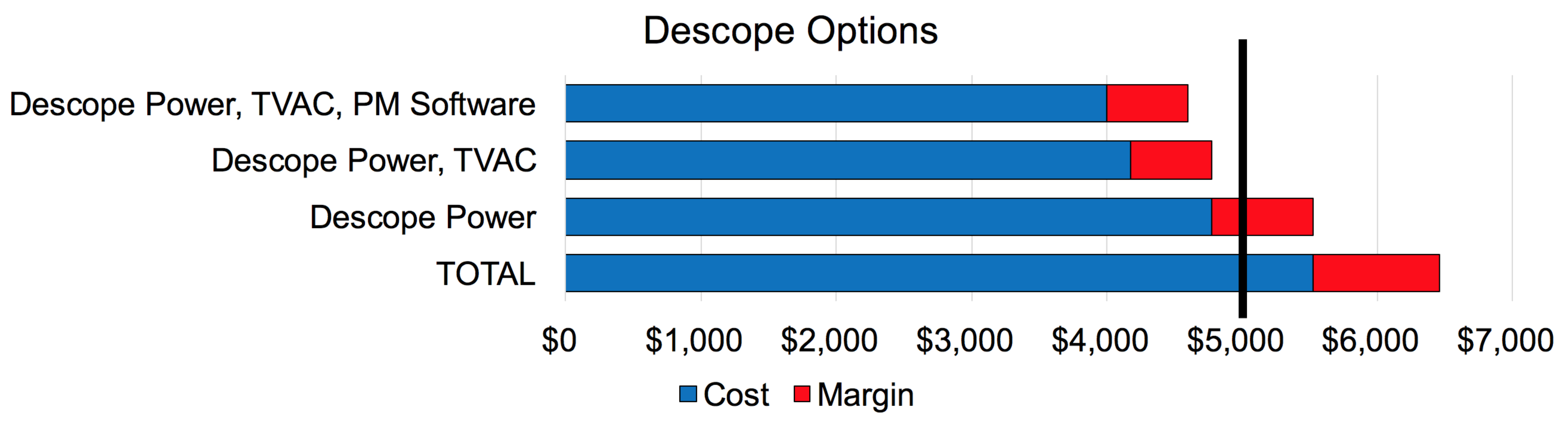
ID	Name	Start	Finish
	RADIANCE	22-Aug-16	12-Dec-16
1	**PDR**	26-Sep-16	11-Oct-16
2	Write Objectives	26-Sep-16	4-Oct-16
3	Revise ConOps	26-Sep-16	4-Oct-16
4	Revise FBD	26-Sep-16	4-Oct-16
5	Create PDR Slides	29-Sep-16	4-Oct-16
6	**Feasibility Studies**	29-Sep-16	8-Oct-16
18	PDR Draft	7-Oct-16	7-Oct-16
19	Revise PDR Slides	4-Oct-16	10-Oct-16
20	PDR Turn-In	10-Oct-16	10-Oct-16
21	RADIANCE PDR	11-Oct-16	11-Oct-16
22	**EEF Proposal**	11-Oct-16	18-Oct-16
23	Write EEF Narrative	11-Oct-16	13-Oct-16
24	Finalize EEF Budget ...	11-Oct-16	13-Oct-16
25	Advisor Review of Pr...	13-Oct-16	17-Oct-16
26	Revise Proposal	17-Oct-16	18-Oct-16
27	EEF Deadline	20-Oct-16	20-Oct-16
28	**CDR**	10-Oct-16	28-Nov-16
29	Create CDR Slides	10-Oct-16	25-Nov-16
30	Finalize Budget	14-Nov-16	20-Nov-16



Total Budget



Budget: Descope Options



We welcome your feedback!

References

[1] Orozco, Luis. “Technical Article MS-2624: Optimizing Precision Photodiode Sensor Circuit Design.” Analog Devices. 2014. Web.
[2] Zorzano, Maria-Paz, Javier Martin-Soler, and Javier Gomez-Elvir. "UV Photodiodes Response to Non-Normal, Non-Colimated and Diffusive Sources of Irradiance."*Photodiodes - Communications, Bio-Sensings, Measurements and High-Energy Physics* (2011): n. pag. Web.
[3] Anderson, John D. *Fundamentals of Aerodynamics*. McGraw-Hill Education, 2011. Print.
[4] French, John. “Middle Atmosphere Diagram.” *Australian Antarctic Division*. N.p. 8 July 2002. Web.
[5] Lazzara, Matthew A. “Radiosonde Weather Observations over Antarctica/Southern Ocean.” *Antarctic Master Directory.* N.p., 20 Oct. 2000. Web.
[6]Sun-Climate Research Center. “Total Solar Irradiance Record.” LASP/Goddard Space Flight Center, N.d. Web.
[7]UCAR. “HAO Balloon Takes To The Skies”. NCAR|UCAR, 17 Jul. 2011. Web.

Image Credit

LASP Irradiance Data - http://spot.colorado.edu/~koppg/TSI/Publications/2007_Kopp_TRF_SPIE.pdf

HiWind Gondola Photos - http://stratocat.com.ar/globos/fotos/hiwind11b.jpg

HiWind CAD Models - Email from HAO-NCAR

IXYS Solar Panel - http://ixapps.ixys.com/DataSheet/SLMD481H12L_20160712.pdf

CUTE-I CubeSat - http://lss.mes.titech.ac.jp/ssp/cubesat/index_e.html

UltraLife Battery - https://www.ultralifecorporation.com/Ecommerce/site/images/Photo2/UBBL24-C1.jpg

Avantes Spectrometer - http://www.avantes.com/products/spectrometers/compactline/item/723-avaspec-mini

Raspberry Pi - http://uk.rs-online.com/web/p/processor-microcontroller-development-kits/8968660/

Flash Drive –

Photodiodes - http://www.digikey.com/product-detail/en/luna-optoelectronics/PDB-C160SM/PDB-C160SMCT-ND/481717

Pressure Sensor - http://www.digikey.com/product-detail/en/honeywell-sensing-and-productivity-solutions/ASDXACX015PA7A5/480-3303-ND/2178292

Humidity Sensor - http://www.digikey.com/product-detail/en/te-connectivity-measurement-specialties/HPP804B130/HPP804B130-ND/697732

ENV Temperature Sensor - https://www.sparkfun.com/products/11931

HK Temperature Sensor - https://www.adafruit.com/product/374

PTC Battery Protection - http://www.nrel.gov/transportation/energystorage/pdfs/45388.pdf

Thermocouple - https://www.adafruit.com/product/270

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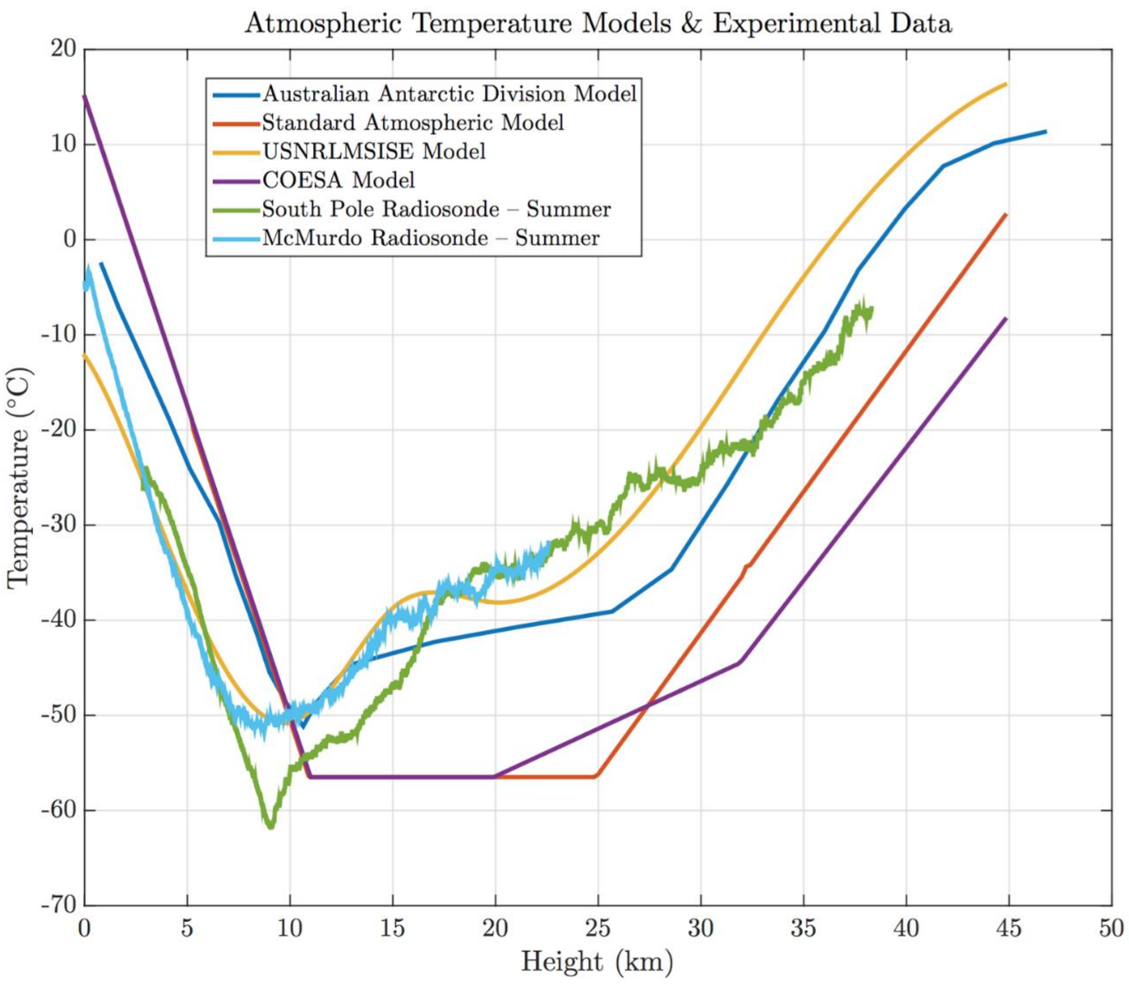
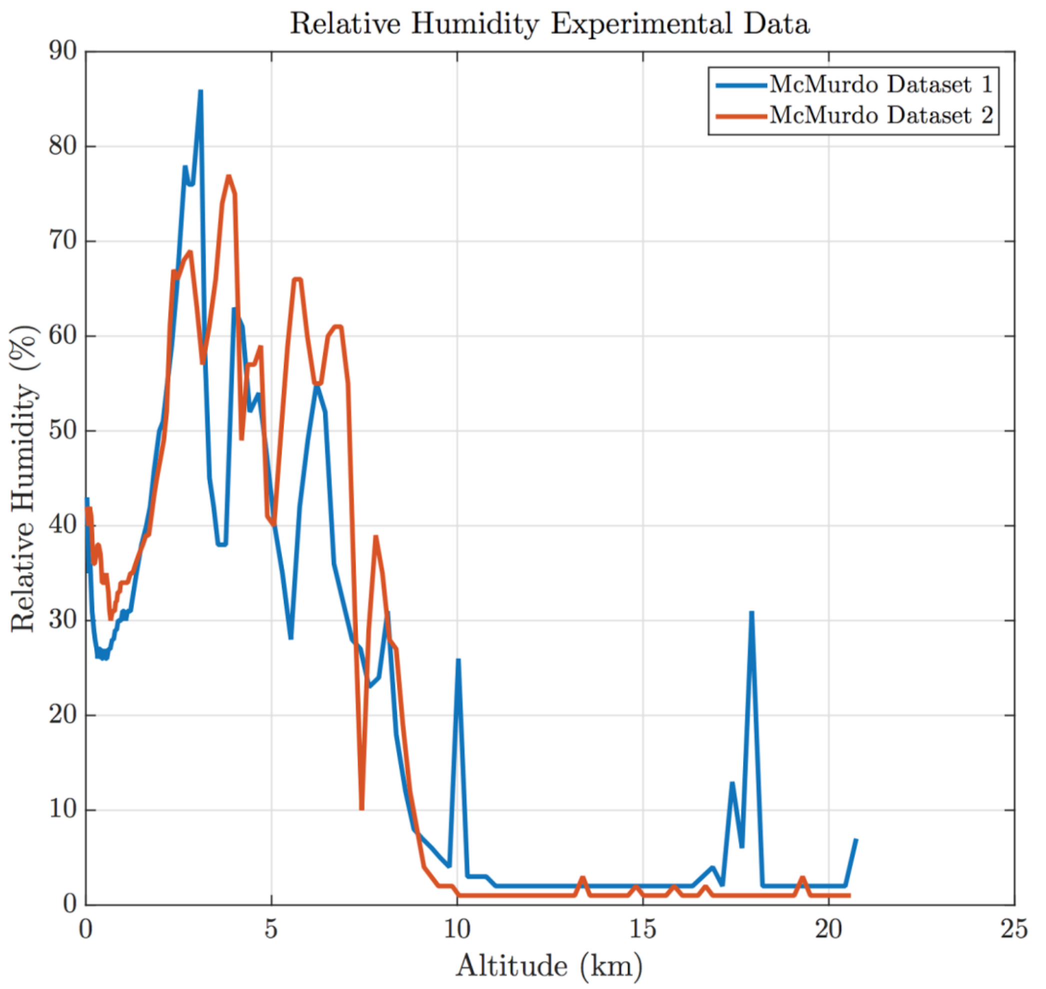
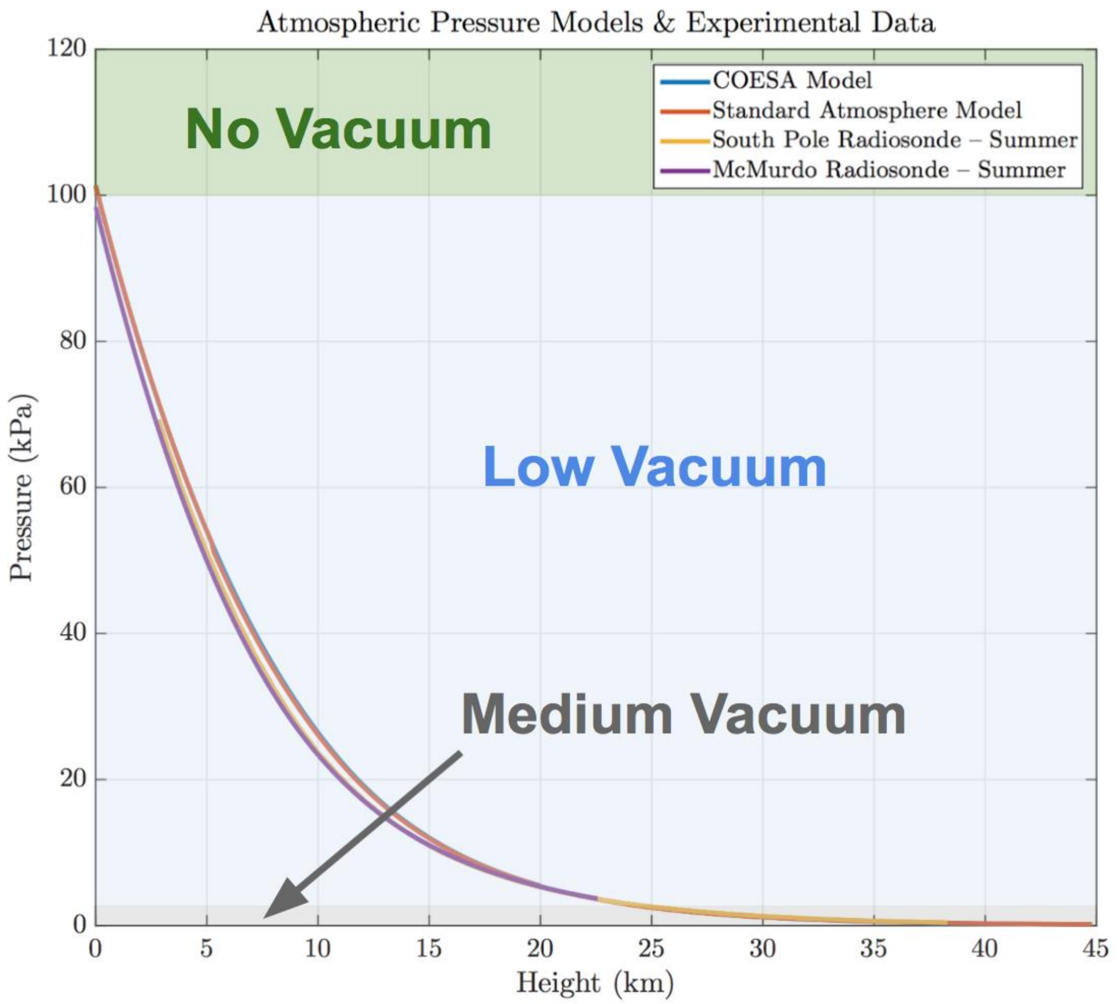
Backups

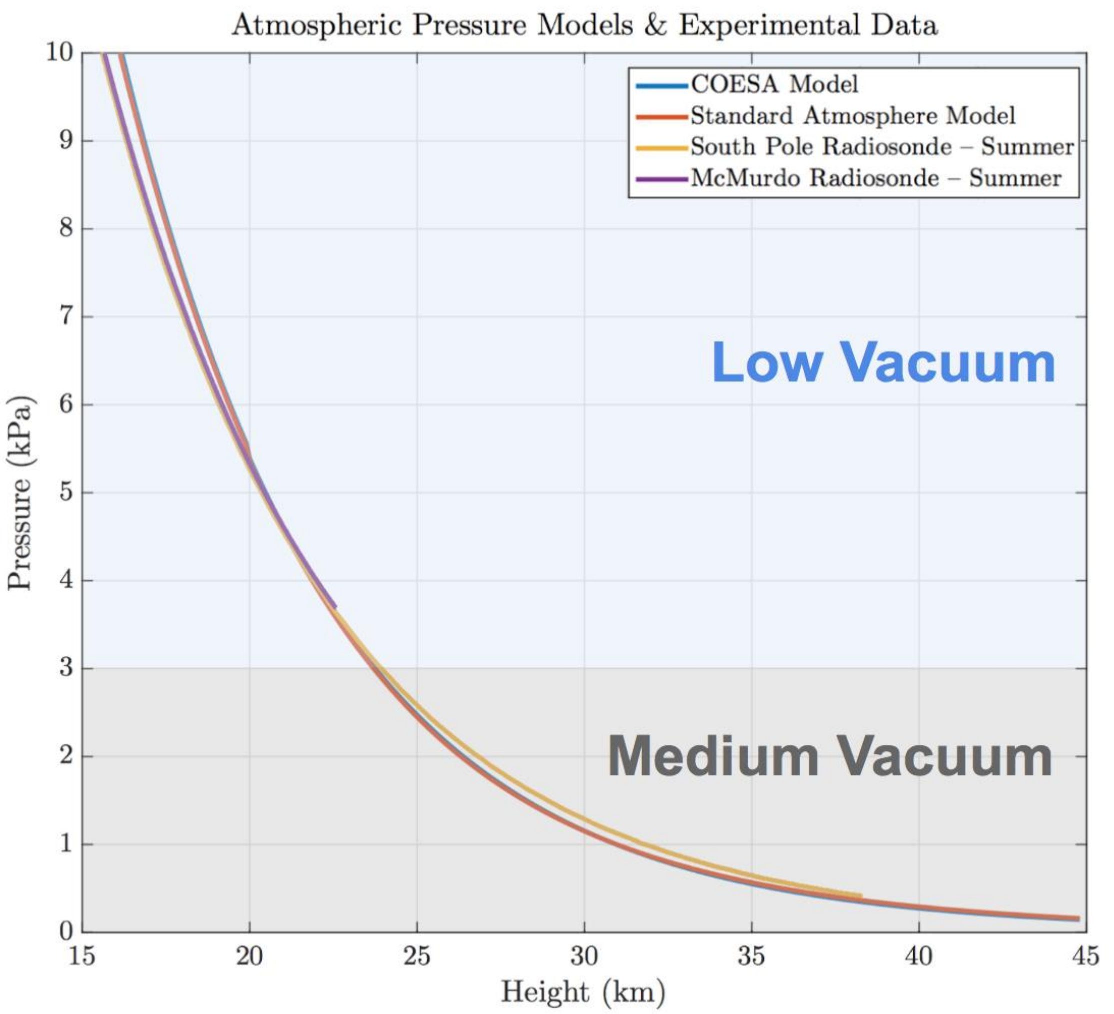
Atmospheric Models



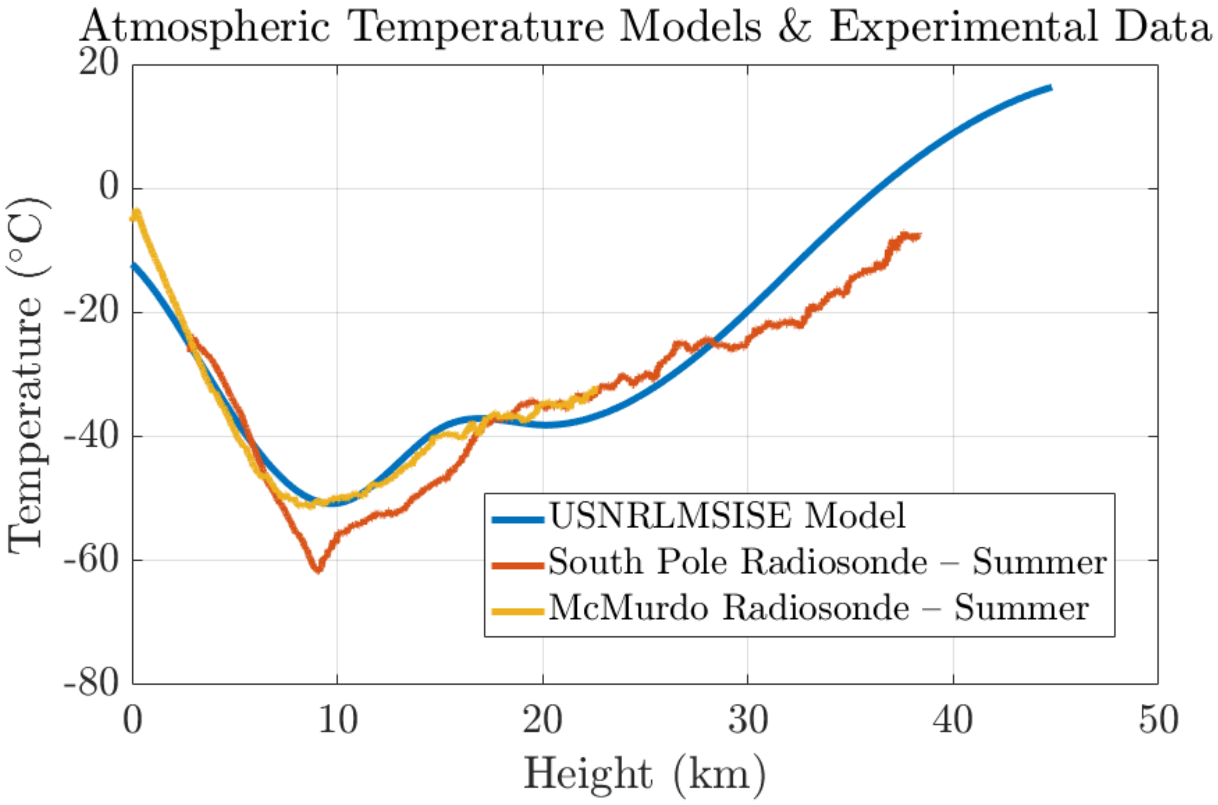


Atmospheric Models



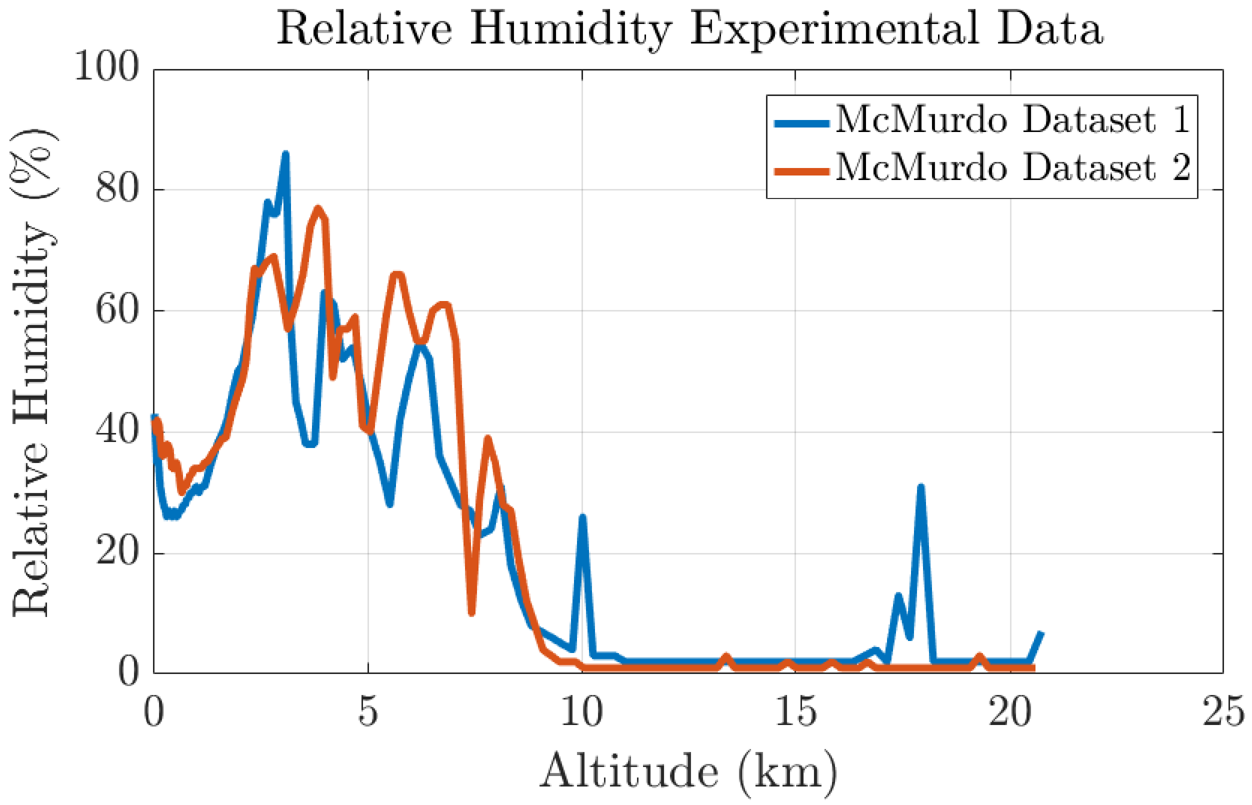


Atmosphere Justification



- Used USNRLMSISE model for continuity
- Both McMurdo datasets follow general trend of model

Atmospheric Humidity



- Humidity ranges between 0 and 90%
- Humidity decreases density which affects convection
- May result in condensation/icing on descent

Materials Selection

- Silicon: Too expensive
- Magnesium: Burns well
- Titanium: Out of budget
- Iron: Oxidizes
- Honeycomb materials would be difficult to manufacture

Materials Type Trade Study

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**

Materials Selection

- Al7075 is a stronger allow that can be machined thinner consisting mostly of Zinc as the primary alloying element
- Al6061 is a cheaper lighter alternative with Mg and Si as the primary alloying elements
- SS 304 is the most common grade – known as 'food grade‘
- SS 316 is the second most common and is known as 'marine grade' and prevents specific forms of corrosion
- SS in general is much more difficult to machine

Structure Material Feasibility

- Al6061-T6
  - 2'x2' sheets of 3/16" can be bought for less than $50
  - Excellent corrosion resistance
  - Lightweight
  - Easy to machine
  - Vacuum and temperature resistant
  - Easily available

Material Alloy Trade Study

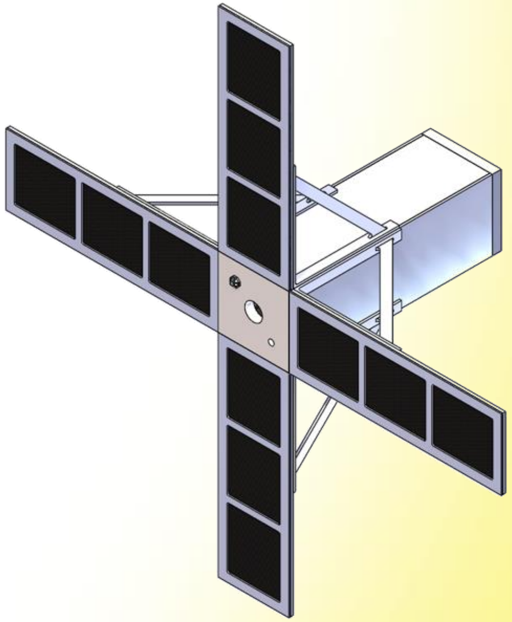
Value	Price $	Durability (MPa)	Ease of Manufacturing	Density g/cm^3	Thermal Conductivity W/m/K	Familiarity
1	> 100	< 50	Need to procure equipment	> 5	> 150	No experience with material
2	100 to 50	50 to 100	Limited access to equipment	5 to 2.5	150 to 100	Knowledge of material
3	50 to 20	100 to 200	Access 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

Criteria (ranked by normalized criteria value)	Normalized Priority Value	Aluminum 6061-T6		Aluminum 7075-T6		Stainless Steel 304		Stainless Steel 316	
Price	0.35	3	1.05	1	0.35	2	0.70	2	0.70
Durability	0.25	4	1.00	5	1.25	5	1.25	5	1.25
Manufacturability	0.10	4	0.40	3	0.30	2	0.20	2	0.20
Density	0.05	2	0.10	2	0.10	1	0.05	1	0.05
Thermal Conductivity	0.05	1	0.05	1	0.05	5	0.25	5	0.25
Familiarity	0.05	4	0.20	4	0.20	2	0.10	2	0.10
Totals	0.85		2.80		2.25		2.55		2.55

Power Feasibility: Solar Panels

- 3 cells per panel
- 4 panels on RADIANCE

Properties of Single Cell at Max Power Point		
Voltage (V)	Current(A)	Power = V*I (W)
6.06	0.178	1.079

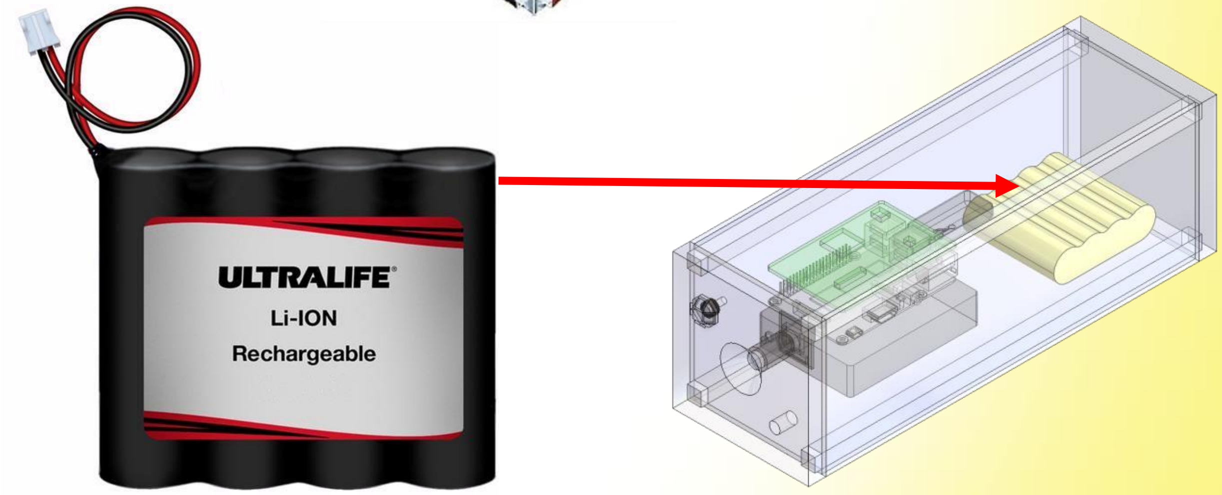


- 3 x 4 = 12 total cells
- Maximum total power: 12.948 W

Battery Baseline Design

Li-on UltraLife UBBL24-FL Battery	
Power	4.8 Ahr @ 0.96A rate
Size	67 x 75 x 21.5 mm

- Heritage on CubeSat projects
  - CUTE-I
- High energy density
- High capacity



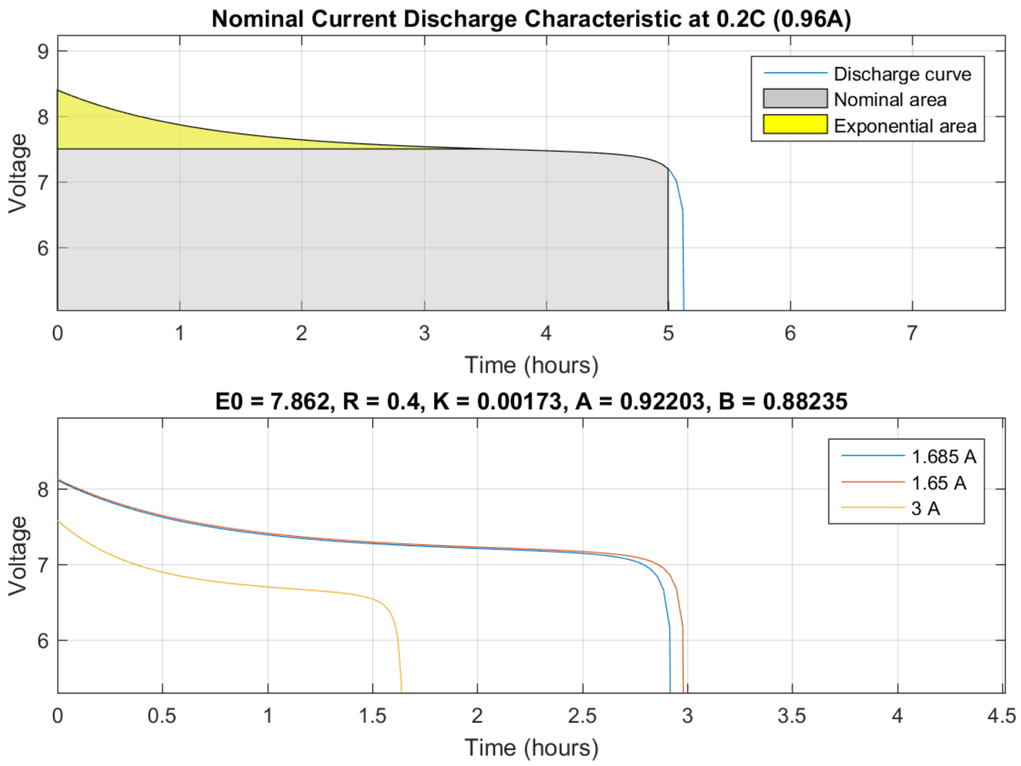
Battery Trade Study

Criteria (ranked by weight)		UBBL21-FL		UBBL24-FL		UBBL20		UBBL07		AT 18650	
Capacity	0.40	1	0.40	4	1.60	1	0.40	5	2.00	2	0.80
Price	0.20	2	0.40	1	0.20	4	0.80	3	0.60	5	1.00
Voltage	0.20	2	0.40	5	1.00	5	1.00	1	0.20	4	0.80
Size	0.20	4	0.80	2	0.40	2	0.40	1	0.20	3	0.60
Totals	1.00		**2.00**		**3.20**		**2.60**		**3.00**		**3.20**

Battery Baseline Design

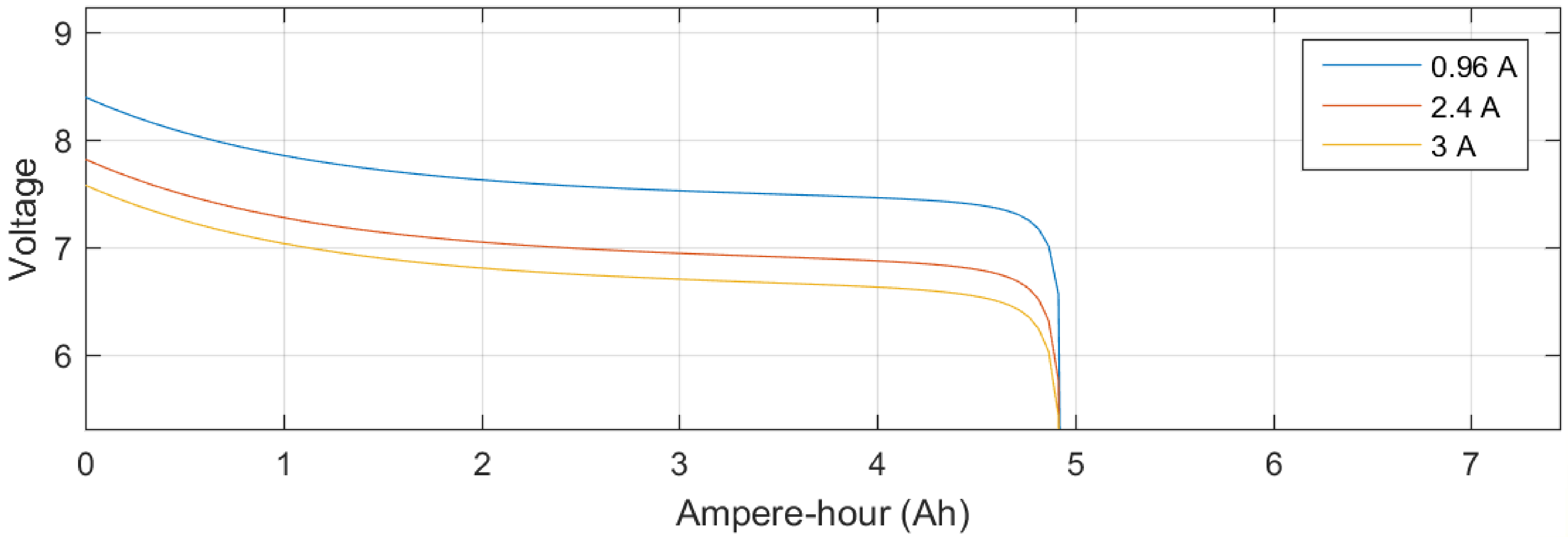
Ultralife UBBL24-FL	
Size	67 x 75 x 21.5mm
Capacity	4.8 A-Hr @ 0.96 A rate
Voltage	7.2 V
Maximum Discharge Current	3.0 A Continuous
Energy Density	181Wh/kg, 450Wh/l
Weight	191 g
Operating Temperature	-20˚ – 60˚ C

Power Feasibility: Batteries

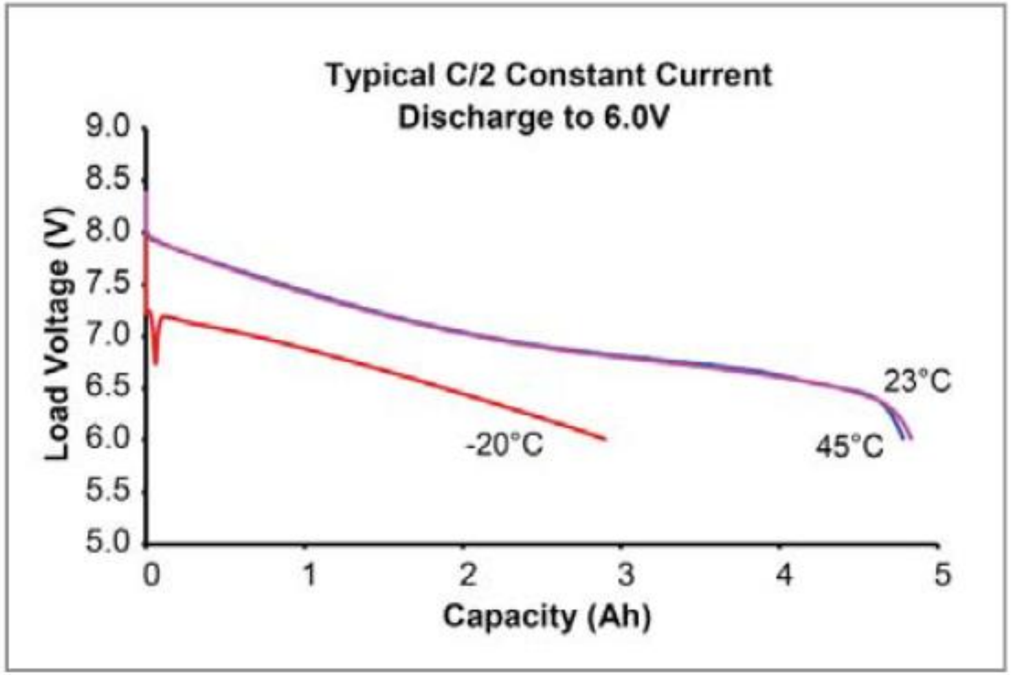


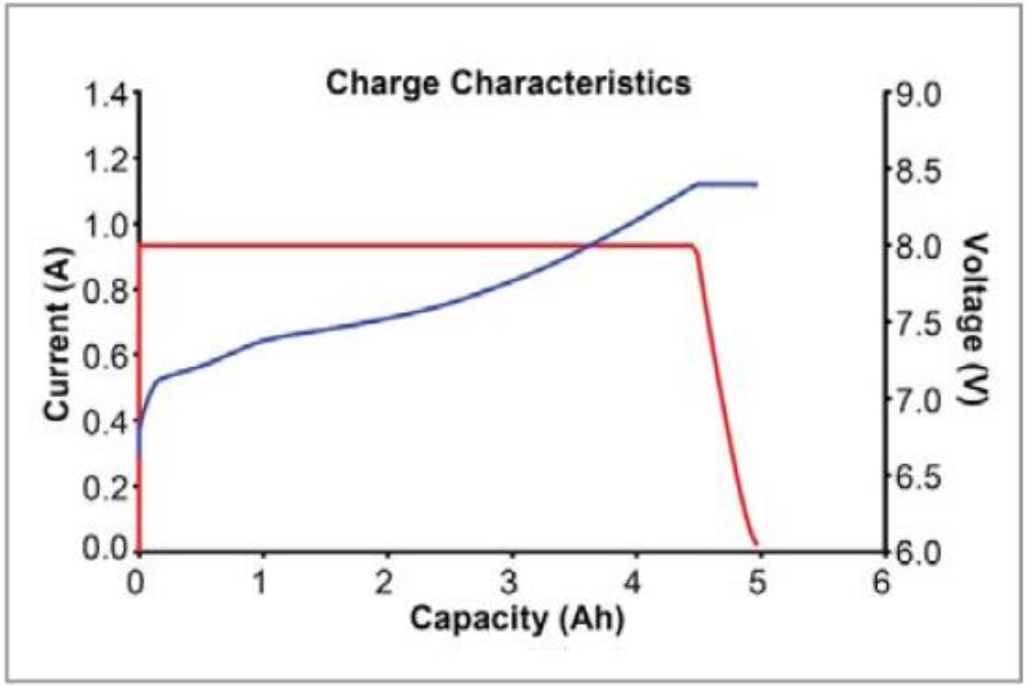
- Modeled using Simulink's built in electronics library
- Validated with experimental results found in Datasheets
- With all sensors on, Battery will last nearly 3 hours (No thermal control)

Power Feasibility: Batteries



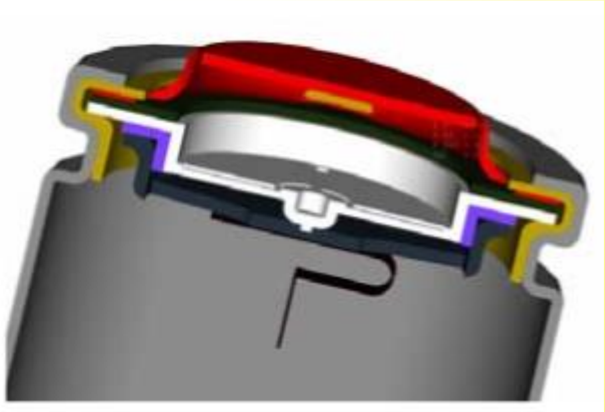
Power Feasibility: Batteries





Power Feasibility: Batteries

- PTC
  - Circuit protection
  - Stands for Pressure, Temperature, Current (sensors)
  - Stops current surges
  - Resettable, but deteriorates after each trigger



Power Feasibility: Batteries

Requirements

- 2 Hours of Ascent
- Assume Worst Case: Only Draw on Battery

Model

- System Draws 2.25 A
- 2.25 x 2 = 4.5 Ahr

Feasibility

- Battery has 4.8 Ahr
- Feasible!

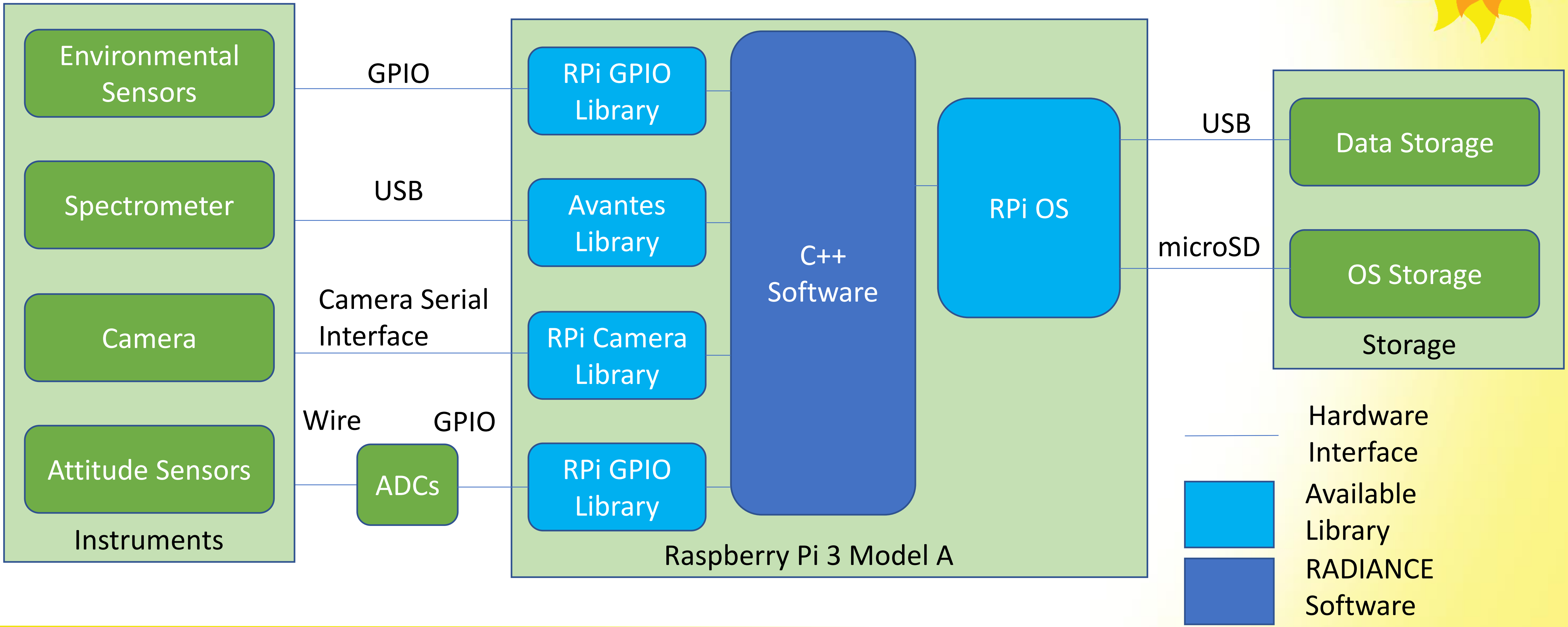
Microcontroller Trade Study

Criteria (ranked by normalized criteria value)	Normalized Priority Value	Raspberry Pi 3 Model 3		Orange Pi Plus 2		Banana Pi M3		Odriod XU4	
Price	0.05	5	0.25	4	0.20	3	0.15	3	0.15
Processing Speed	0.10	3	0.30	4	0.40	4	0.40	5	0.50
# of Threads	0.15	4	0.60	4	0.60	5	0.75	5	0.75
RAM	0.15	2.5	0.38	5	0.75	5	0.75	5	0.75
Power Usage	0.35	5	1.75	4	1.40	2	0.70	2	0.70
Compatibility	0.15	5	0.75	3	0.45	1	0.15	4	0.60
Familiarity	0.05	5	0.25	2	0.10	1	0.05	5	0.25
Totals	1.00		4.28		3.90		2.95		3.70

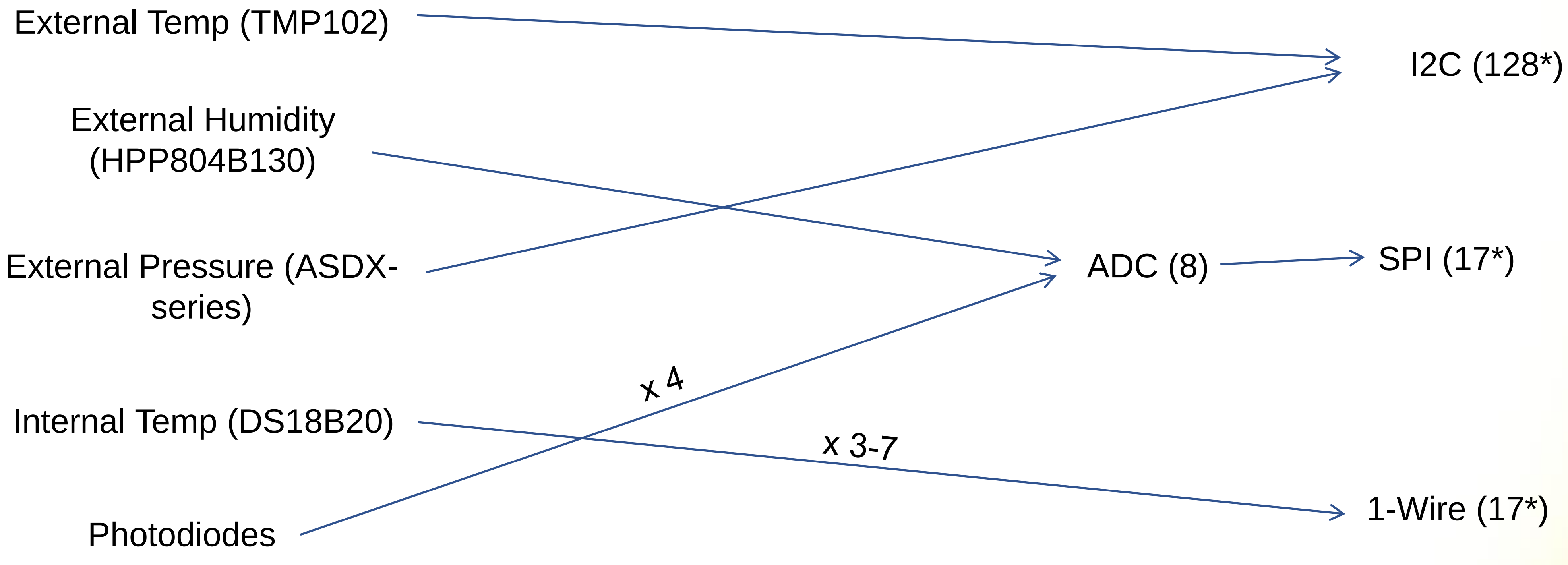
Microcontroller I/O Capability

- Spectrometer/data storage uses 2 USB ports, 4 are available
- Camera uses CSI, 1 is available
- OS/Storage uses microSD, 1 is available
- HK sensors use a variety of protocols(I2C/SPI/1W); number of GPIO pins available may be a problem when using ~15 sensors. Worst case we solve this using a GPIO extender, best case we use clever sensor mapping

Software Interfaces



Sensor Port Mapping



Microcontroller Design(Measurements)

Quantity	Component	Time per measurement	Data Transfer Time	Total
1	Camera	Typical Exposure Time: 0.25 s	2.5MB @ 30MB/s(USB2.0) = 8.33e-2 s	0.333s
1	Spectrometer	Typical Integration Time: 0.17 s	5 kB @ 30MB/s(USB2.0) = 1.67e-4 s	0.170s
3	HK Sensors	I2C Bus Speed: 2.5e-6 s	30B@12.5kB/s(I2C) = 2.4e-3 s	1.68e-2s
4	Attitude Sensor	ADC Sampling Rate: 1.33e-5 s	2B @ 12.5kB/s(I2C) = 1.6e-4 s	6.92e-4s

Total Measurement Time: 0.52s(<1s) ✓ **(Fully feasible)**

Microcontroller Design (Measurements)

Component	Time/Measurement [s]
Camera	0.333
Spectrometer	0.170
HK Sensors	0.0168
Attitude Sensor	0.000692

→ **Total Time/Measurement: 0.52s**

Execution Time Estimation

- HK and attitude sensors
  - Estimate 210B (one measurement per sensor) of raw data
  - Process: Write test program on similar hardware (Raspberry Pi 1 Model B) and measure execution time
  - Answer: Test program takes 0.010s for processing all 210B

➡ **Total Processing Time: 0.010s**

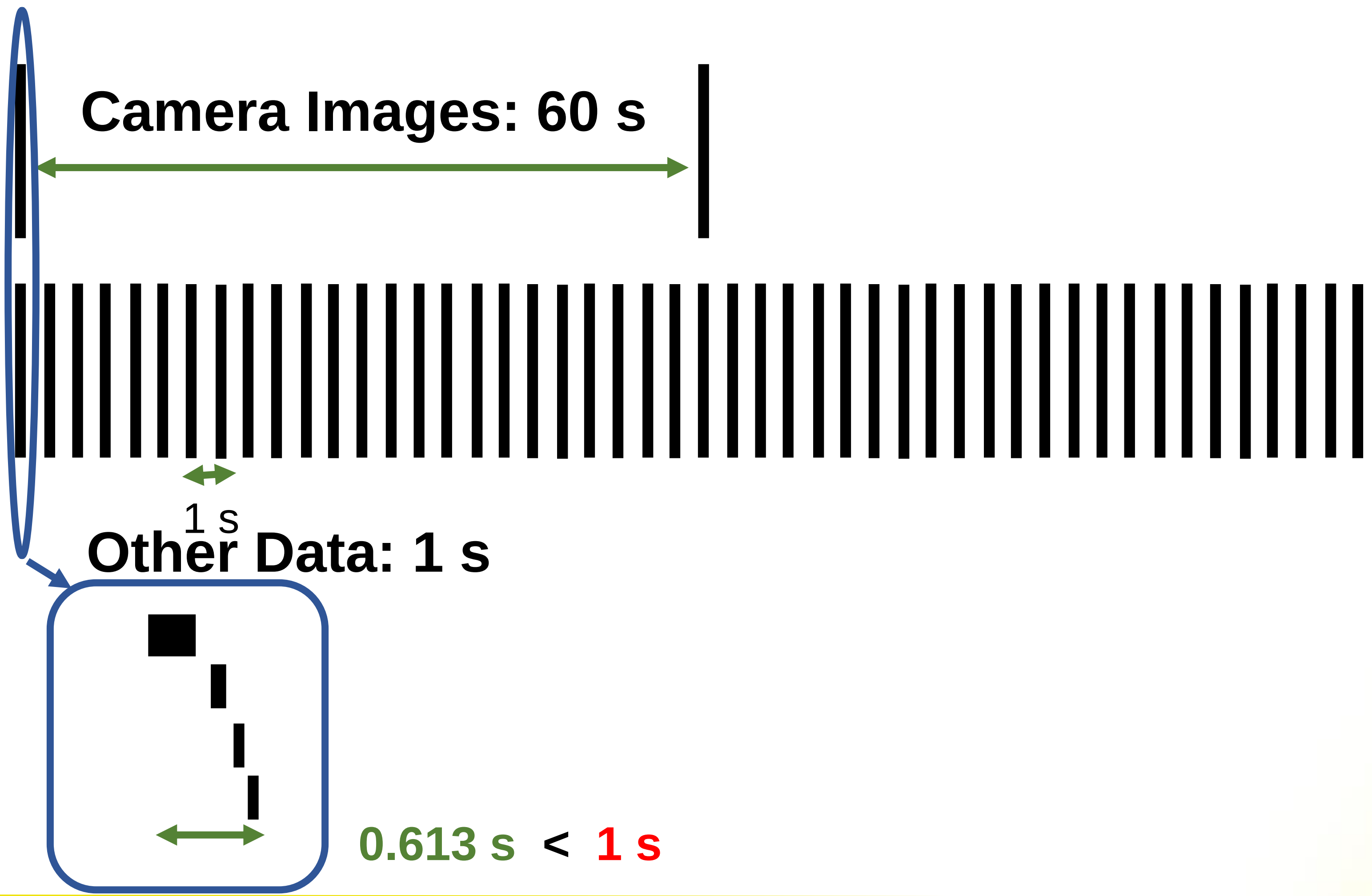
- Need to write 2.51MB at 30 MB/s

$$\text{Time Per Frame} = \text{Measurement} + \text{Processing} + \text{Storage}$$
$$= 0.52\text{s} + 0.010\text{s} + 0.083\text{s} = 0.613\text{s}$$

➡ **Data Storage Time: 0.083s**

➡ **Total Measurement Time: 0.613s (<1s)** ✔ **(Fully feasible)**

Timing Sequence

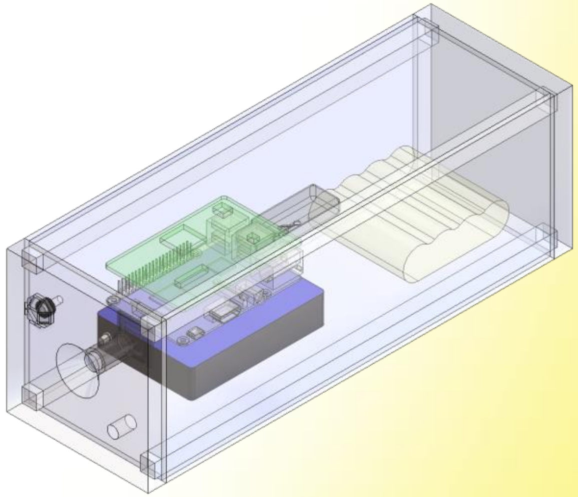


Language Selection Rationale

- Both Python and C++ are options
- Python requires the use of PyQt4 for interfacing with Avantes's library
- Our group is much more familiar with Python
- Python is interpreted and is 10-100x slower on average, worst case 400x
- Most measurements are being taken every second
- C++ has a better ability to be optimized when speed is a concern

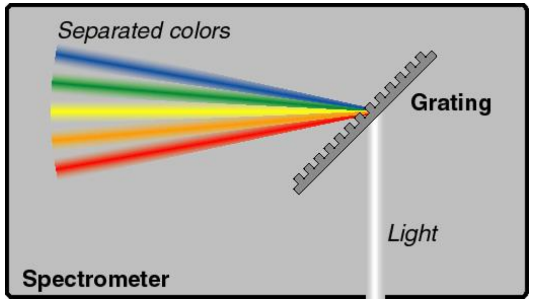
Spectrometer Baseline Design

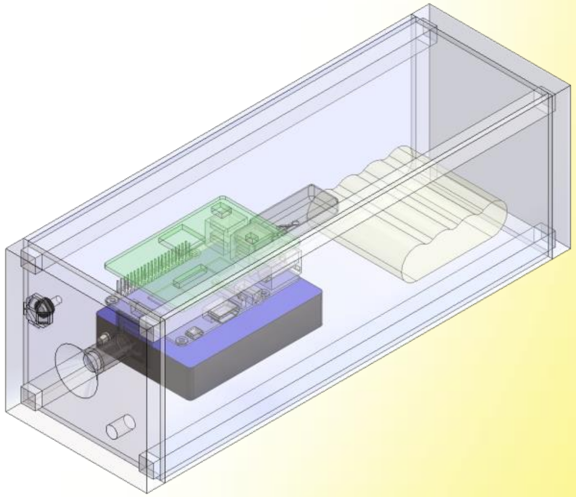
Category	Specs
Power	250mA, 5V, 1.25W
Data	16 bit A/D converter 4KB per measurement 4.61 GB for full mission (1Hz)
Software	Library written in C++ Can interface with all Linux distributions



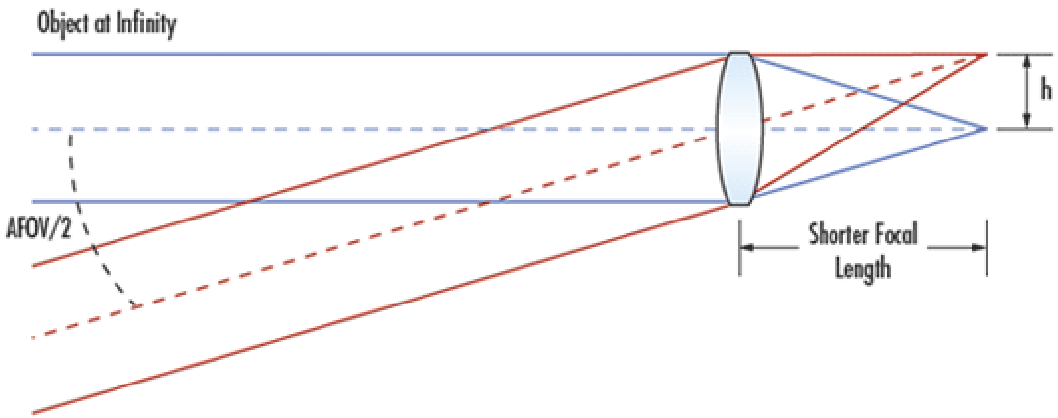
Spectrometer Baseline Design

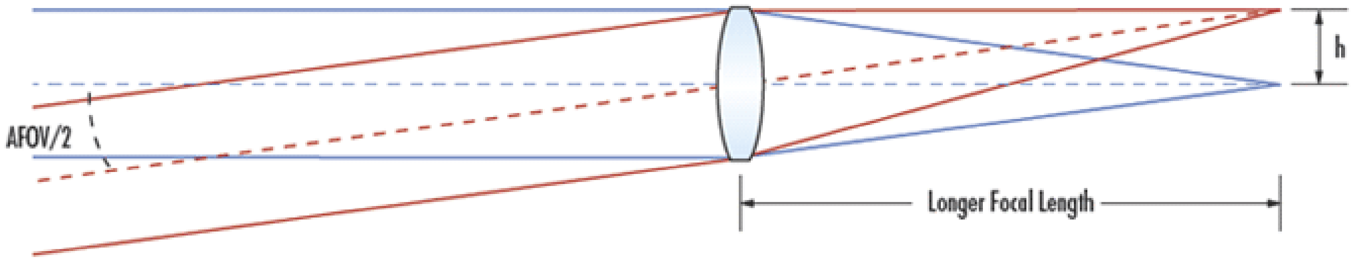
Slit size (μm)						
2048(L)						
Grating (lines/mm)	10	25	50	100	200	500
300	0.80-0.90	1.12-1.25	2.35	4.65	9.10	21.00
600	0.40-0.53	0.70	1.20	2.40	4.60	10.80
1800	0.10-0.18	0.20-0.29	0.34-0.42	0.80	1.60	3.60

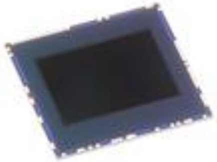




Camera Calculations






Sony IMX219

$$AFOV(°) = 2 \; x \; tan^{-1}\left(\frac{h}{2f}\right)$$

$$h = 2.7mm$$

$$2\arctan(\frac{2.70}{2f}) = 5°$$

$$f_{desired} = 30.92mm$$

$$f_{actual} = 30mm$$

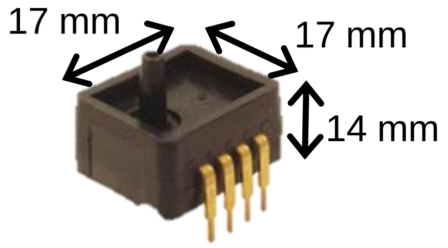
$$2\arctan(\frac{2.70}{2(30)}) = 5.16°$$

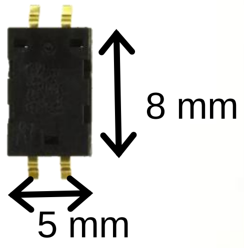
Camera Feasibility

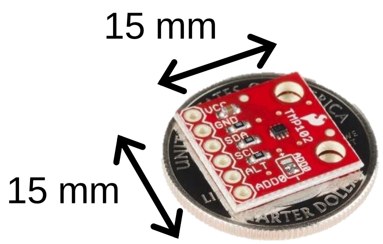
Design Constraint	Criteria	Design	Feasibility
Size	Focal length less than 10cm	Focal length 3cm	✓
Field of View	2-10° FOV	5.16° FOV	✓
Price	< $100	$51	✓
Power	< 1W	.6W while in operation	✓
Data Storage	128GB	45GB taken throughout flight	✓

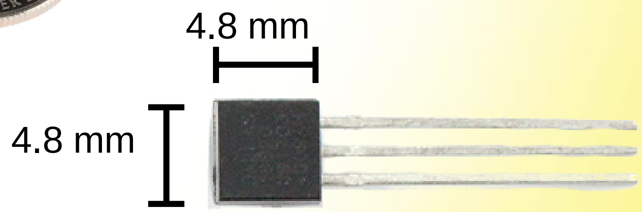
Sensors

Sensor Type	Model	Specifications	Price
Environmental Sensors			
Pressure	Honeywell ASDX-series	0 to 15 psi (up to 103 kPa)	$44.71
Humidity	TE HPP804B130	1-99% RH	$19.70
Temperature	TMP102	-55 to +150 °C	$3.95
Housekeeping Sensors			
Temperature	DS18B20	-55 to +125 °C	$3.95









ENV Feasibility: Pressure

Honeywell ASDX-series Barometric Pressure Sensor

- ASDXACX015PA7A5 Sensing Range 0 to 15psi (to 103 kPa)
- Sold through Digikey, Arrow Electronics, other vendors
- 17 mm-17 mm-14 mm
- I2C or SPI digital interface options
- $45

ENV Feasibility: Humidity

TE Humidity Temperature Sensor HPP804B130

Operating Range -60 to +140 °C

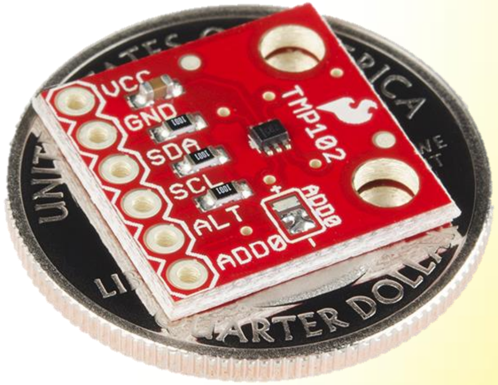
Sensing Range 1-99% RH, 1% error

Analog Output, requires an ADC

$19.70 from Digikey

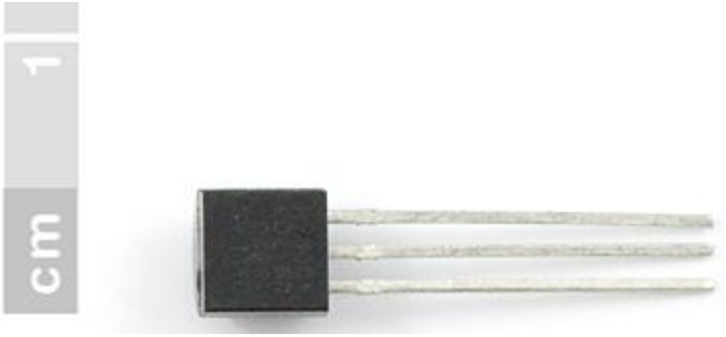
ENV Feasibility: Temperature

- Digital Temperature Sensor Breakout with TMP102
  - Sensing range -55 to +150 °C, error 0.75 °C
  - I2C digital interface
  - $3.95 from SparkFun



HK Feasibility: Temperature

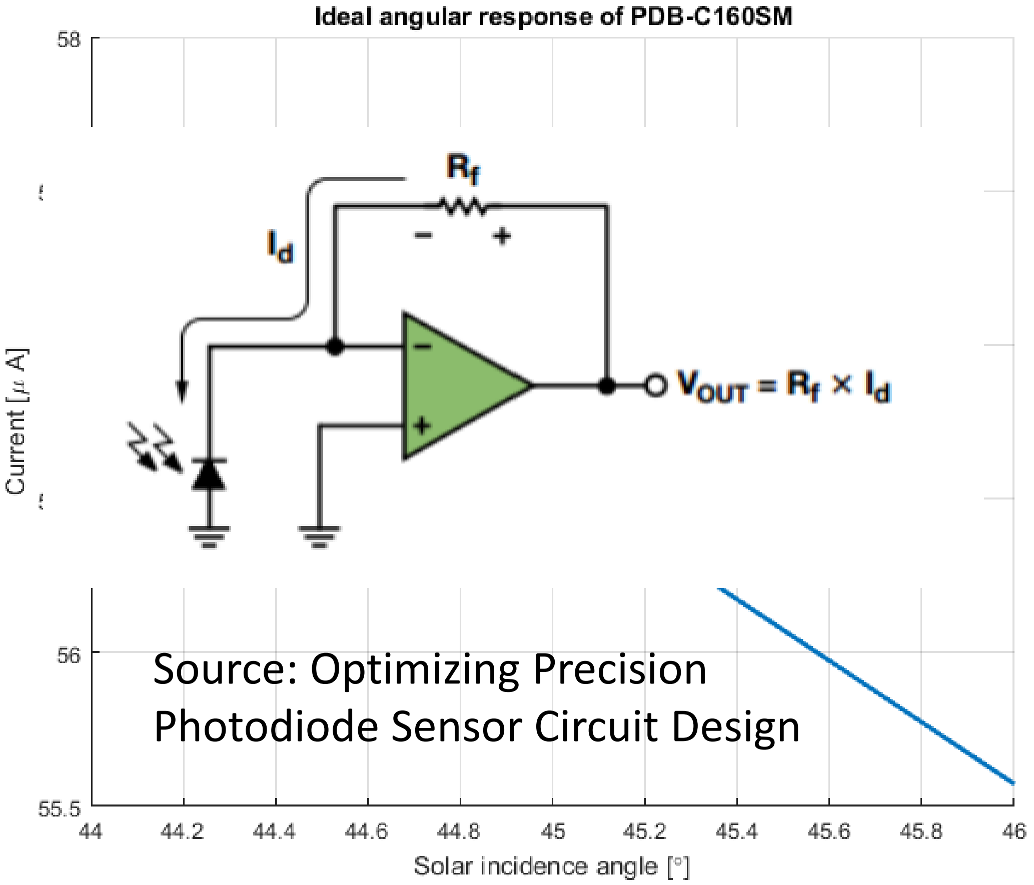
- DS18B20 Digital temperature sensor
  - $3.95 from Adafruit
  - Sensing Range -55 to +125 °C, error 0.5 °C above -10 °C
  - x3:
    - Microprocessor
    - Batteries
    - Solar Panel Array



Data Storage Feasibility

- Measurements being taken:
  - Spectrometer: one 4 kB spectra every second
  - Camera: one 2.5 MB image every minute
  - Environmental: measure temperature, pressure, humidity every second
  - Housekeeping: 2 voltmeters, 2 ammeters, 3 thermistors every second
  - Attitude: 4 photodiodes and computed angle every second

Attitude Determination Feasibility



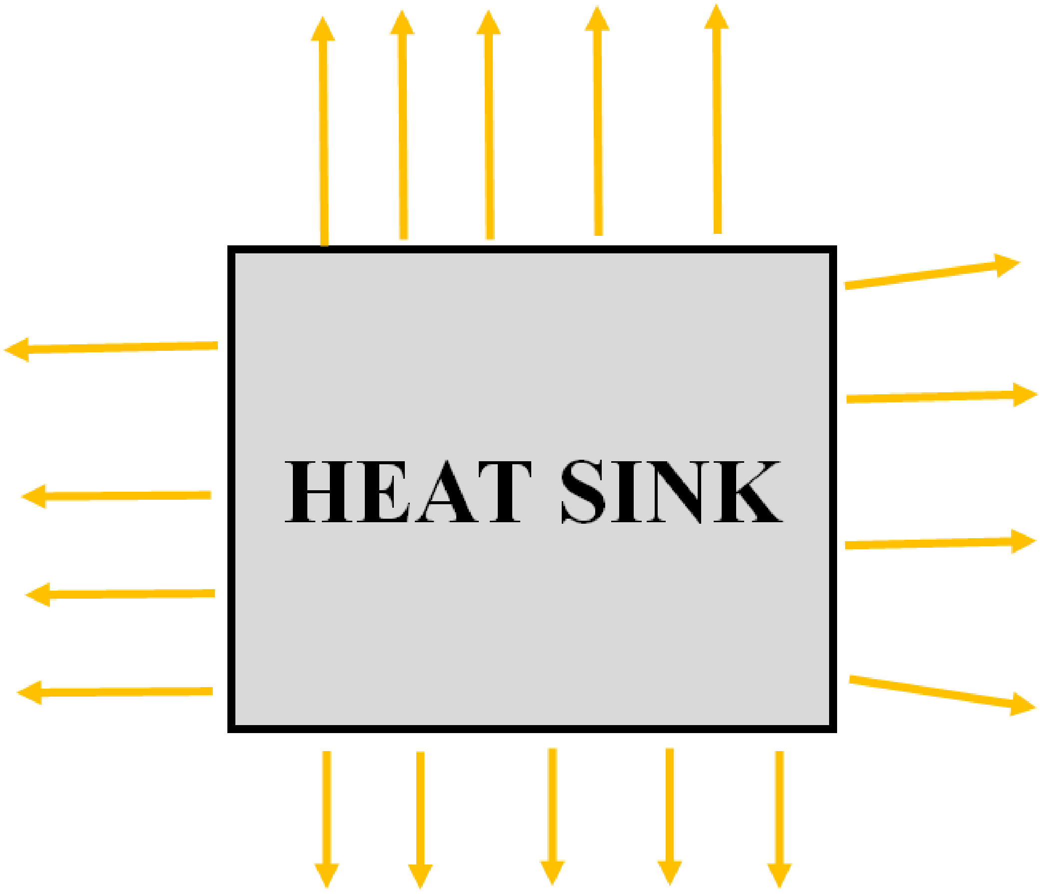
Source: Optimizing Precision Photodiode Sensor Circuit Design

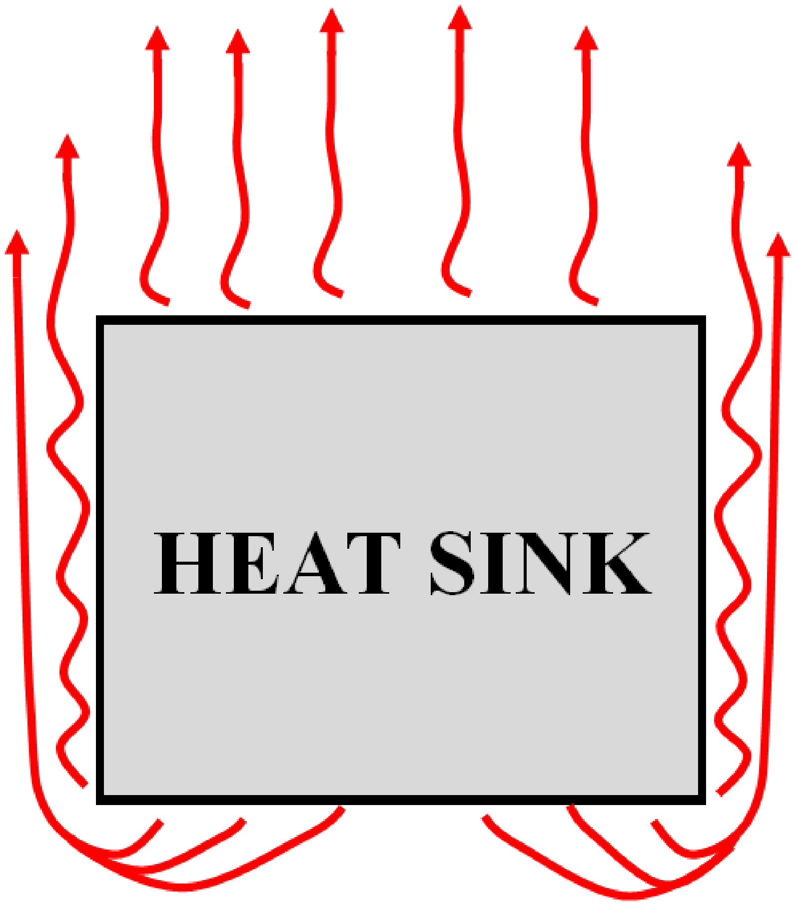
- Solar incidence angle on each photodiode is nominally 45° ± 1°.
- Angular sensitivity in this range:
  - Average slope: -16.4543 nA/arcminute
  - Standard deviation: 0.1665 nA/arcminute
  - Minimum: -16.7374 nA/arcminute
  - Maximum: -16.1679 nA/arcminute
- Measuring nA
  - Use op amp and resistor to magnify signal
  - Signal into ADC
  - Digital signal read by Pi

Attitude Determination Feasibility

Requirement	Description	Feasibility
4.1	The off-sun angle shall be determined to ±1 arcminute.	✓
4.2	Attitude data shall be recorded synchronously with other science data at a rate of one measurement per minute.	✓

Thermal Modes





Thermal Assumptions

- Bulk temperatures (No transience within components)
- Perfect connections
- No forced convection (wind)
- Thermal conductivity of air decreases with pressure linearly
- No heat from solar panels or HiWind interface
- No Reflectivity

Thermal Convection Equations

$$\dot{Q} = hA\Delta T \qquad h = \frac{k}{L_c} Nu \qquad Ra = \frac{gC_p\rho\beta(T_s - T_\infty)L_c^3}{k\nu}$$

Nusselt Number Table	Range of Ra	Nu	Characteristic Length
Vertical Plate	all	$Nu = \left(.825 + \frac{.387RA_L^{1/6}}{[1+(.492/Pr)^{9/16}]^{8/27}}\right)^2$	H
Horizontal Plate Top Side	$10^4 - 10^7$ $10^7 - 10^{11}$	$Nu = .54Ra_L^{1/4}$ $Nu = .15Ra_L^{1/3}$	$L_c = \frac{A_s}{P}$
Horizontal Plate Bottom Side	$10^5 - 10^{11}$	$Nu = .27Ra_L^{1/4}$	$L_c = \frac{A_s}{P}$

Humidity Corrections

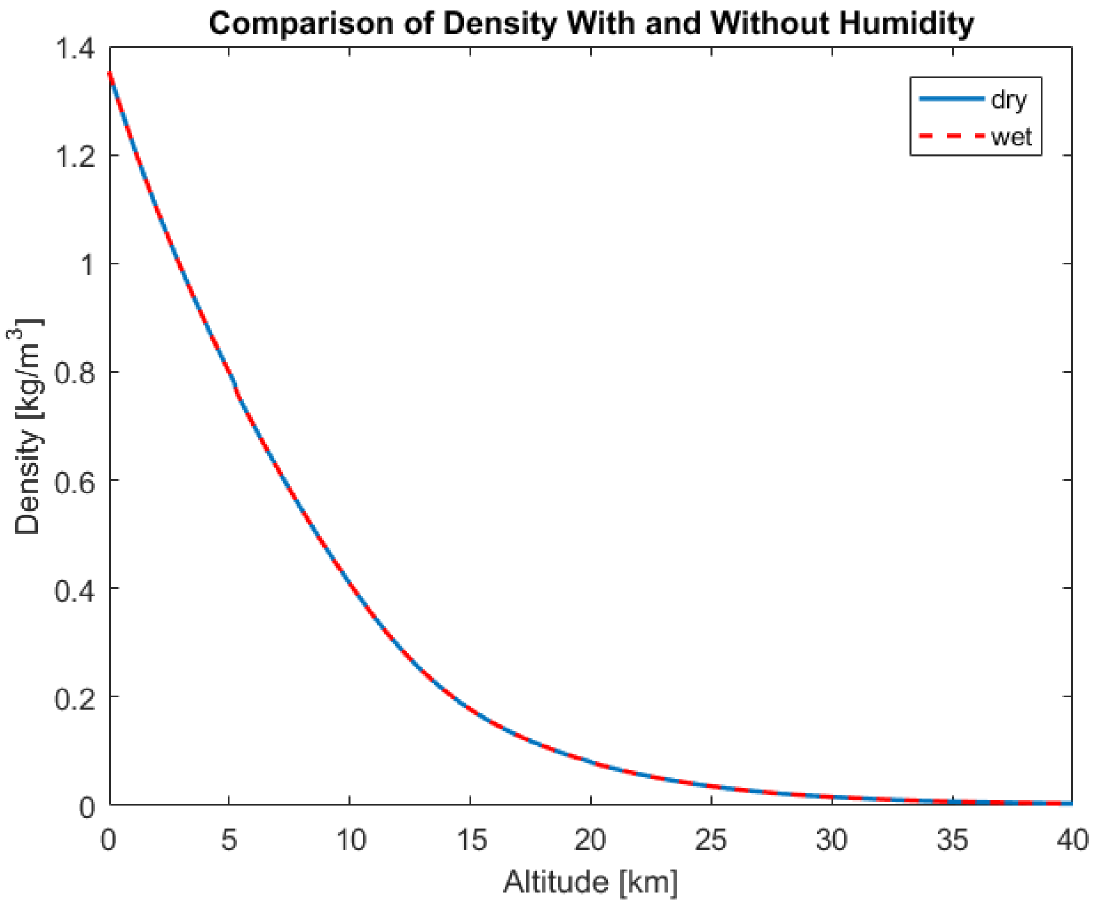
$$\rho = \frac{P}{RT_v}$$

$$T_v = T(1 + .61S_h)$$

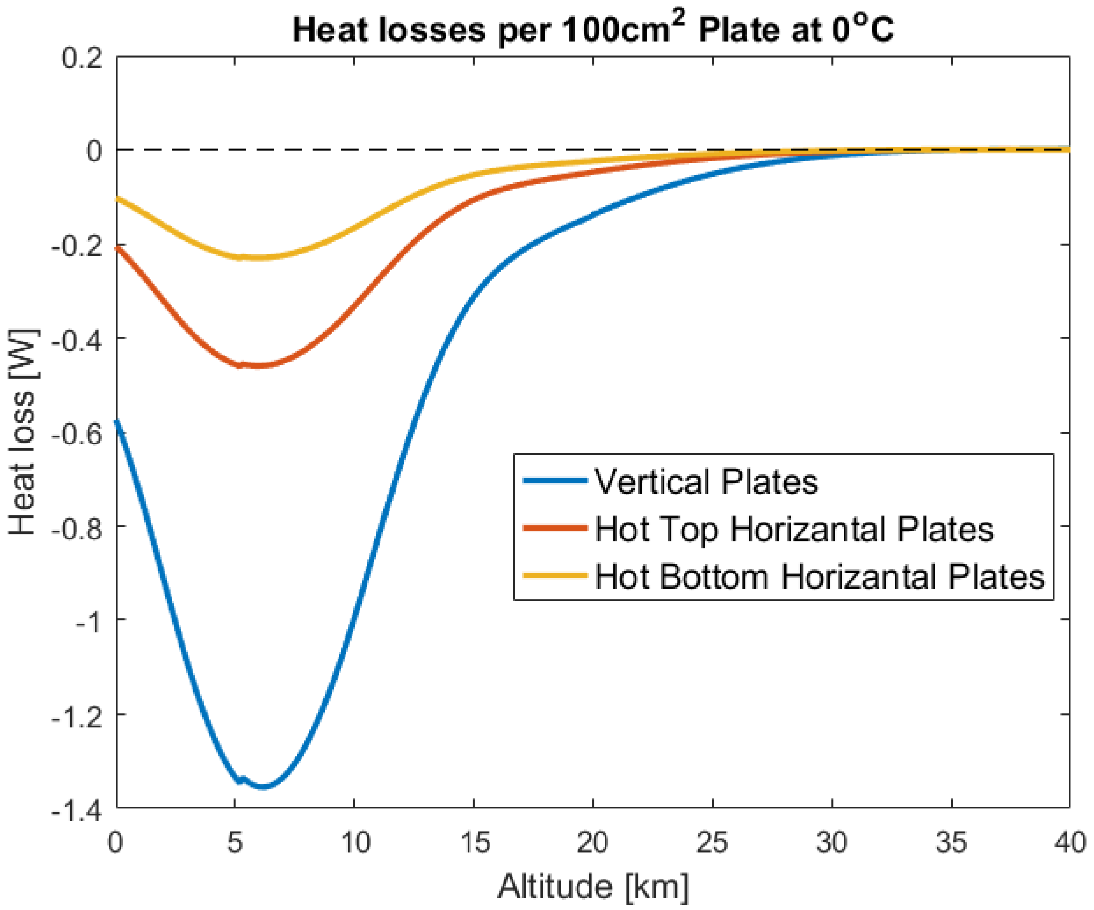
$$S_h = \frac{.622P_{H2O}}{P_\infty - .378P_{H2O}}$$

$$P_{H2O} = (P^*_{H2O})(RH)$$

$$P^*_{H2O} = 6.11x10^{\frac{7.5T}{237.3+T}}$$

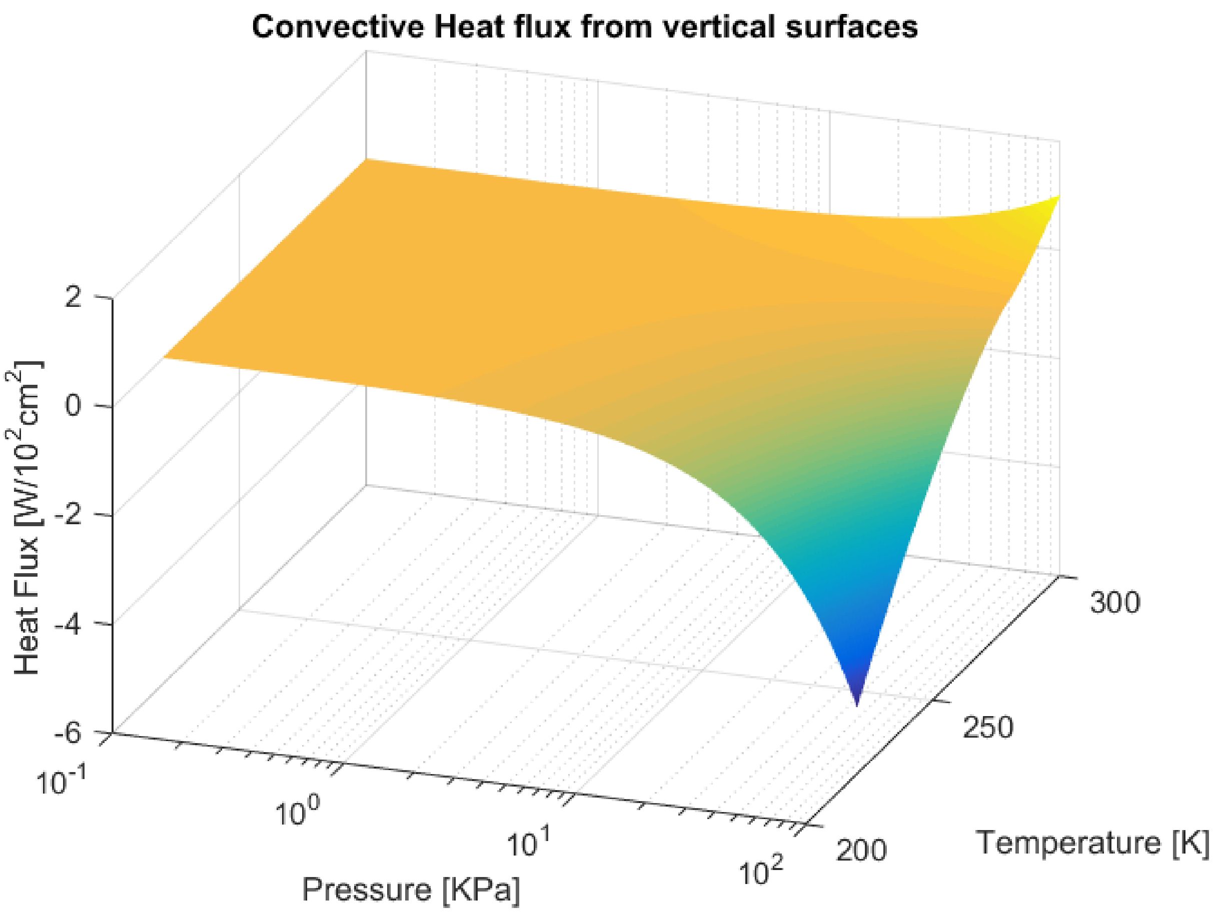


Convective Losses



- Maximum convection occurs at 7 km
- Vertical plates convect more
- Upper plates have greater convection than lower plates

Convection Solution Space



Thermal Radiation Equations

Heat Radiated

$$\dot{Q} = \sigma A T^4 \epsilon$$

$$\sigma = 5.6703x10^{-8}$$

Heat Absorbed

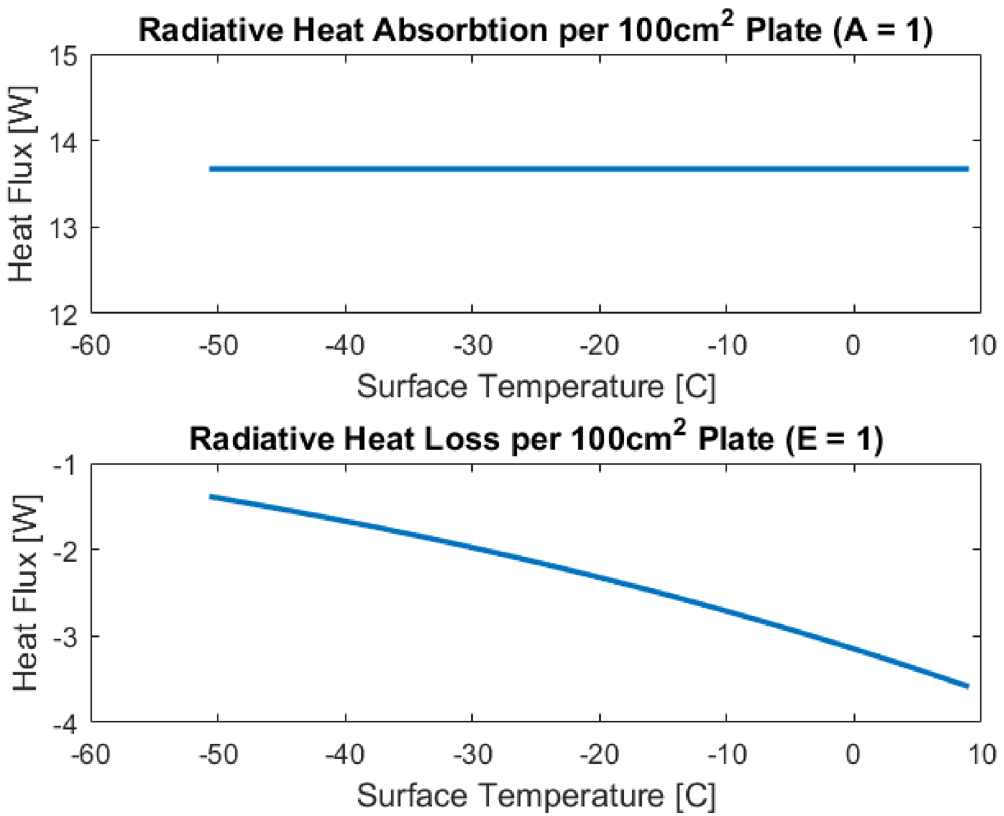
$$\dot{Q}_{in} = \dot{Q}_{Source} A \alpha$$

$$\dot{Q}_{Ground} \approx 1050[W/m^2]$$

$$\dot{Q}_{Ground+Albedo} \approx 1120[W/m^2]$$

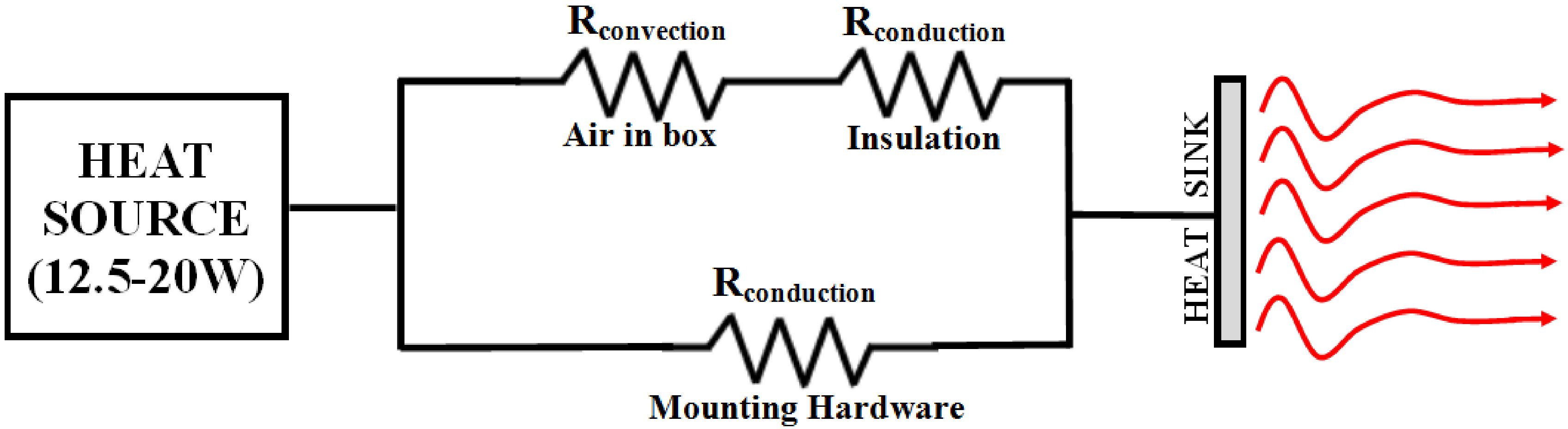
$$\dot{Q}_{Vacuum} \approx 1367[W/m^2]$$

Radiative Losses



- One panel will be pointed toward the sun
- The other 11 will be exposed to minimal solar radiation

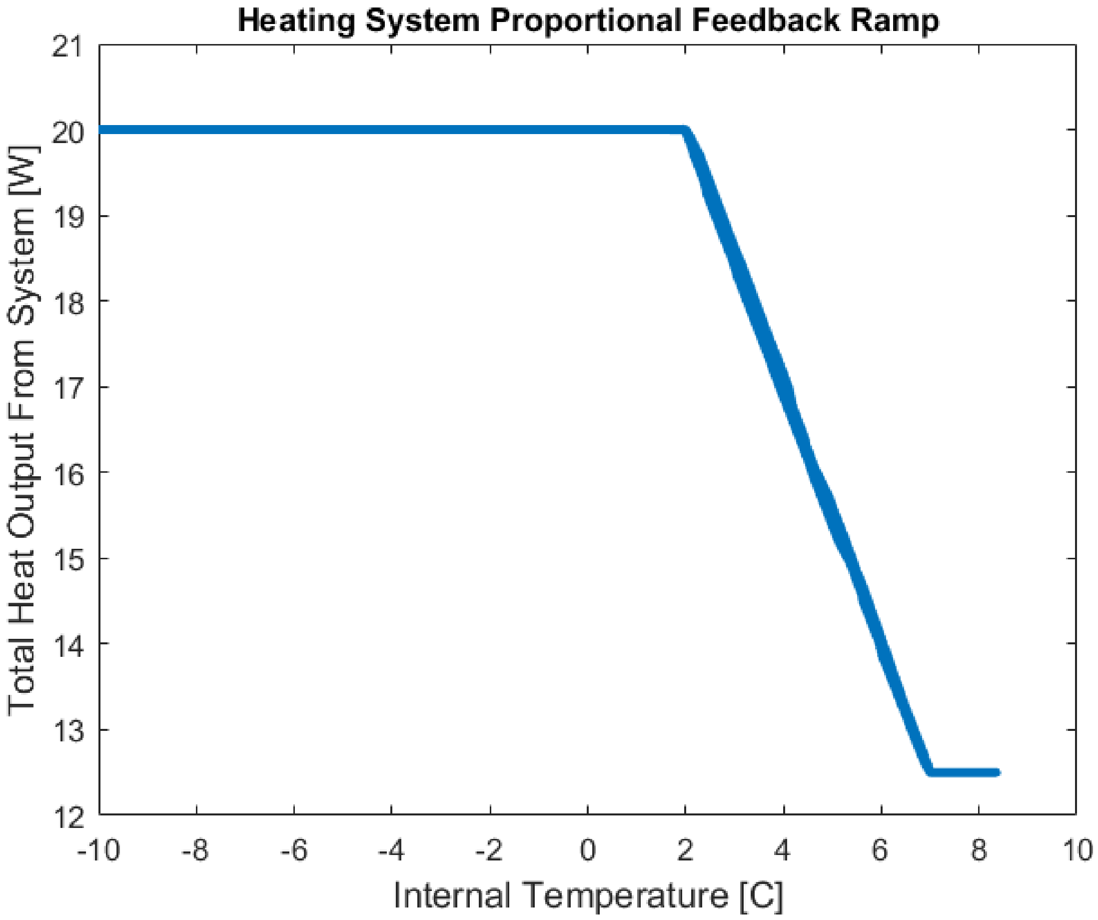
Insulation Equations



$$R = \frac{L}{KA}$$

$$\dot{Q} = \frac{T_1 - T_2}{R}$$

Active Control Heating Ramp



- Variable heating to prevent too much power draw through flight
- 2° buffer between max heat and min internal temperature
- Cruise is at about 13.5 W

Thermal Model Inputs

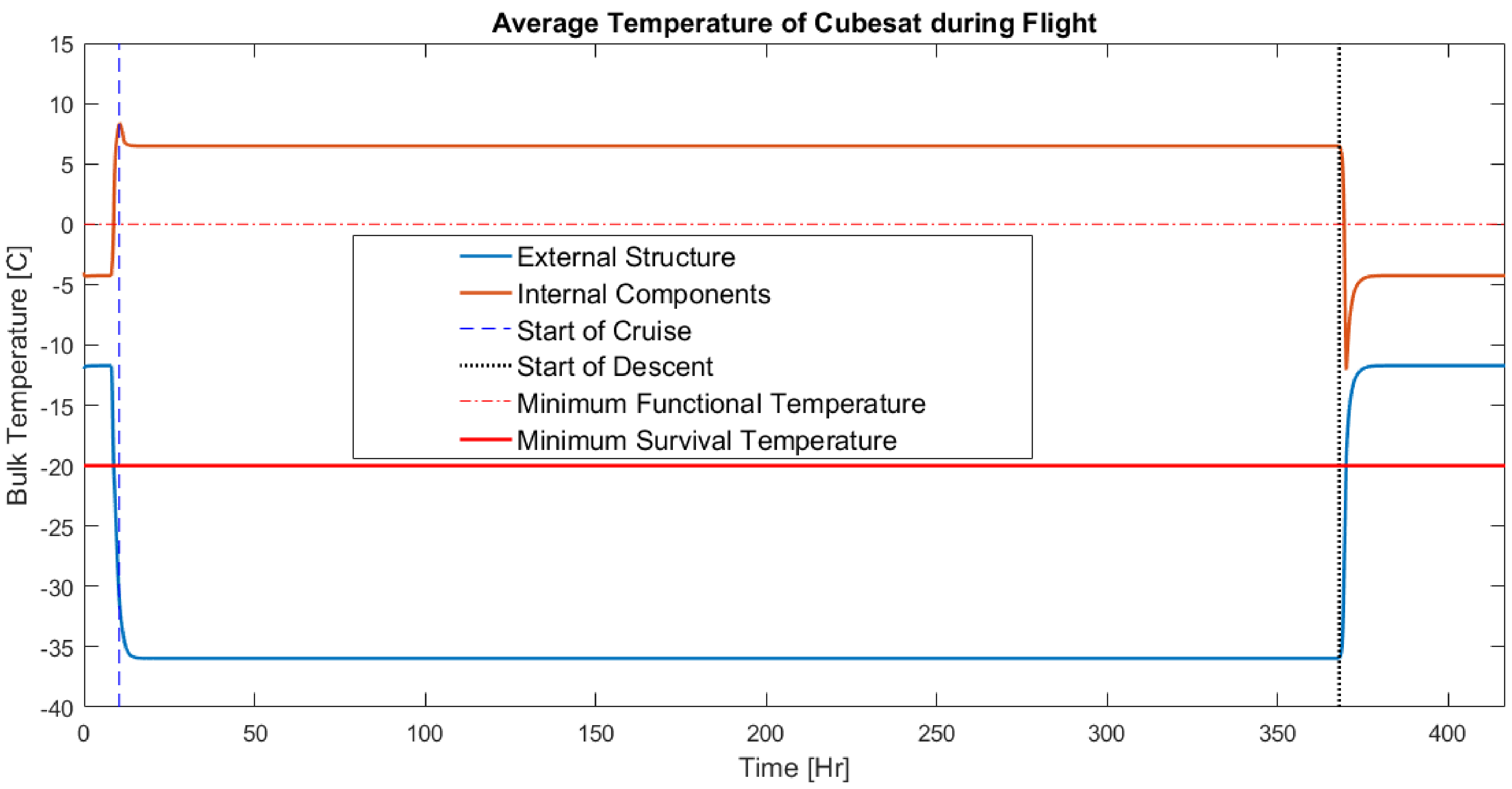
- Mass of external structure: 2 kg (c = 900 J/kgK)
- Mass of internal structure: 2 kg (c = 500 J/kgK)
- Thickness of insulation: 1 cm
- Emissivity/Absorptivity: .7/.3
- Min/Max power draw: 12.5/20 W
- Ascent Time: 2 hrs
- Mounting Hardware Resistivity: 3 K/W

Thermal ODE Explanation

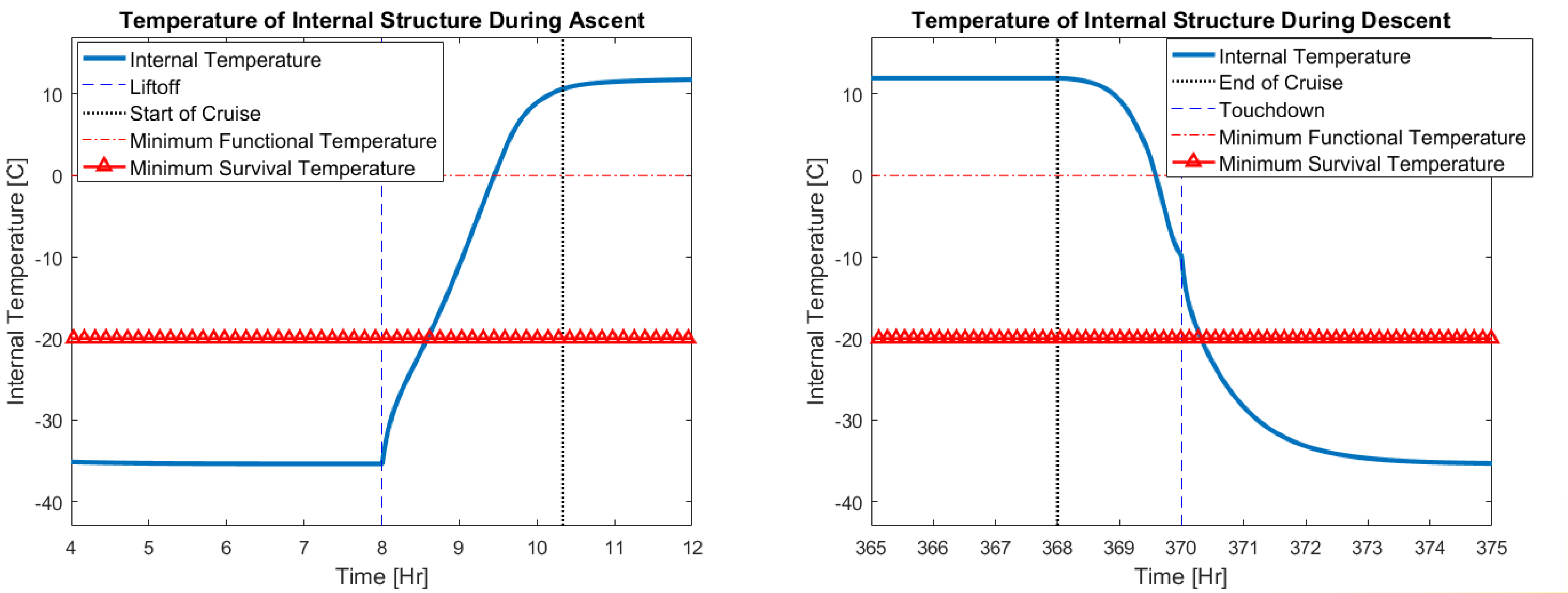
- This thermal problem is a **STIFF** problem that cannot be solved trivially

- ODE15S employed rather than ODE45 (ODE45 diverges)

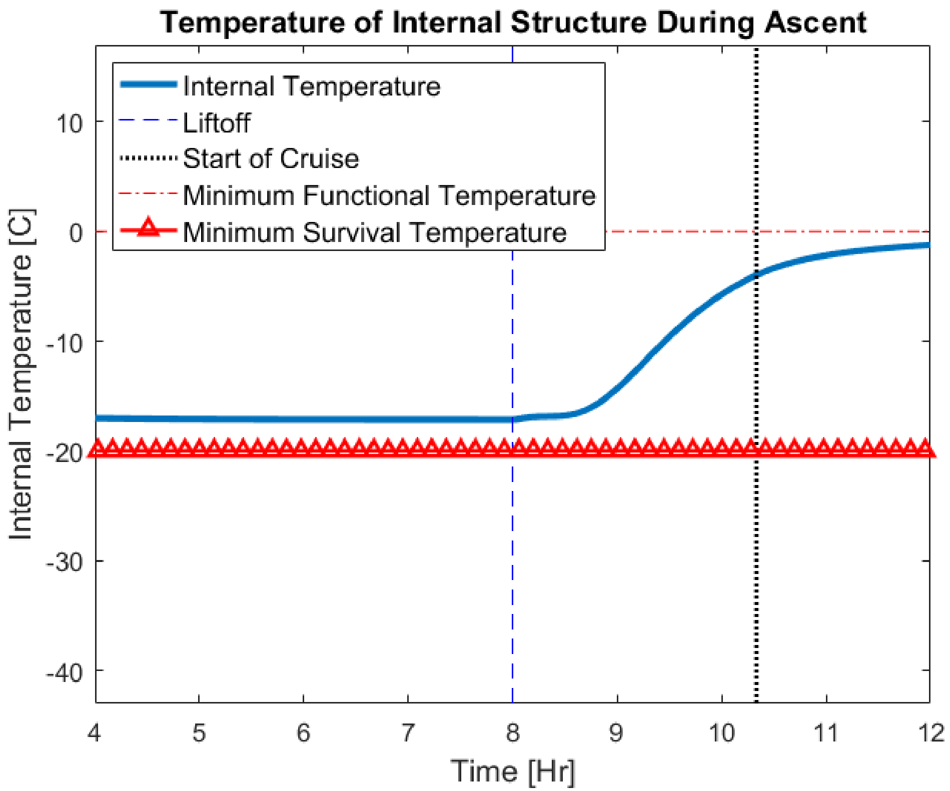
Full Thermal Simulation

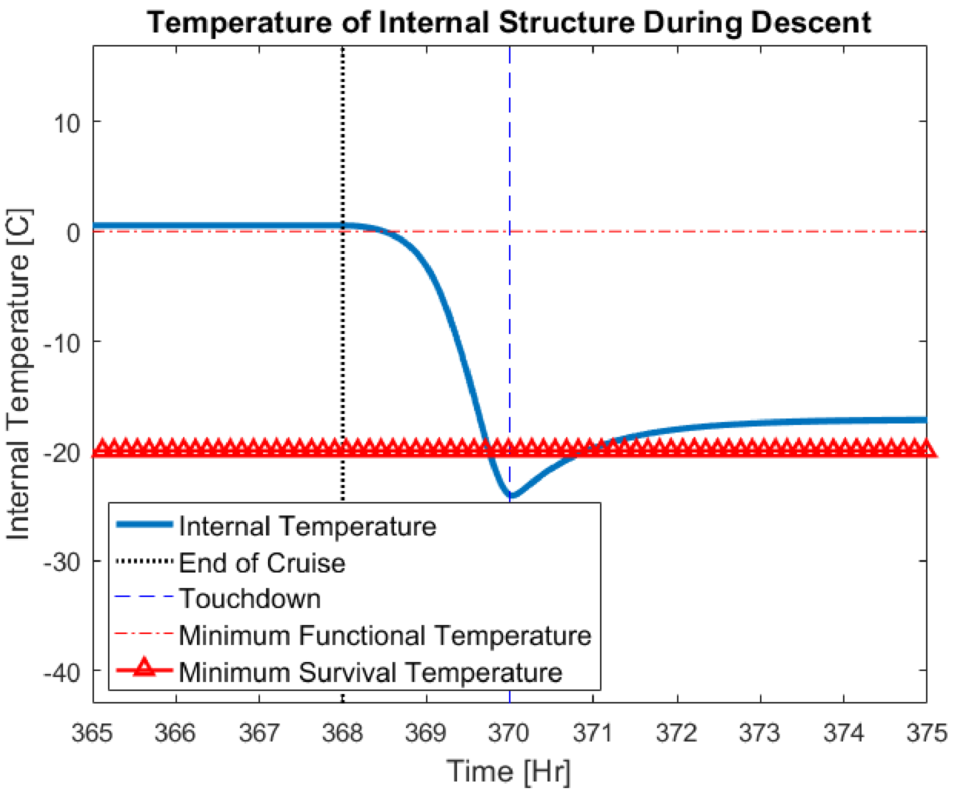


No Power on Ground Case



No Active Heating Case





Known Thermal Issues

- Solar panels and interface are not accounted for yet
- Wind not accounted for yet
- Surface of box not yet determined (outgassing issues)

Interface Summary

Component	Size	Weight	Power	Data
Spectrometer	129.2 cm^3	0.174 kg	1.25 W	30 MB/s
Pressure Sensor	2.569 cm^3	N/A	0.0125 W	12.5 kB/s
Humidity Sensor	0.189 cm^3	N/A	0.02 W	12.5 kB/s
Temperature Sensor (ENV)	0.228 cm^3	N/A	0.288 W	12.5 kB/s
Temperature Sensor (HK)	0.111 cm^3	N/A	0.02 W	12.5 kB/s
Camera	5.369 cm^3	0.003 kg	0.7 W	30 MB/s

Interface Summary

Group	Component	Size	Weight	Power	Data
C&DH	Raspberry Pi	80.920 cm^3	0.045 kg	6 W	N/A
	Flash Drive	2.450 cm^3	0.002 kg	0.940 W	N/A
	Diodes	0.0237 cm^3	N/A	0.215 W	12.5 kB/s
EPDS	Solar Cells	170.640 cm^3	0.288 kg	12.948 W	N/A
	Battery	108.0375 cm^3	0.191 kg	21.6 W	N/A
Thermal	Resistive Heaters	2.048 cm^3	0.042 kg	5 W	N/A