RADIANCE

A 3U CubeSat Prototype to Measure Solar Irradiance

Spring Final Review, May 4, 2017

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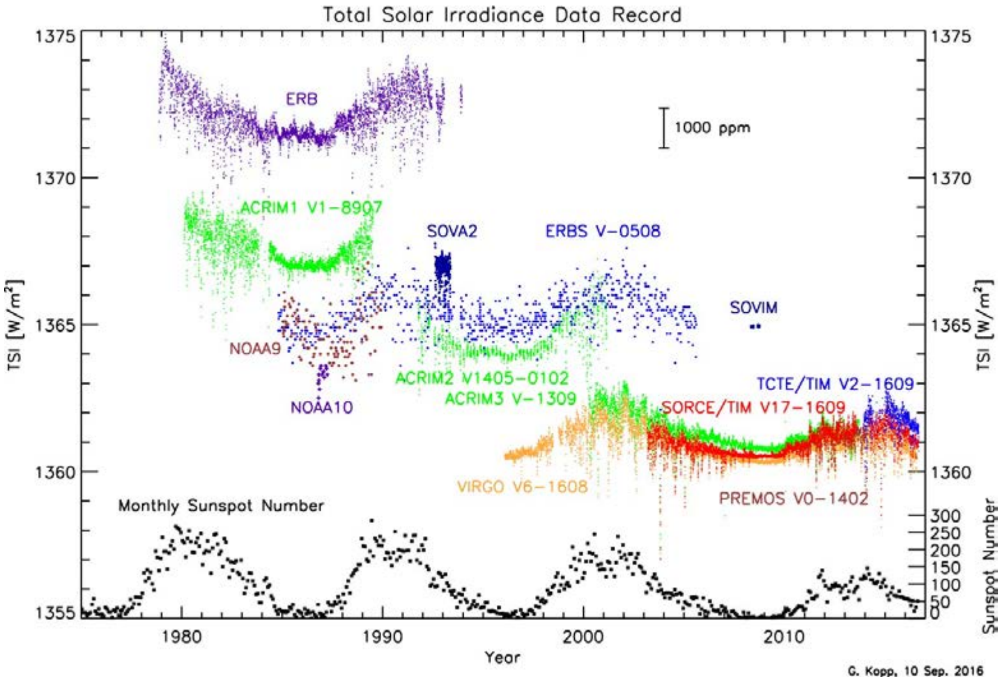
Outline

Purpose and Objectives	Jenny	5%
Design Description	Lance	15%
Test Overview	Katie	15%
Test Results	Brandon, Katie	45%
Systems Engineering	Alec	10%
Project Management	Jenny	10%

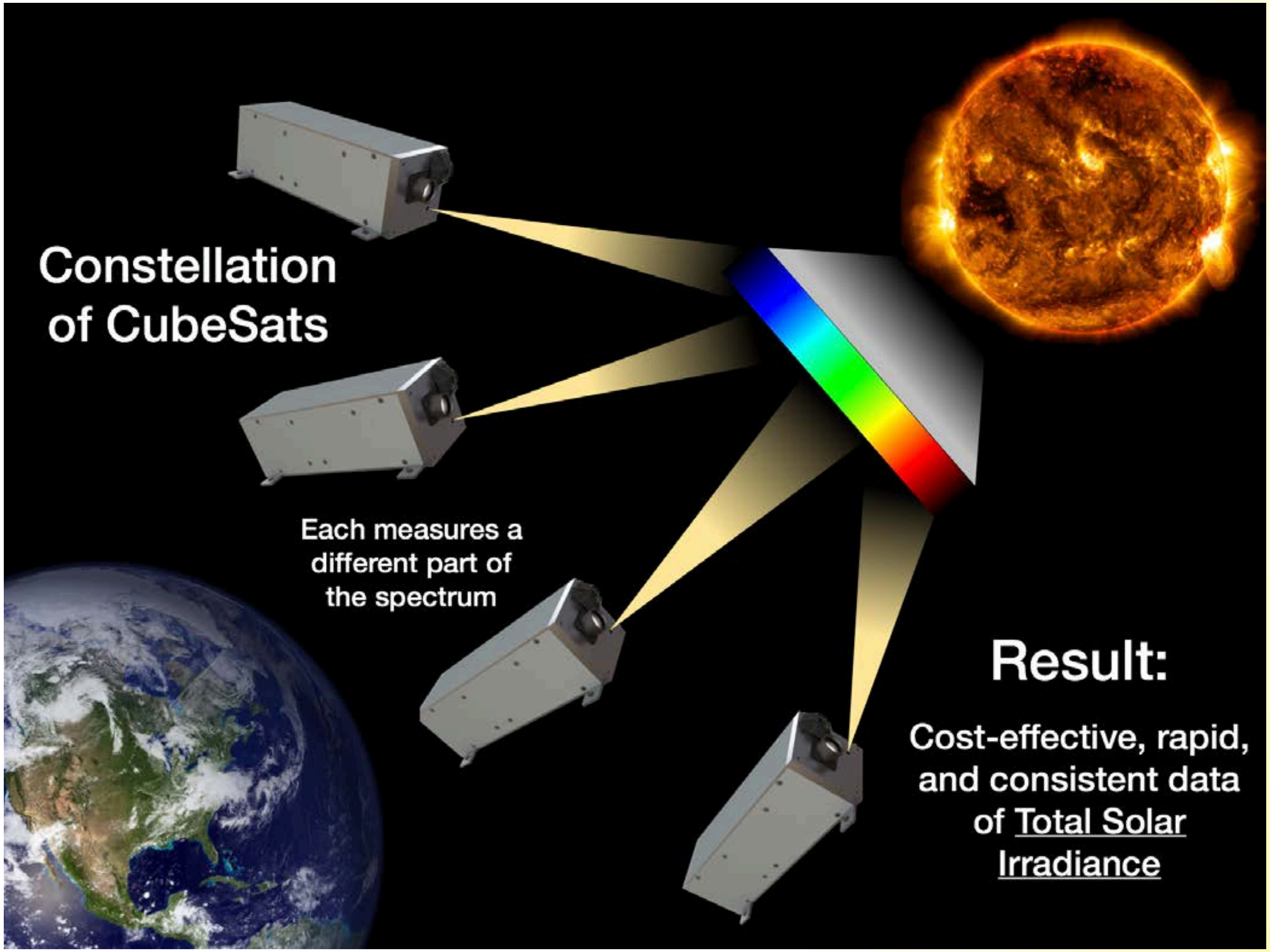
Project Motivation



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 and time-consuming

Project Future



Project Description

- Mission Statement

  RADIANCE is a 3U CubeSat-style payload that will collect solar irradiance data, images, attitude information, 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.

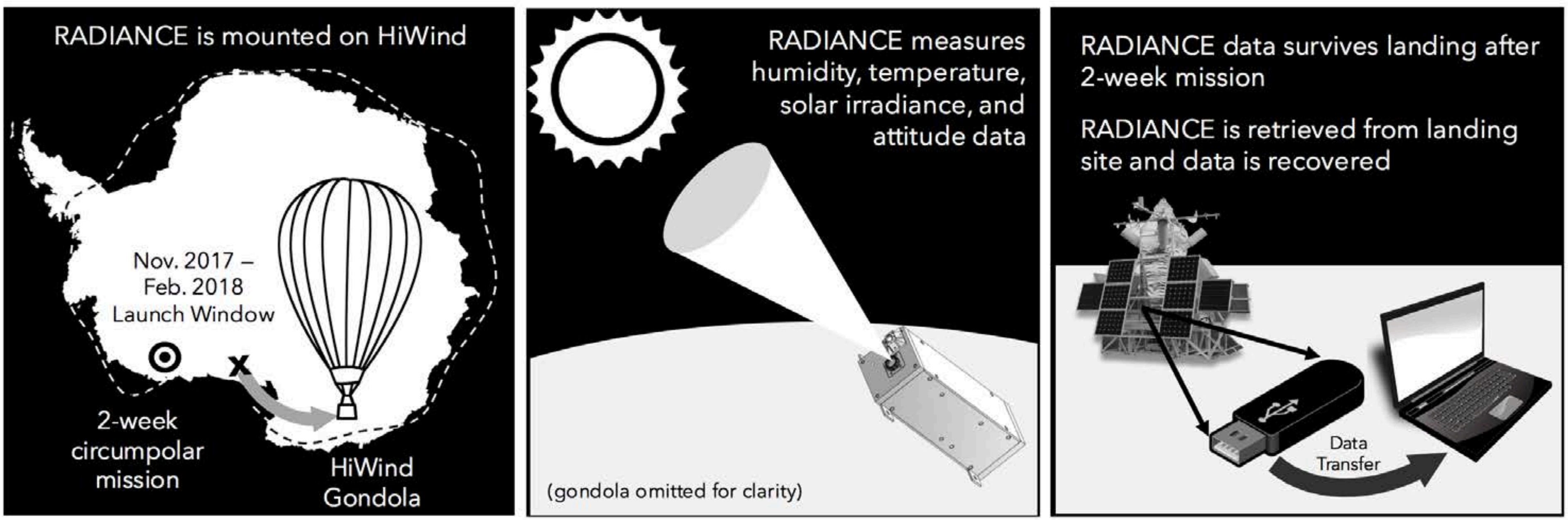
- Project Statement

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

HiWind Gondola & Flight

- **Mission:**
  - Ground: 8 hours
  - Ascent: 2 hours
  - Flight: 2 weeks
  - Descent: 1 hour
- **Gondola:**
  - 4.5 m wide
  - 5.0 m tall
  - 2000 kg

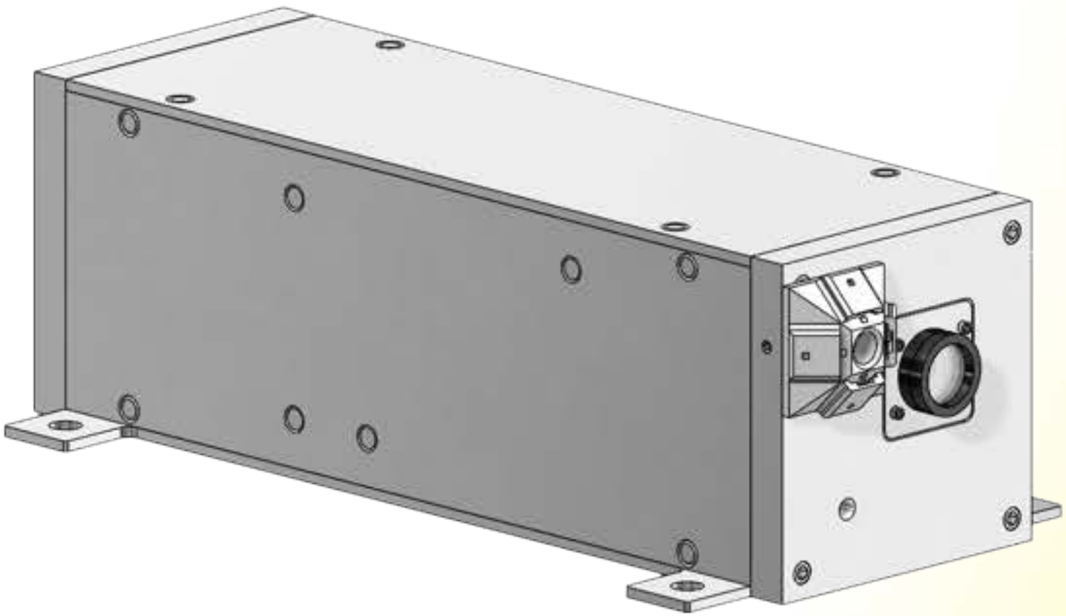
Concept of Operations



Project-Level ConOps

Power Up

Using external power source equivalent to 15 W of expected HiWind power



Levels of Success

System	Level Met	Details
Instr.	3	Take solar irradiance measurements at better than 1.5nm resolution covering 250-1000nm Capture 1 photo/min of the Sun for full flight Provide calibration of the instrument
C&DH	3	Record solar irradiance, attitude, environmental, and housekeeping data on a durable data storage device with sufficient capacity
Thermal	1	All systems survive ascent and descent, all systems operate during the cruise

Levels of Success

System	Level Met	Details
ADS	2	Determine and record attitude to 1 arcminute of accuracy relative to the sun vector
	1	Determine and record attitude to 1° of accuracy relative to the sun vector
EPDS	1	Package operates on HiWind power supply
Structure	1	Structure must be within 10cm x 10cm x 32cm Data is recoverable after up to 5 Gs on landing Structure can be affixed to HiWind

Design Overview

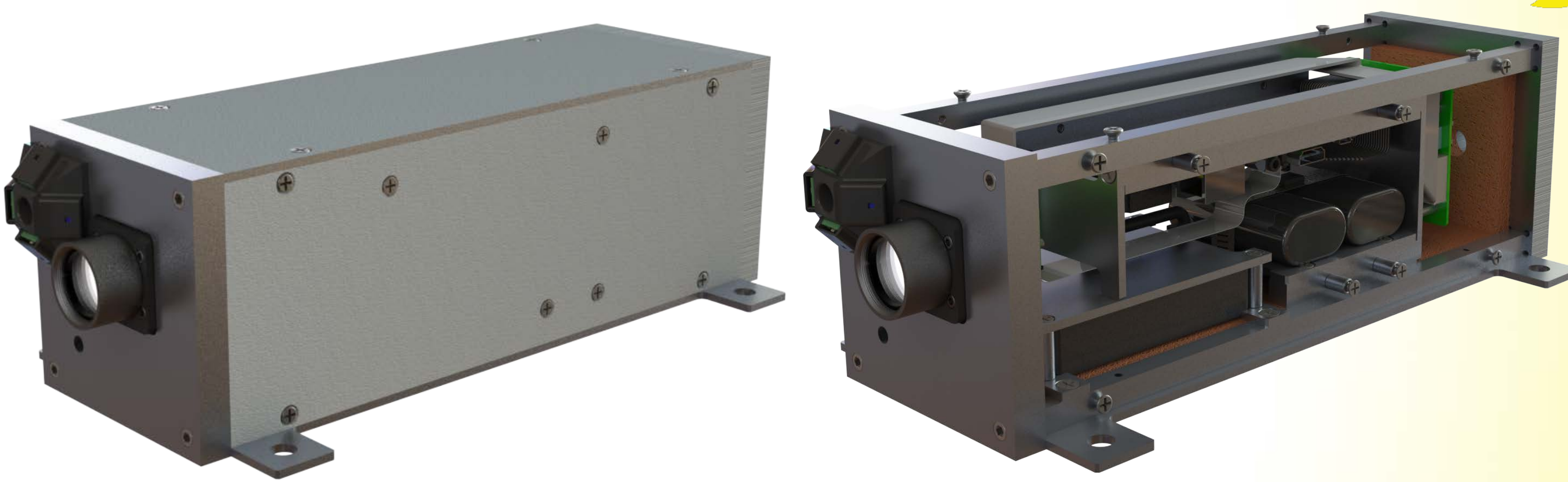
Functional Requirements

RADIANCE shall…

FR1: Take solar irradiance measurements.
FR2: Survive the environmental conditions of a high-altitude balloon flight up to 40 km.
FR3: Return data.
FR4: Determine its attitude.
FR5: Interface with the HiWind Gondola.
FR6: Capture images of the Sun in the visible spectrum.

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

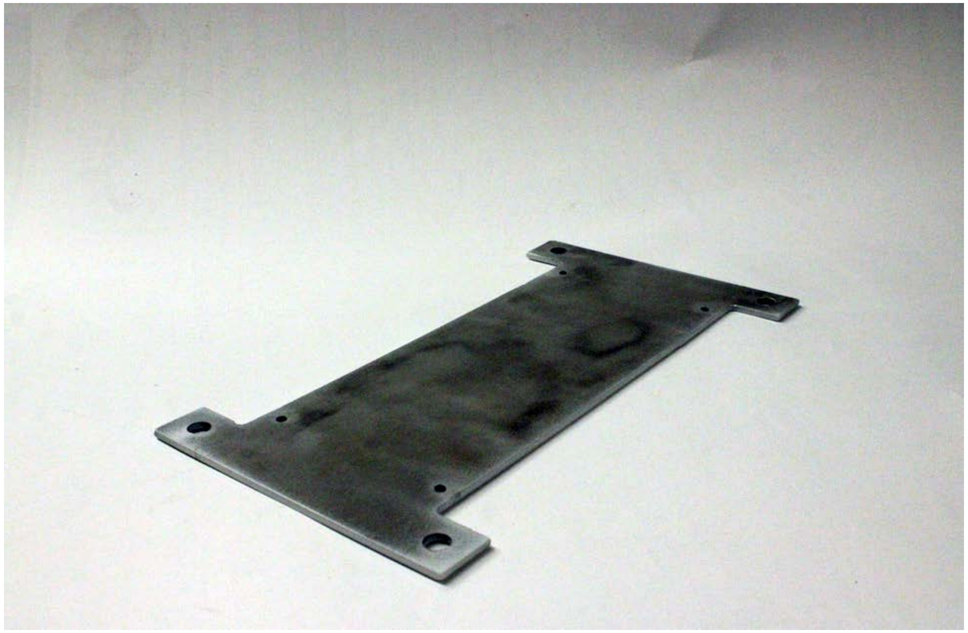
Executive Summary



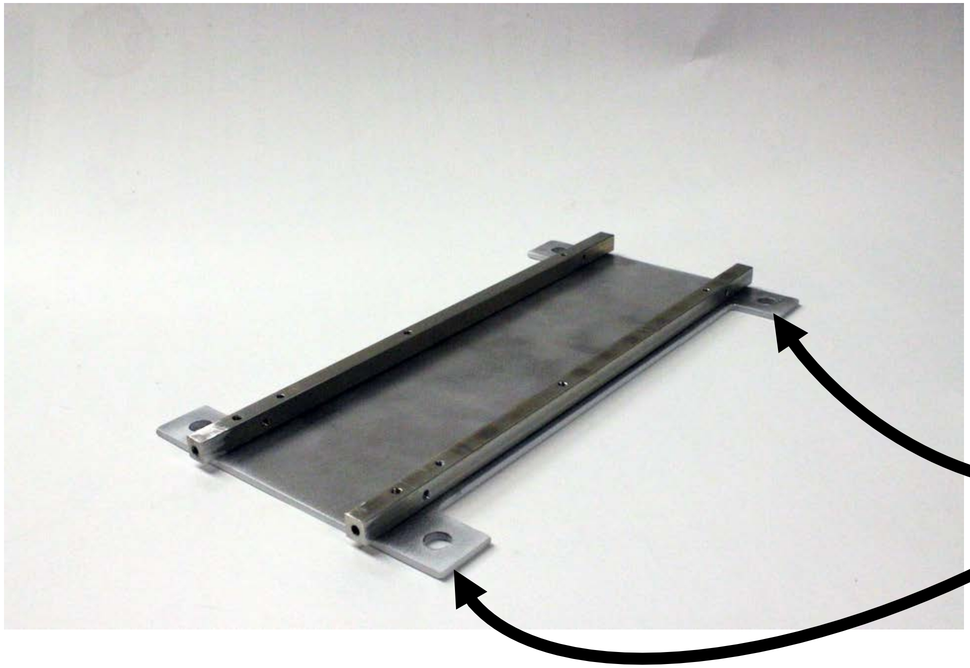
Parameter	Overall Values	Req.
Dimensions	31.81 cm x 15.1 cm x 10 cm	DR5.1
Mass	3.0 ± 0.05 kg	—
Power	3.2 to 19.6 W usage, ~3.2 W average at cruise	DR5.4
Thermal	-3 to 60°C internally, spot-heated in critical places	FR2

Complete Assembly

System Overview

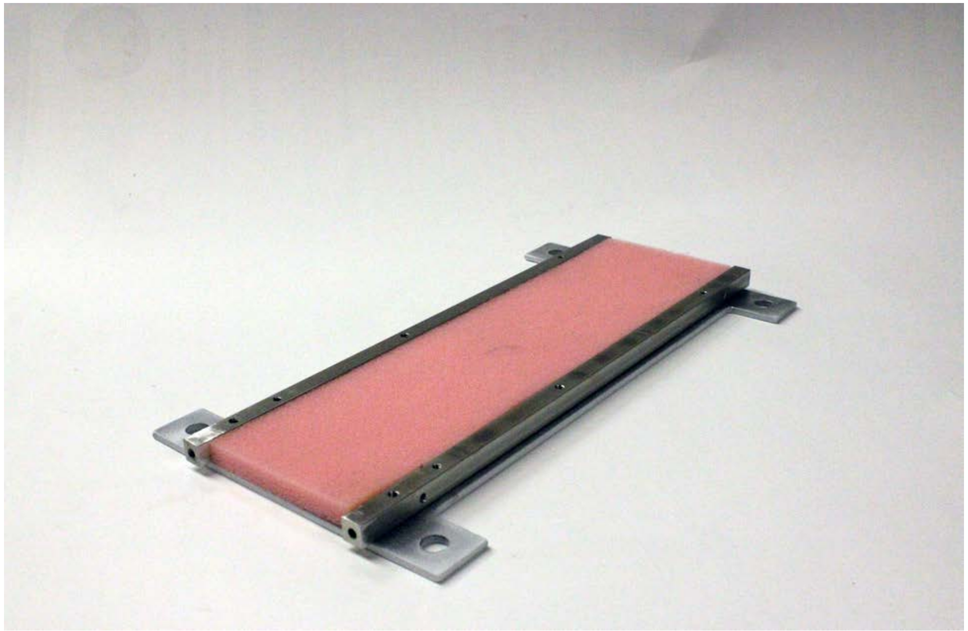


System Overview



- Internal structure attached to external struts with screws
- Attachment points to HiWind

System Overview



System Overview

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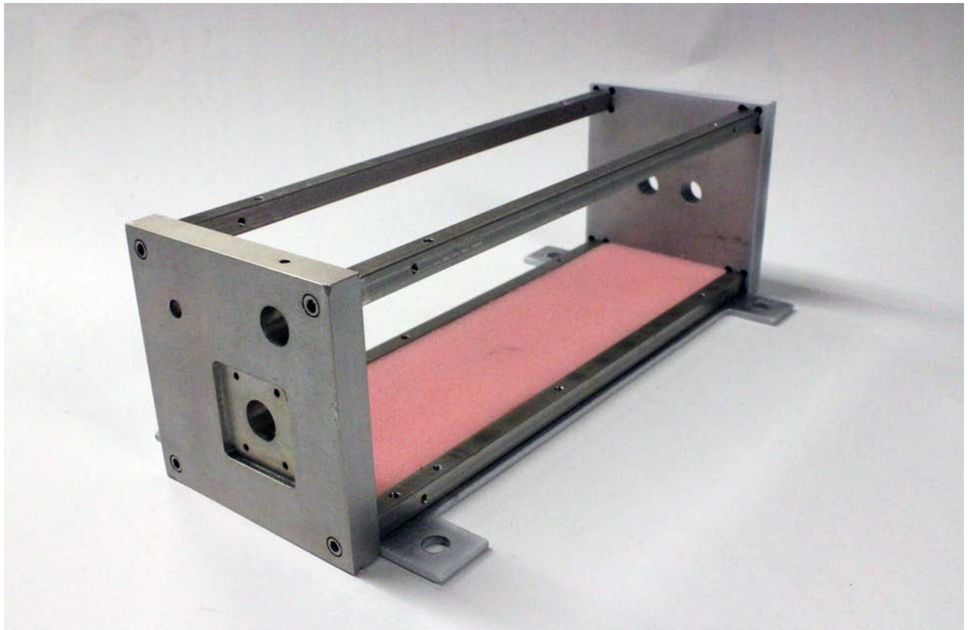

System Overview

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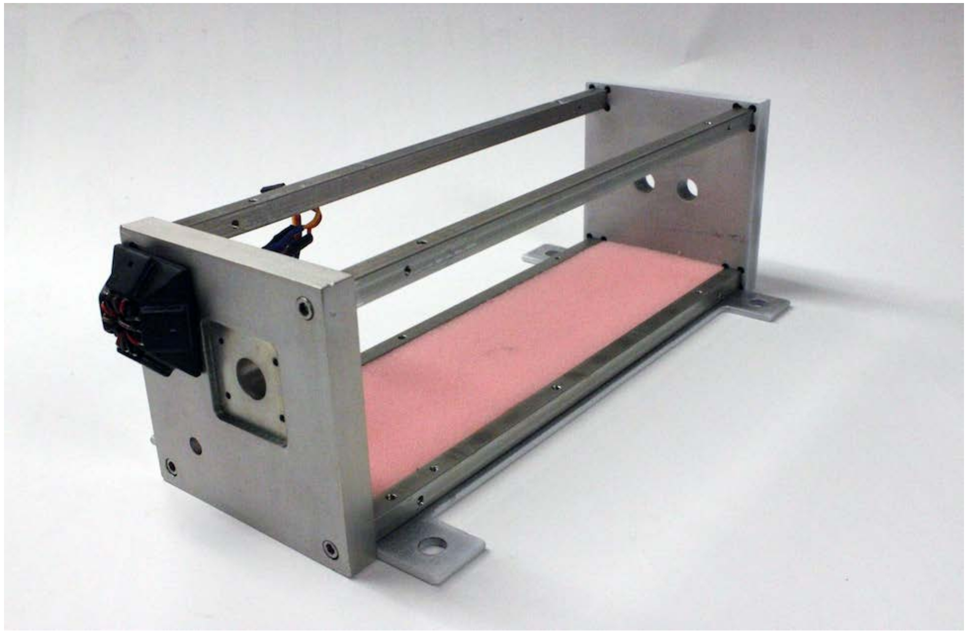
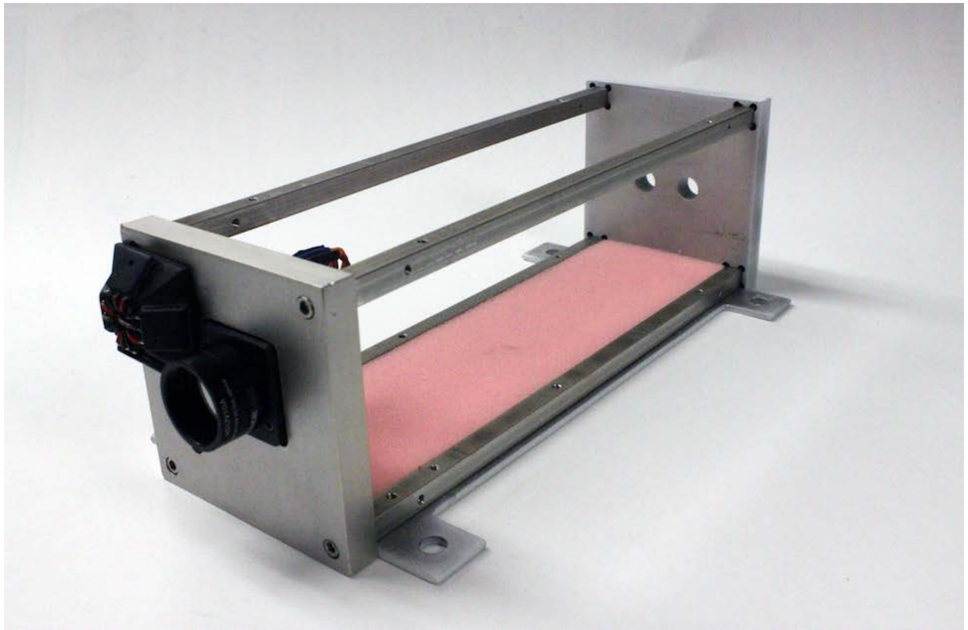


- Photodiode array and circuit board for attitude determination
- 4 photodiodes offset at 45° to determine off-sun angle to ≤ 1°

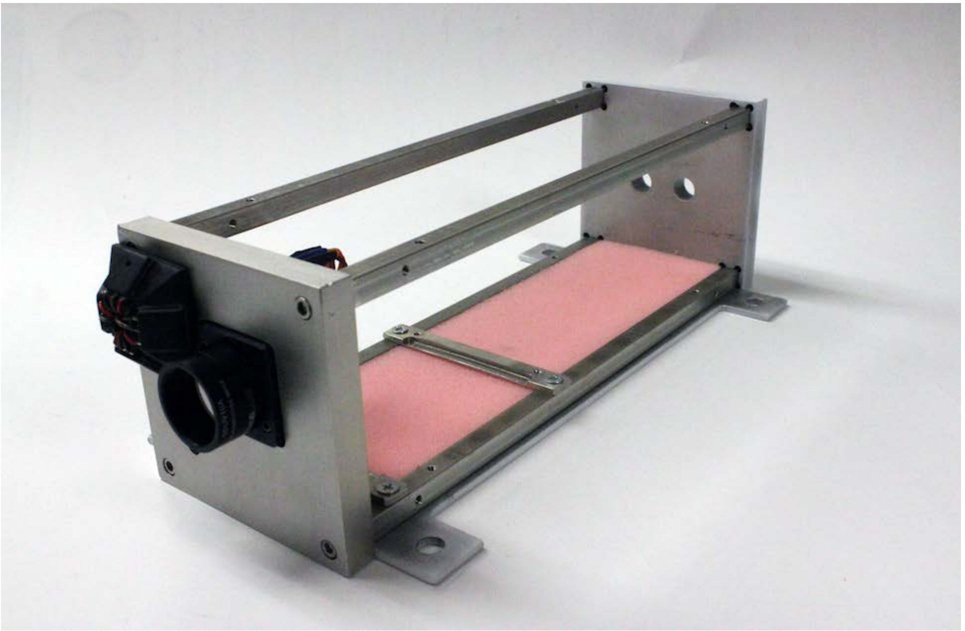
System Overview

System Overview



- Camera assembly, including:
  - Raspberry Pi Camera
  - Adjustable focus lens and mounting
  - Double-layer neutral density filter

System Overview

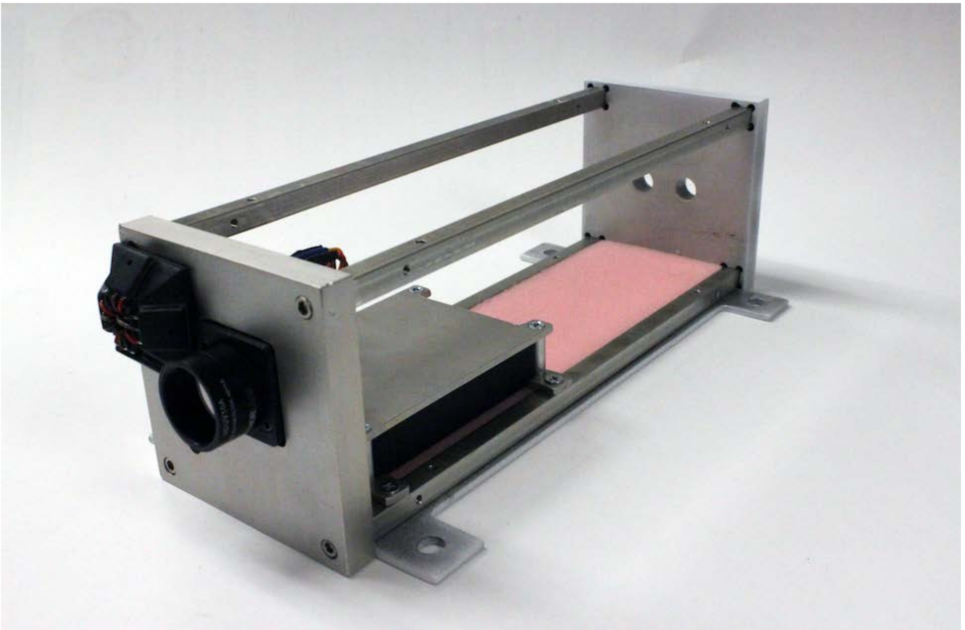


System Overview

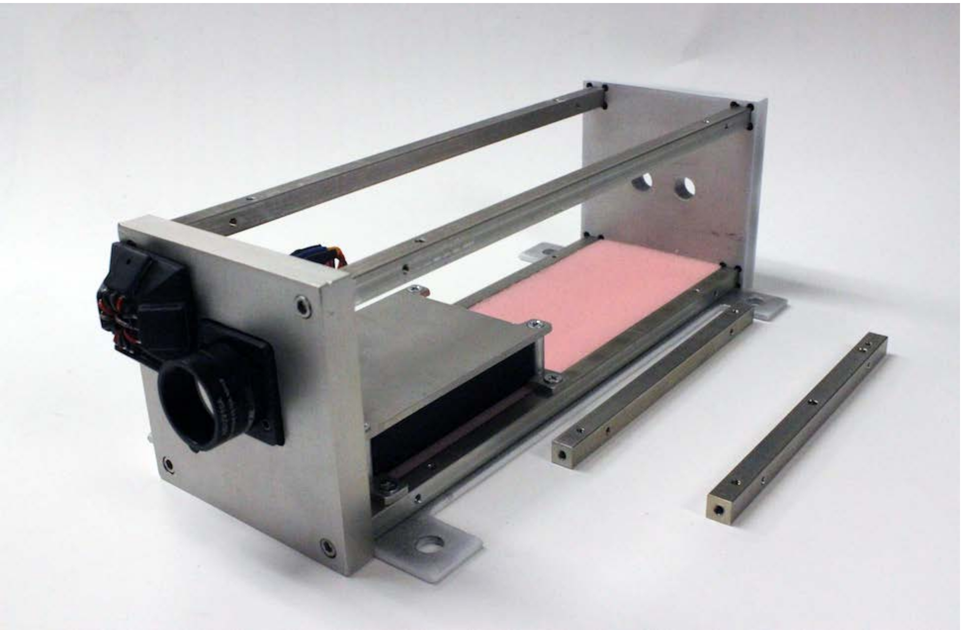
- Spectrometer and fiber optic cable from Avantes

	Req.	Solution
Resolution	≤ 1.5 nm	1.4 nm
Wavelength	250-1000 nm	200-1100 nm
Cost	~$3000	$2946
Size	Must fit	90x68x20 mm
Power	< 3W	1.25 W
Interface	RPi required	RPi capable

System Overview



System Overview



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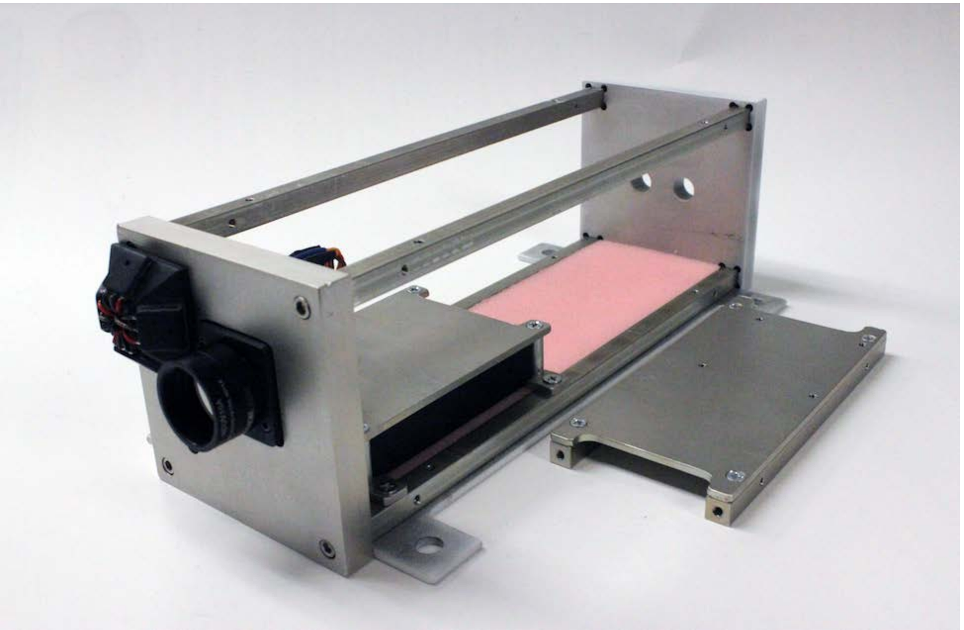

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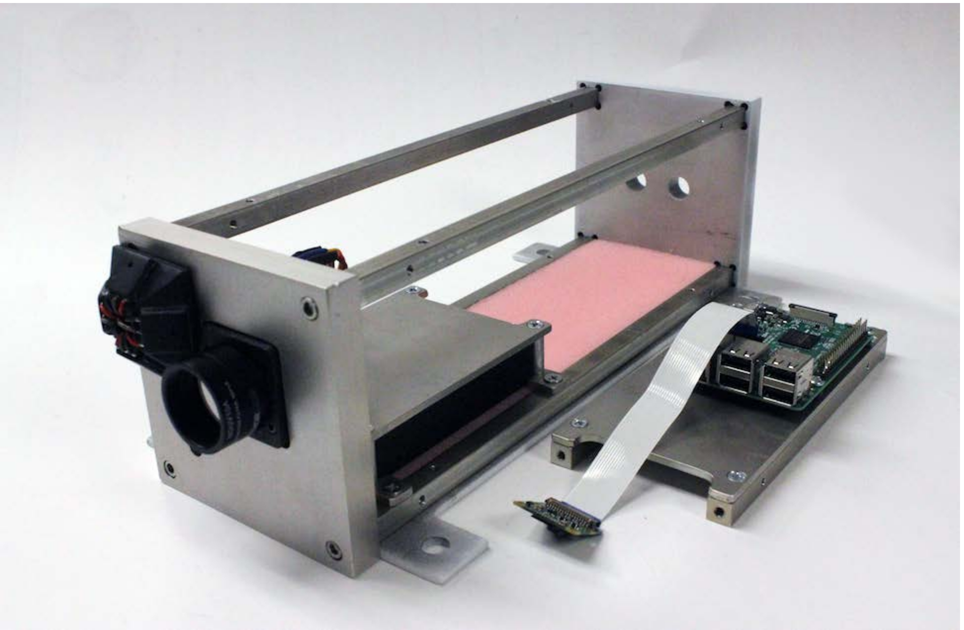
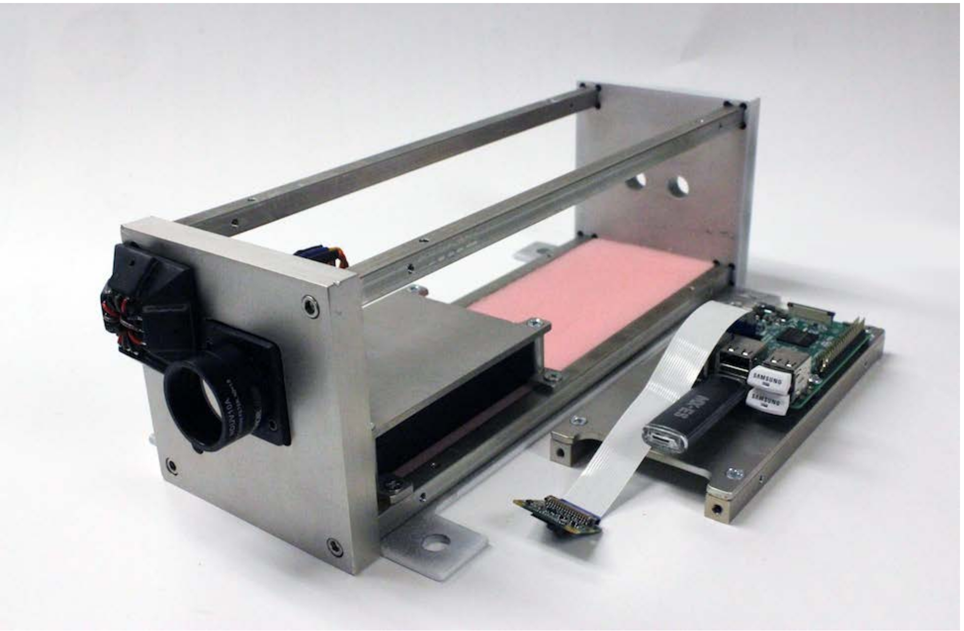


- Raspberry Pi microcontroller

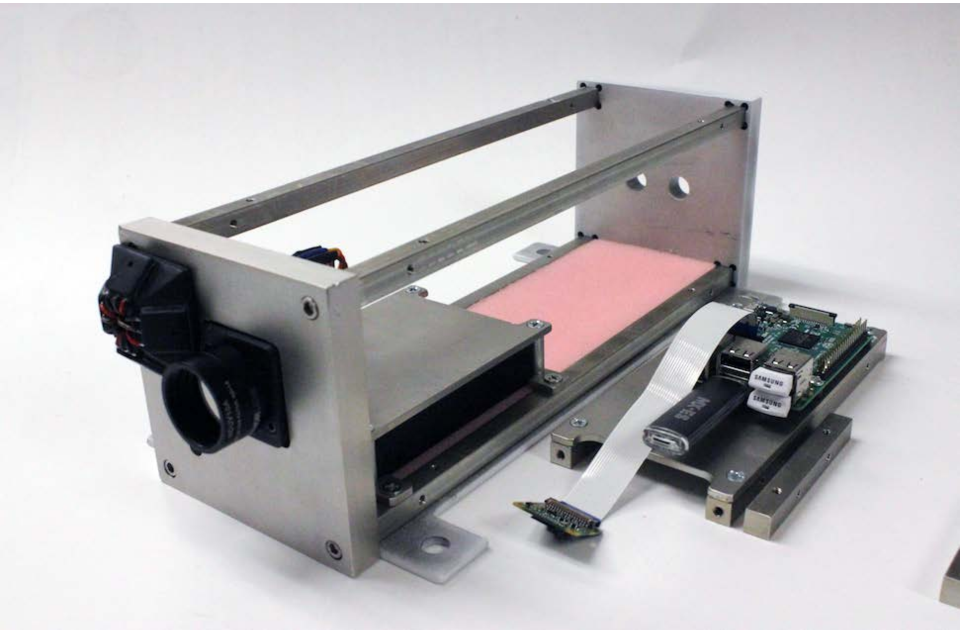
	Req.	Solution
Size	Must fit	85x56x17 mm
Cost	< $100	$36
Versatility	High	COTS
Interface	RPi needed	RPi capable

System Overview



- Three USB storage devices:
  - 1 single-level cell (SLC) drive
  - 2 multi-level cell (MLC) drives

System Overview



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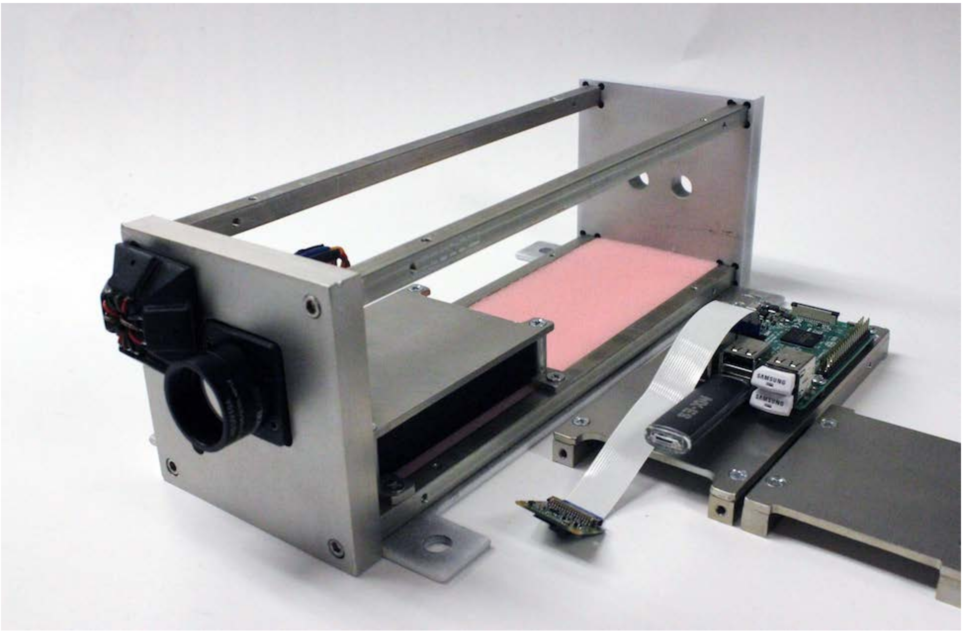

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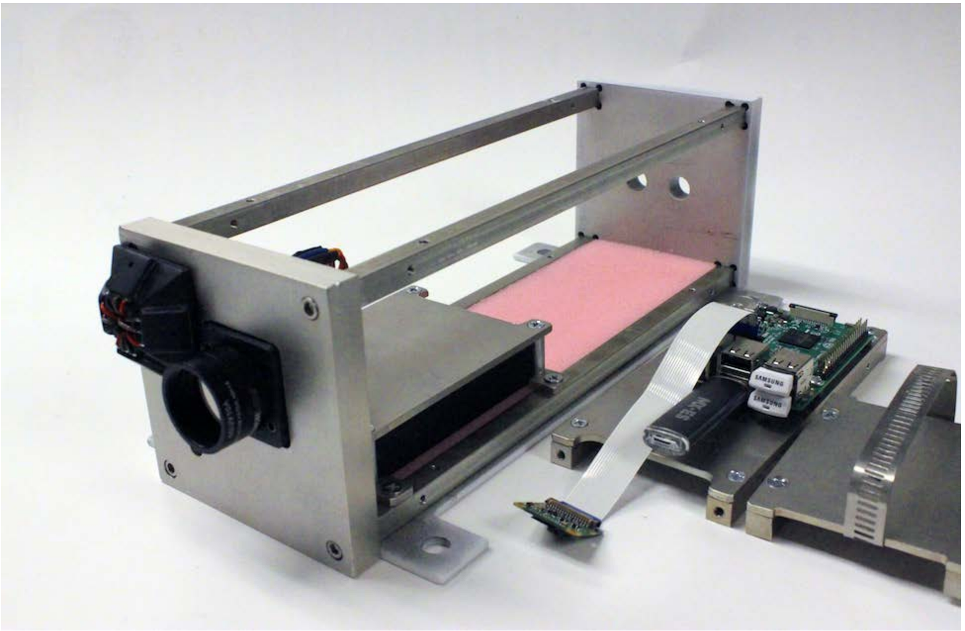

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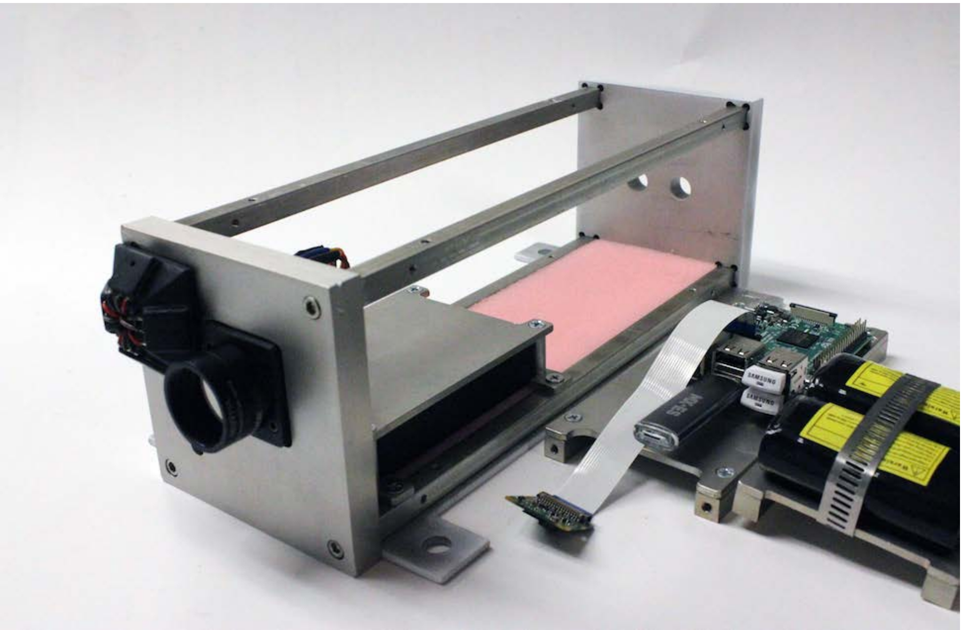
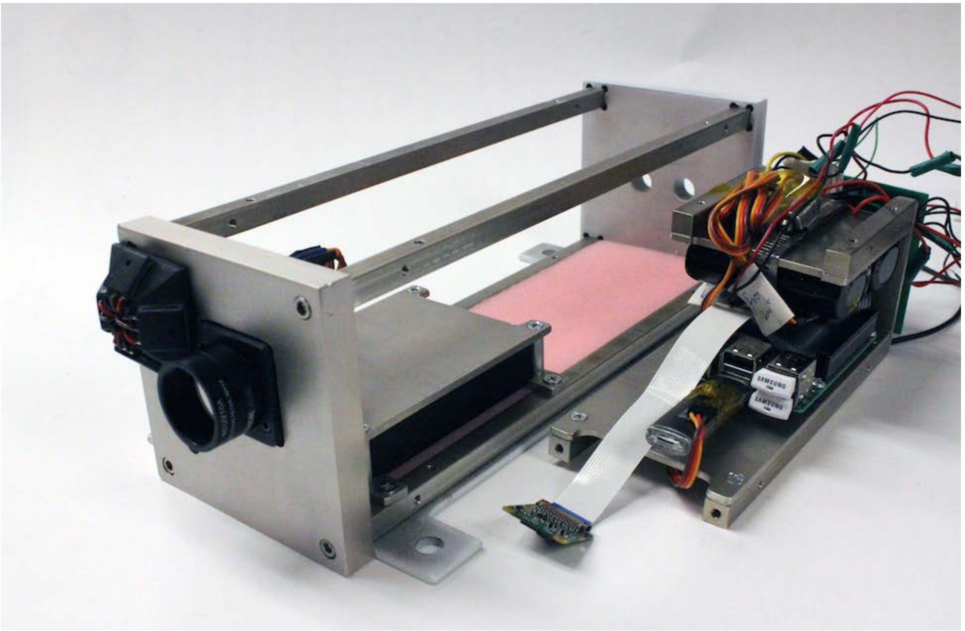


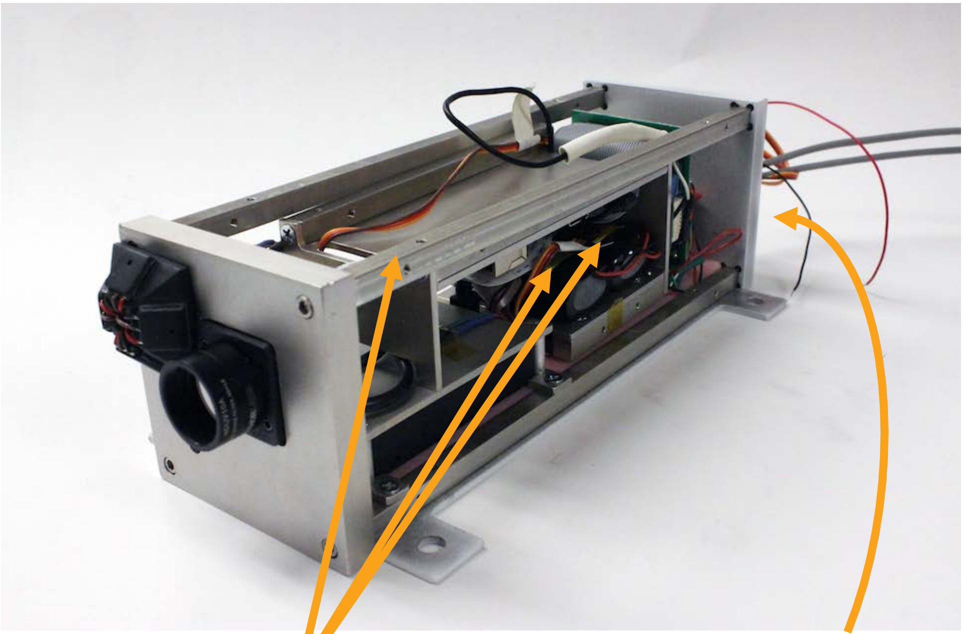
- Two Lithium Ion batteries
  - Needed to power active thermal system

System Overview



- Custom power board for control and distribution

System Overview

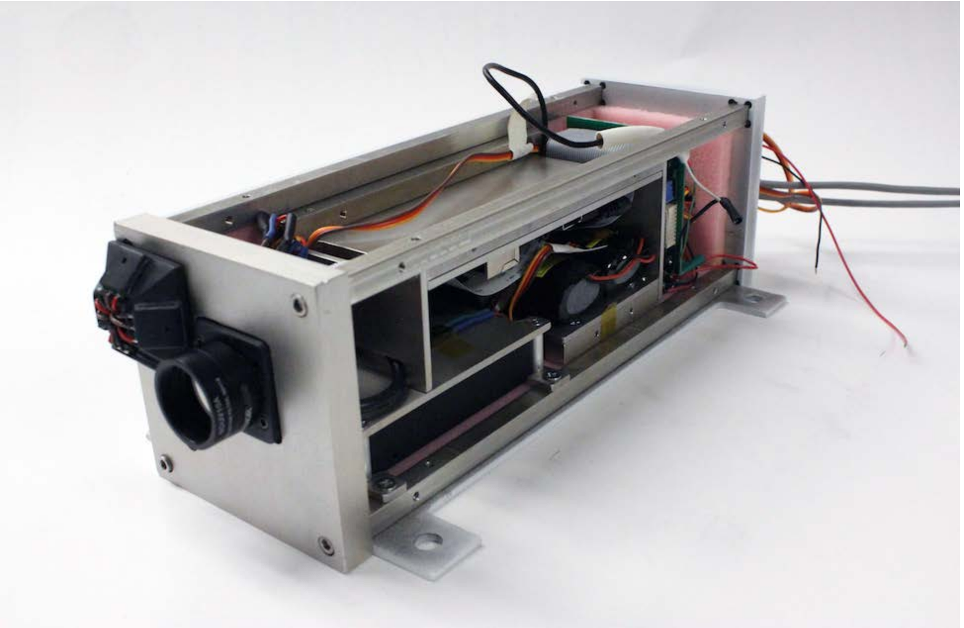


HK Sensors

ENV Sensors
(On Back)

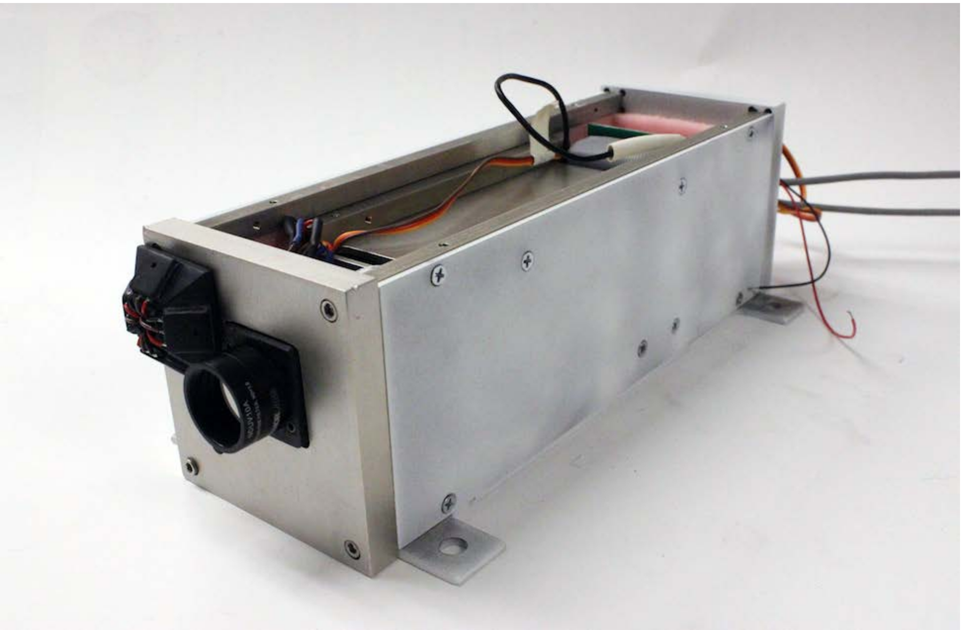
- External sensors (temperature, relative humidity) for atmospheric measurements
- Internal temperature sensors for active thermal monitoring

System Overview

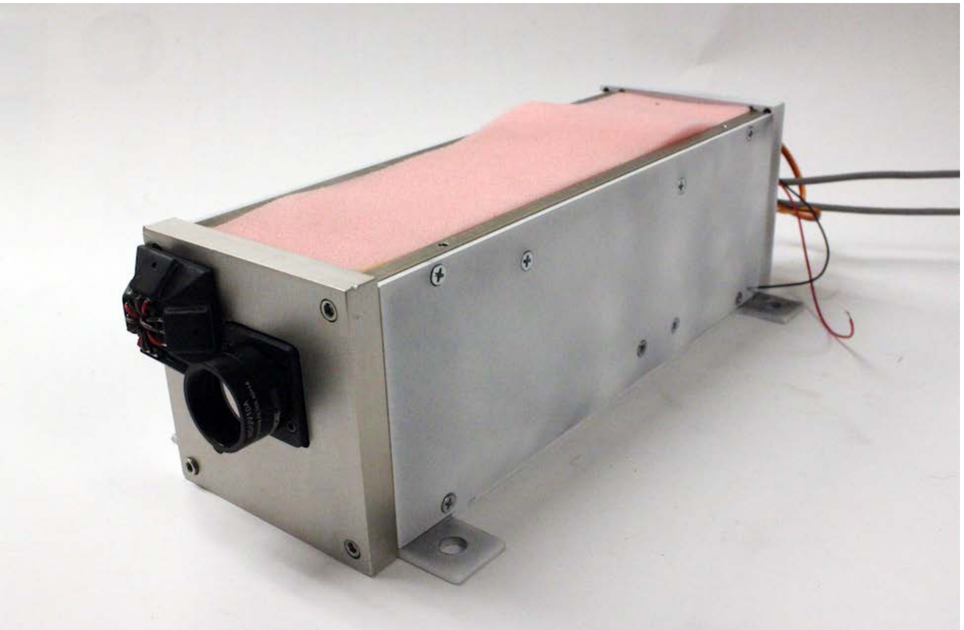


- Polyurethane foam insulation
- Thin film resistive heaters for active thermal control

System Overview



System Overview



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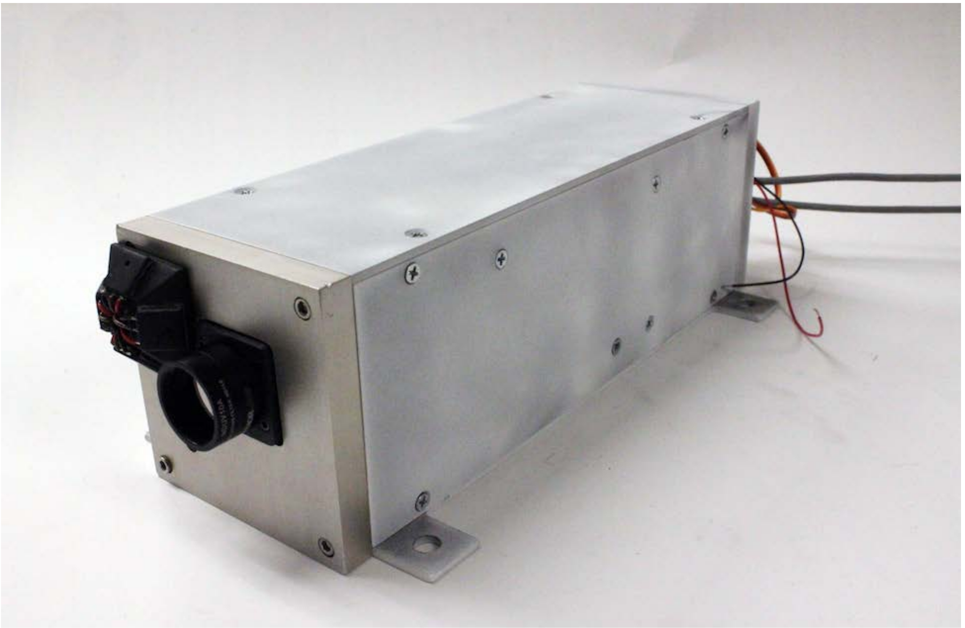
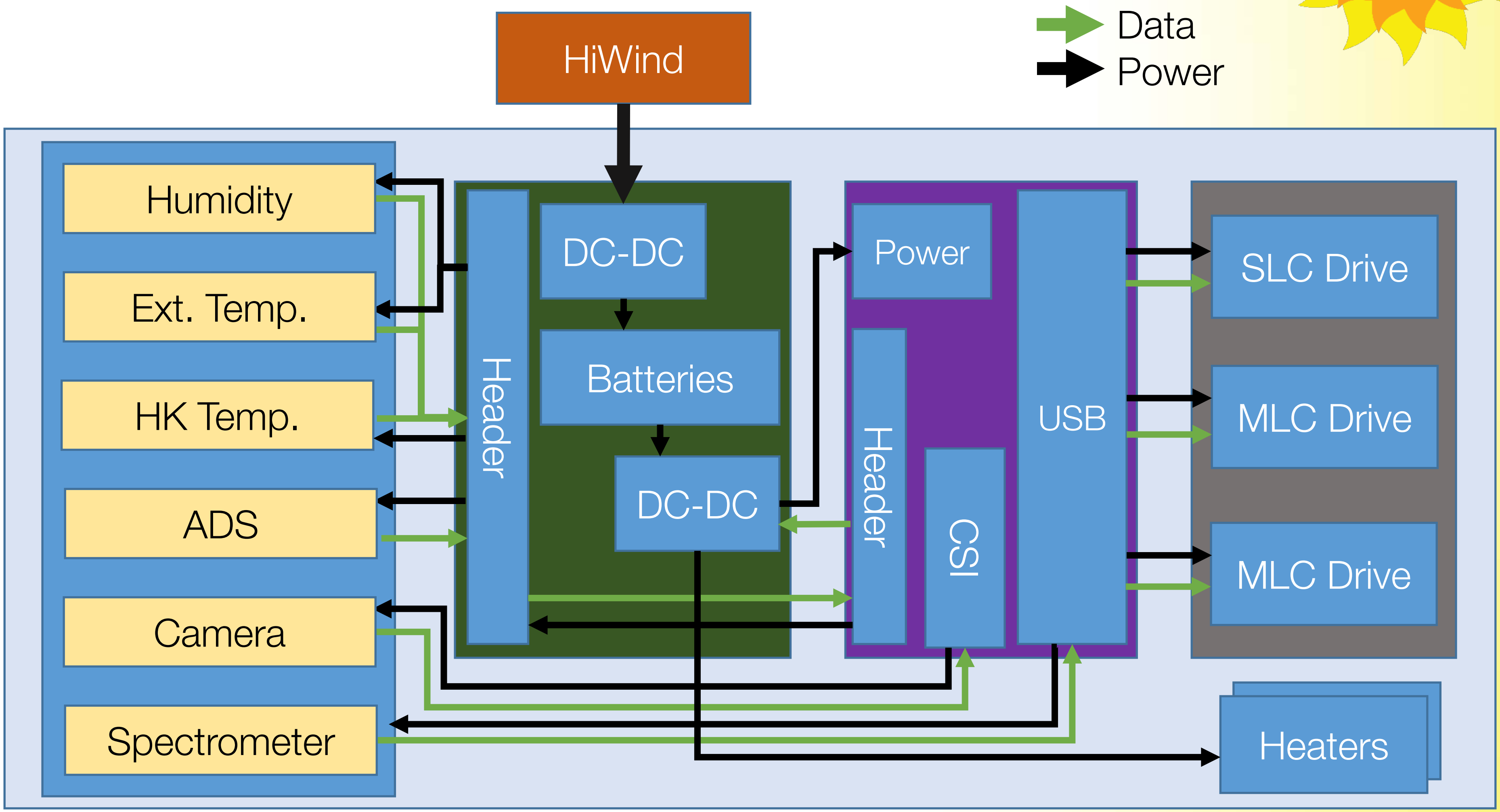


Functional Block Diagram



Changes Since TRR

- Power board
  - Updated wiring during integration
  - Changed some resistor values to handle more current
- Camera FOV reduced to ~1.57° from original 6.32°
- Timing loop has changed
- Neutral density filter values adjusted from qualitative assessment of camera images

Critical Project Elements

CPE	Justification	FR
Thermal Control	All components must meet thermal requirements	2
Power	Power board design is complex	5
Software	Efficient software design is critical to mission success	3
Camera, Lens	Challenging assembly to ensure in-focus images	6
Attitude Determination	Complex design, small parts, challenging hardware/software interface	4

No changes since MSR or TRR.

Test Overview

Component Testing

Component Testing | Subsystem Testing | Integration Testing

Purpose:

- Verify components turn on
- Verify measurements are reasonable
- Compare with expected performance from data sheet
- Investigate need for calibration (and perform calibration)

Component Testing

Component Testing	**Subsystem Testing**	Integration Testing

Purpose:

- Verify and integrate operation of subsystems
- Verify interaction between software and hardware
- Validate CAD model and attitude determination model

Component Testing

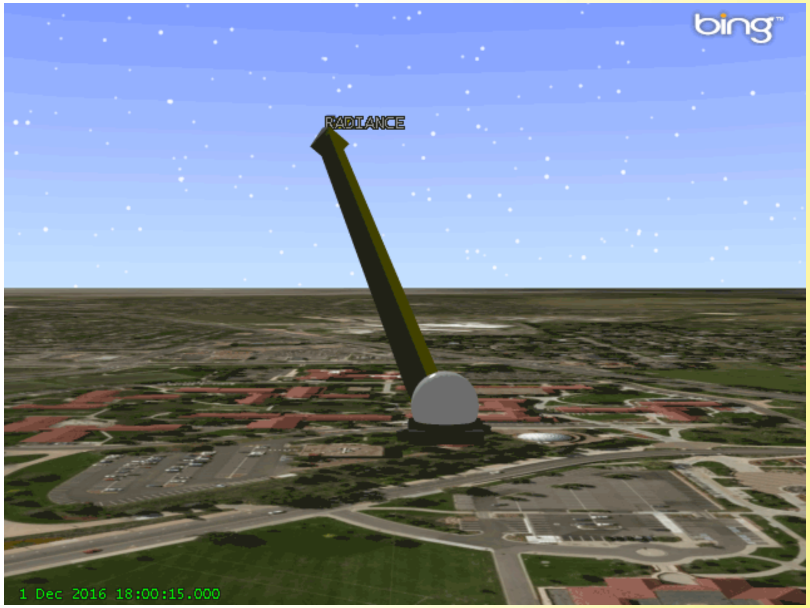
Component Testing | Subsystem Testing | **Integration Testing**

Purpose:

- Verify and demonstrate integrated operation of full system
- Validate SolidWorks thermal, C&DH storage capacity, and timing models

Attitude Test Overview

Test:	**Verify** resolution of attitude determination measurements
Why?	FR4 requires ≤ 1° accuracy
How?	1. Mount system to telescope 2. Track the sun 3. Turn off tracking software 4. Allow ADS to measure drift angle
Resource	Sommers Bausch Observatory



TVAC Test Overview

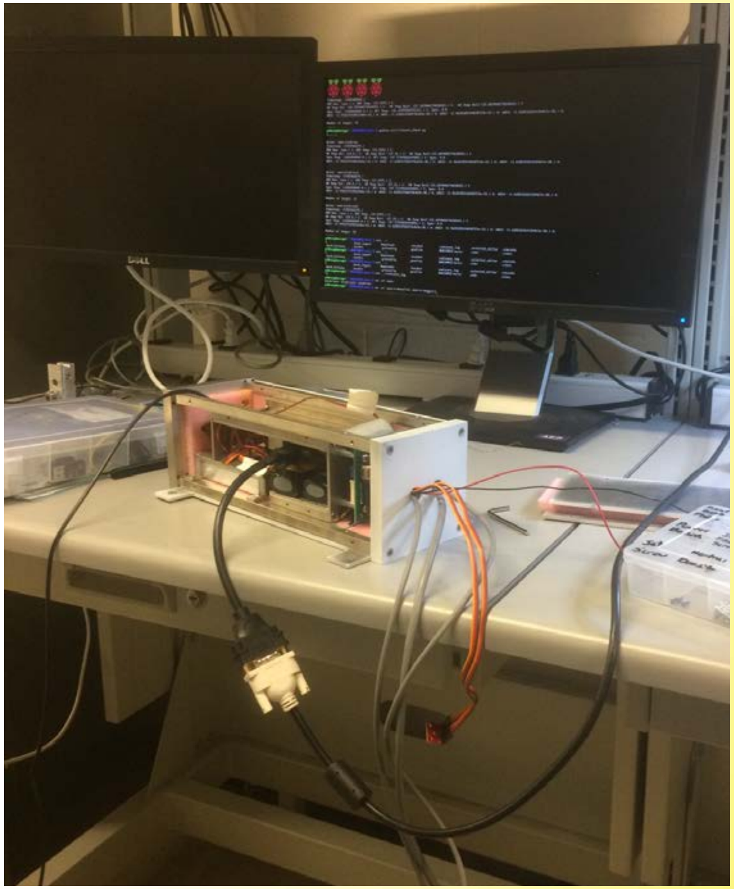
Test:	**Validate** thermal model during cruise conditions
Why?	System must survive the environmental conditions of flight.
How?	1. Allow chamber to reach desired temperature 2. Power on system 3. Pump down to ~200 Pa 4. Allow system to reach thermal equilibrium
Resource	TVAC Chamber at HAO

Environmental Chamber

Test:	**Validate** thermal model during ascent conditions
Why?	Want the system to operate during the environmental conditions of ascent.
How?	1. System rests for one hour at pre-launch ground temperature (-10°C) 2. Expose system thermal ascent profile 3. Record voltage and temperature data
Resource	Environmental chamber in Bioastronautics Lab (CU)

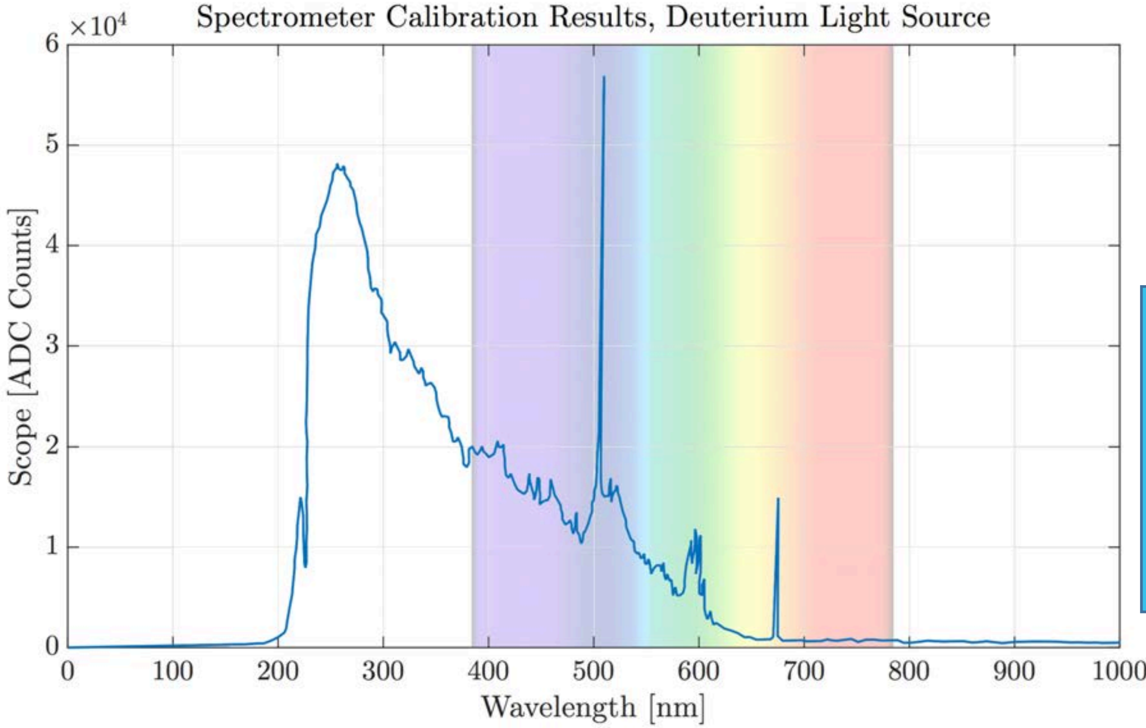
Benchtop Test Overview

Test:	**Validate** benchtop thermal model
Why?	Gives confidence to other thermal models not tested due to TVAC issues.
How?	1. Assemble system with side panels 2. Power on system 3. Allow to run for 2 hours 4. Record temperature and voltage data
Resource	Trudy Schwartz's Lab



Test Results: Component Tests

Spectrometer Calibration



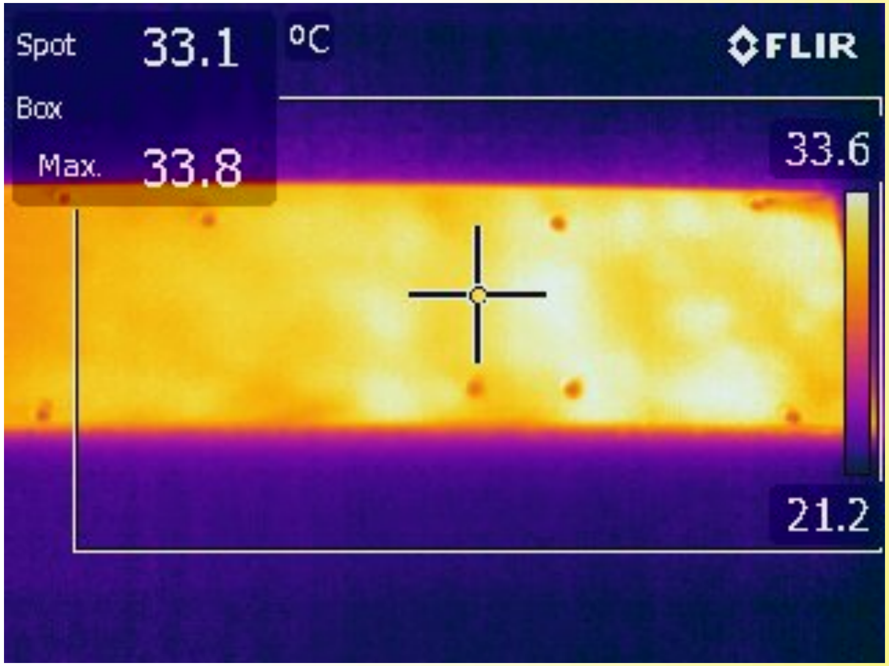
Instr. LoS: 3

FR 1: The system shall measure solar irradiance.
DR 1.1.2: The spectrometer shall be calibrated

- Avantes Deuterium light source
- Calibration stored on spectrometer

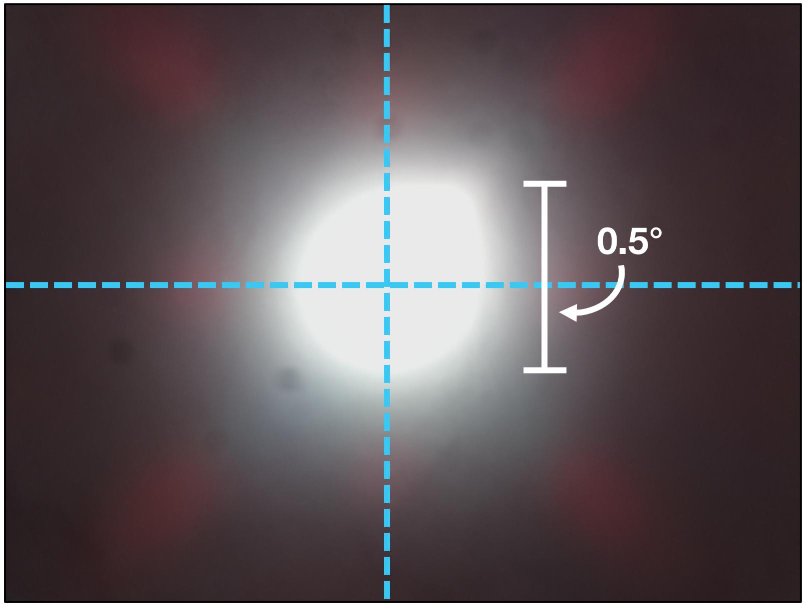
Emissive Coating Verification

- Thermal camera used
- Goal is $\epsilon = 0.85$
- $P = \epsilon\sigma A T^4$
- $\epsilon_{\text{cam}}(T_{\text{cam}})^4 = \epsilon_{\text{actual}}(T_{\text{actual}})^4$
- $\dfrac{\epsilon_{\text{hot}}}{\epsilon_{\text{cold}}} = \dfrac{(T_{\text{cold}})^4}{(T_{\text{hot}})^4}$



Actual Emissivity
$\epsilon = 0.80 \pm 0.07$

Camera Images



FR 3: The system shall image the sun.

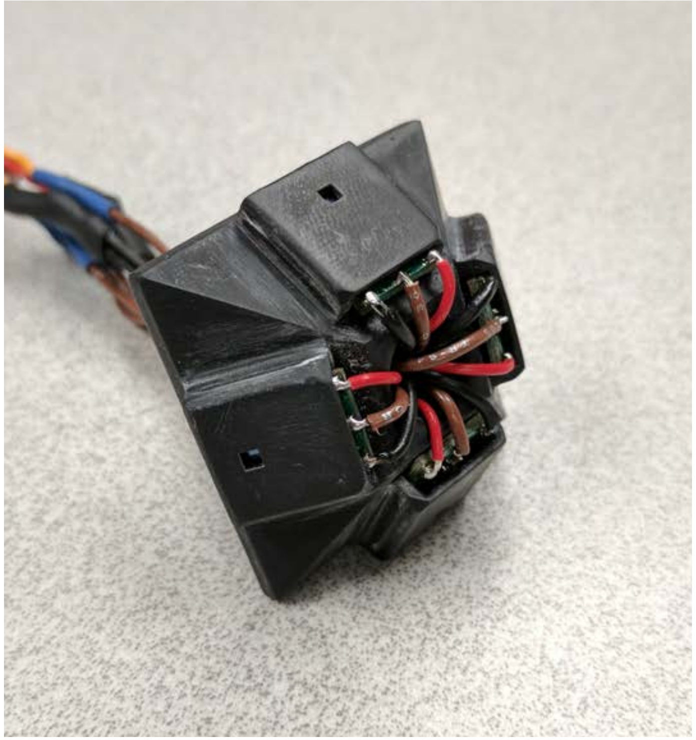
Instr. LoS: 3

Camera FOV		
Expected	Actual	Req.
1.21°	~1.57°	< 10°

Preliminary Photodiode Array

- First photodiode tests in sun gave photocurrents on order of 2.5 mA
- Changed transimpedance amp to 1 kΩ instead of 5 kΩ feedback resistance
  - Prevent saturating the ADCs

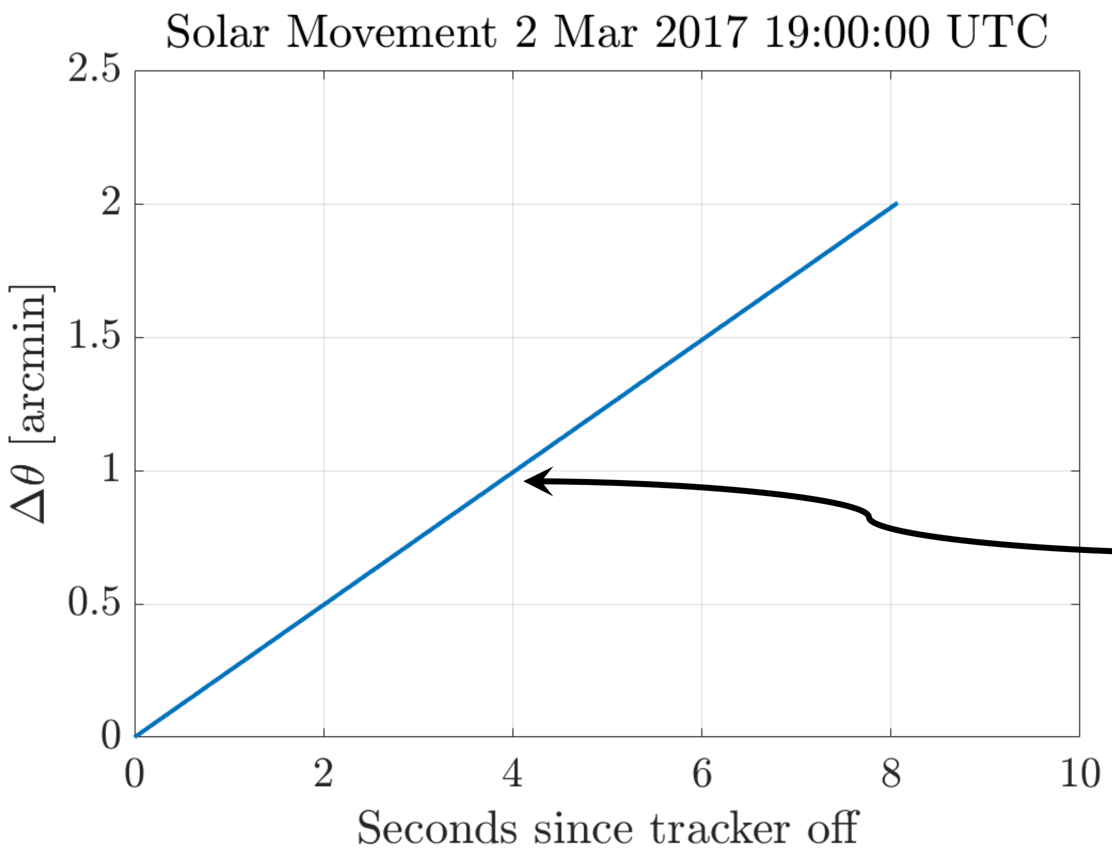
Attitude Determination Test



FR 4: The system shall determine its attitude.
DR 4.1: The off-sun angle shall be determined to better than one degree of accuracy.

Attitude LoS: TBD

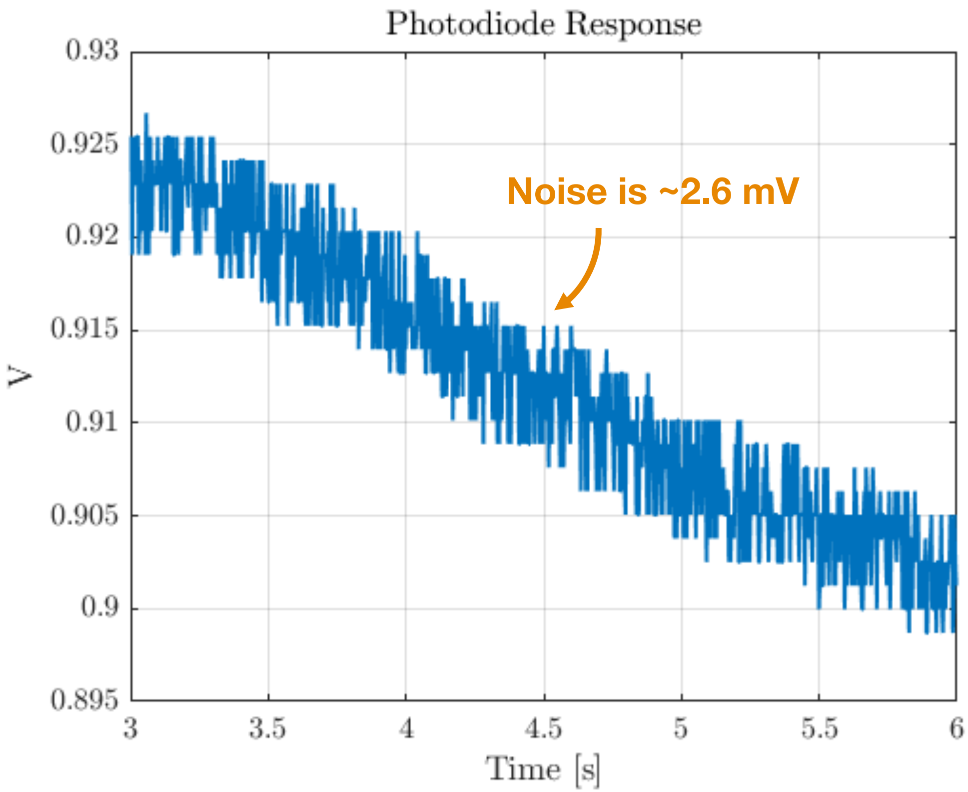
Attitude Determination: Model



Solar angle rate = 0.2482 ± 0.0003 arcmin/sec
(over 3 minute test)

1 arcminute of movement occurs 4.03 seconds after turning off the sidereal tracker

ADS Noise Requirement



- Tested photodiode response with handheld LED light source
  - Shaky hands
  - LED not as powerful at red wavelengths as the sun
- Noise is ~2.6 mV
- Required for 1° accuracy: < 32.6 mV
- Required for 1’ accuracy: < 0.5 mV

Attitude Determination: Expected Results

- Full test occurred week of April 24th
- Results discussed during presentation

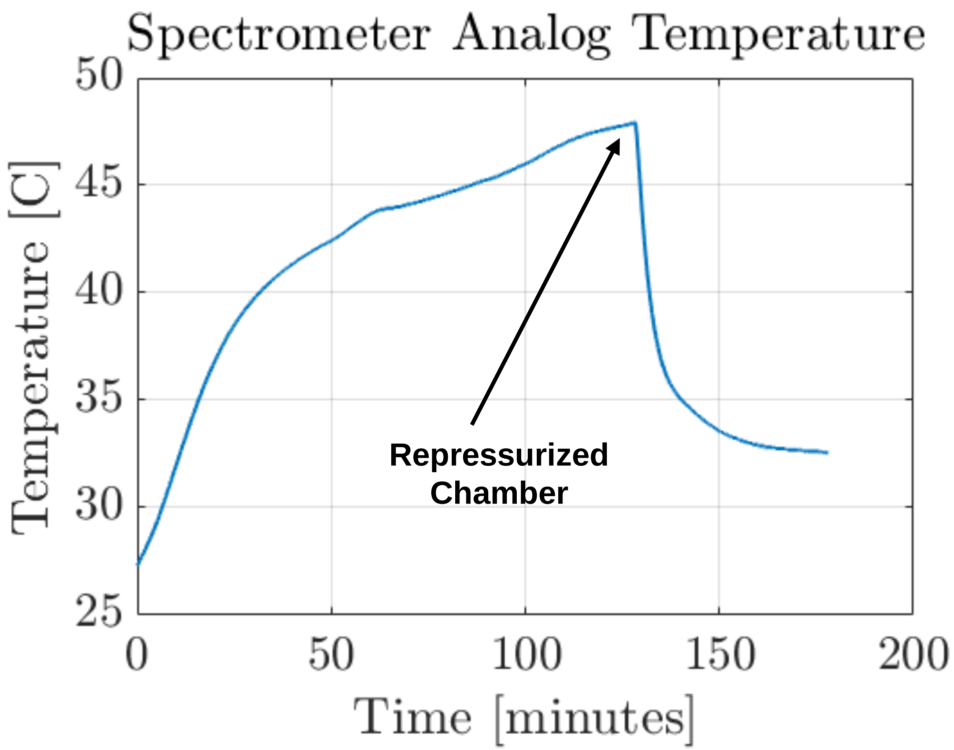
Test Results: Integration

TVAC: Model

- SolidWorks transient simulation
- Assume convection coefficient = 0 for vacuum
- Actual radiative coating emissivity from IR analysis

Property	Value
Convection Coefficient	0
Radiation Temperature	18°C
Conduction Temperature	18°C
Radiative Coating Emissivity	0.80

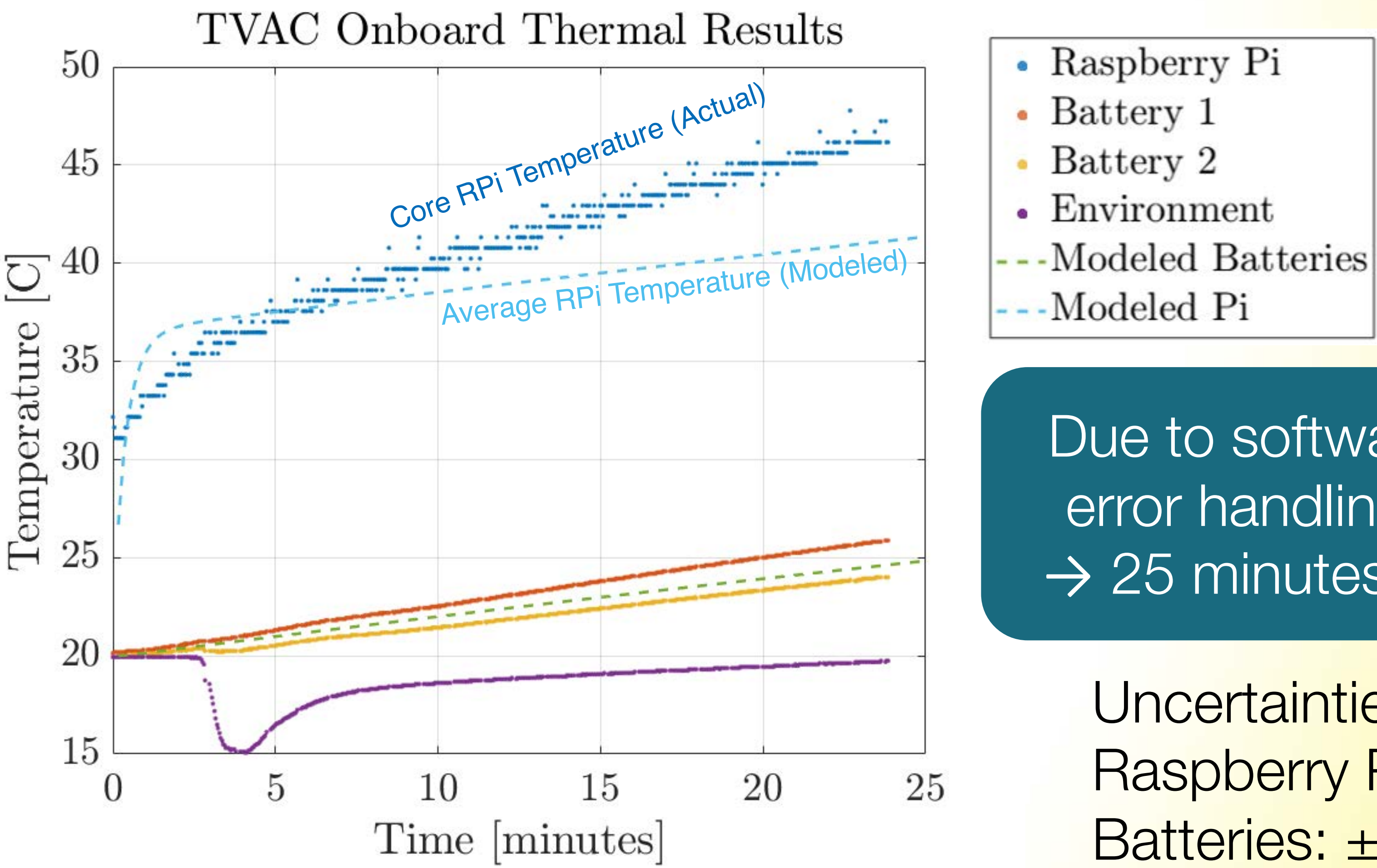
TVAC: Spectrometer Analog



Uncertainty: ±0.06°C

- Started simultaneously with RADIANCE onboard systems
- Captured data through entire test
- Data questionable due to proximity to heater

TVAC: Results



Due to software bug, error handling failed → 25 minutes of data

Uncertainties:
Raspberry Pi: ± 2°C
Batteries: ± 0.06°C

TVAC: Conclusions

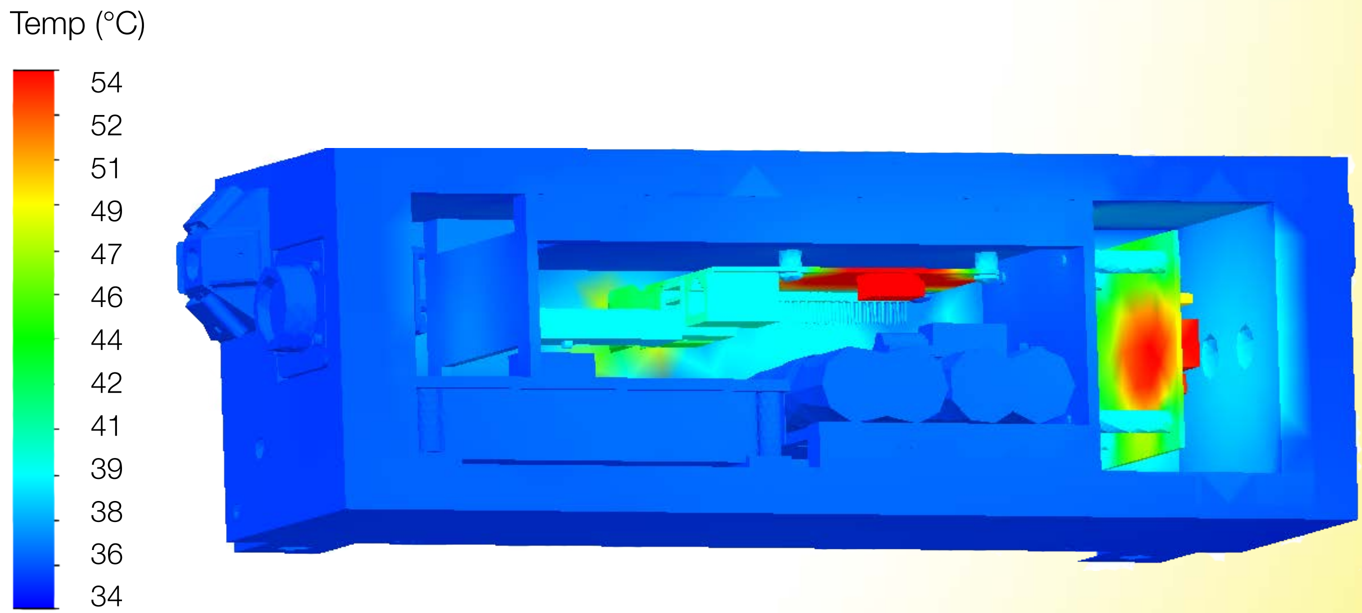
- Transient solutions for components actively producing heat are questionable
- Models for components not actively producing heat are supported by current test data
- Longer tests are needed to validate transient models.
- Current test data encourages confidence in transient models

Thermal LoS: 1

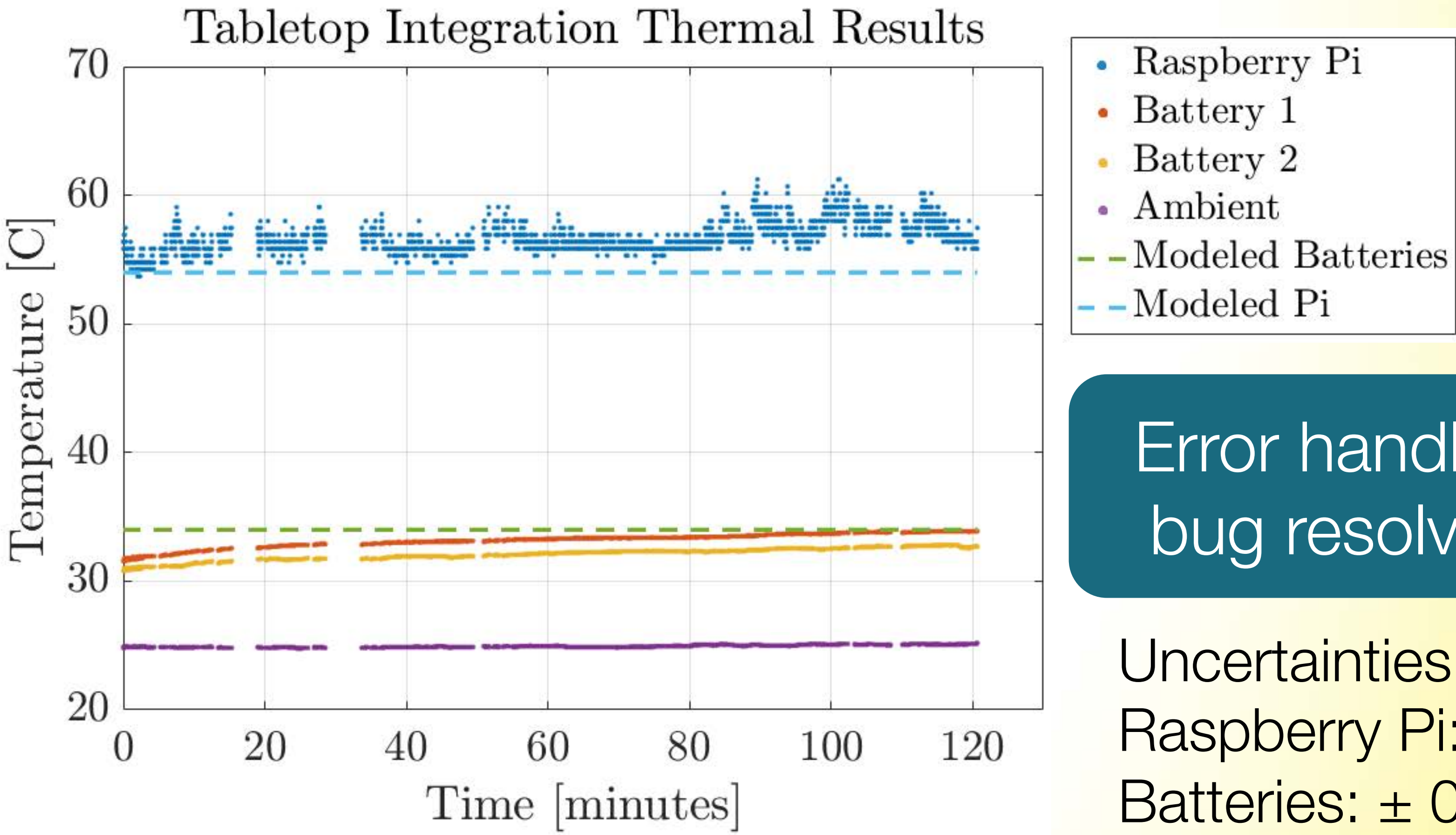
FR2: The system shall survive the environmental conditions of flight
DR 2.4 The system shall survive the pressure range from 200 Pa to 100 kPa

Benchtop Thermal: Model

- SolidWorks steady state simulation
- Convection coefficient = 4.4
  - From basic principles MATLAB model
- Radiation and convection temperatures = 25°C
- Actual radiative coating emissivity from IR analysis $\epsilon = .80$



Benchtop Thermal: Results



Error handling bug resolved

Uncertainties:
Raspberry Pi: ± 2°C
Batteries: ± 0.06°C

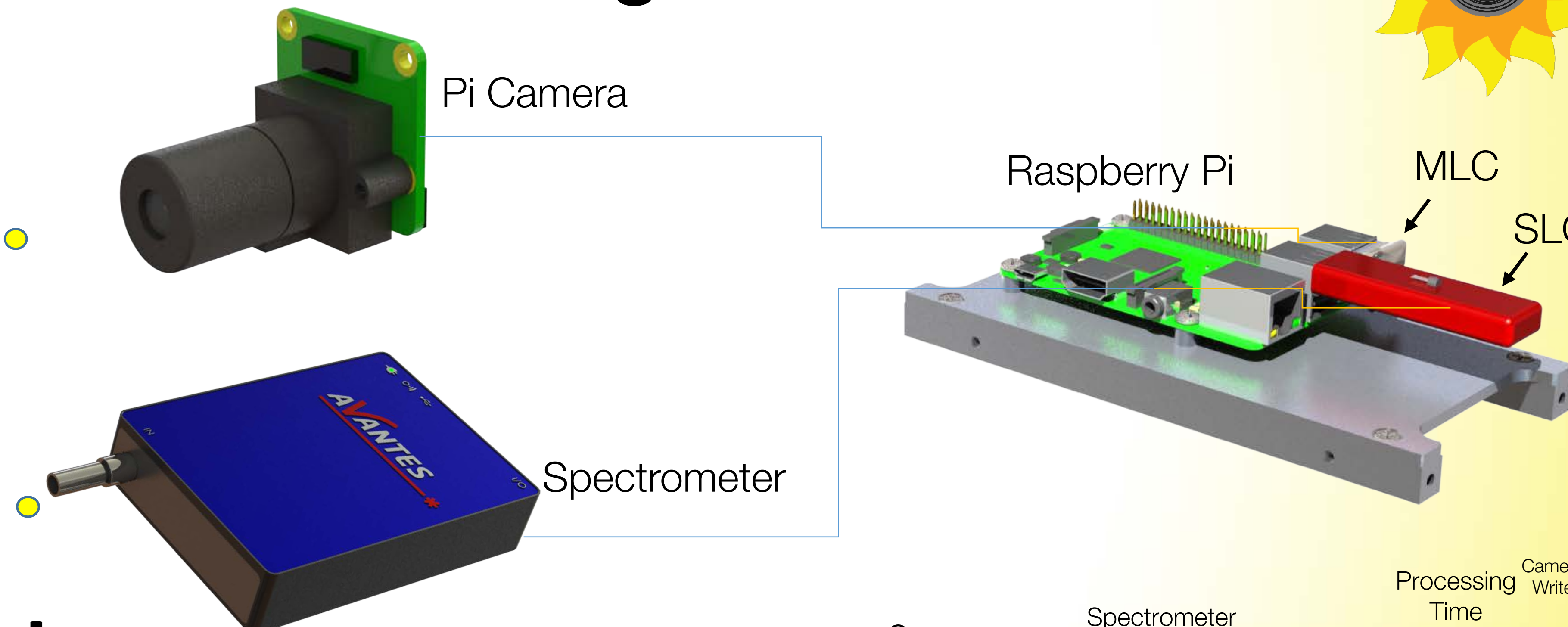
Benchtop Thermal: Results

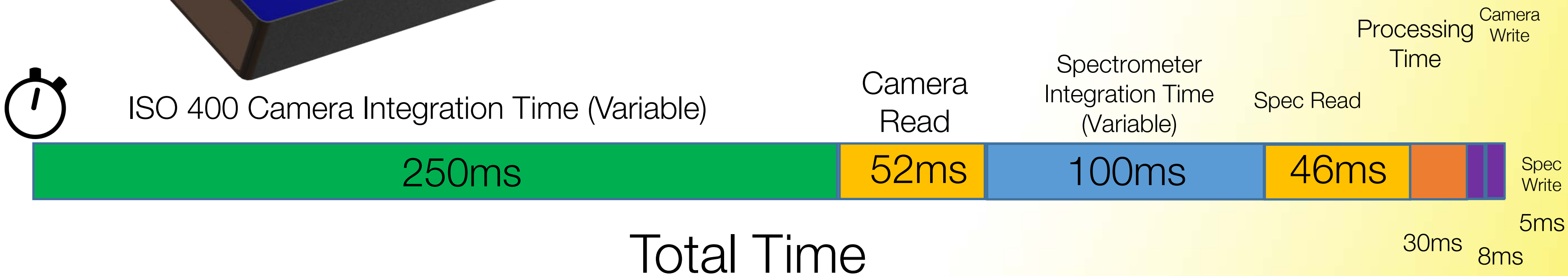
- Models for atmospheric steady state are supported by current test results
- Raspberry Pi likely will always run hotter than model due to CPU proximity to temperature sensor
- Testing at vacuum is needed to validate vacuum steady state models.
- Current test data encourages confidence in transient models

Thermal LoS: 1

FR2: The system shall survive the environmental conditions of flight.

C&DH Timing: Model





Total Time

Time: 0.491 s

C&DH Timing: Results

Item	Time
Spectrometer Integration Time	1.05 ms
Spectrometer Read Time	5 ms
Camera Integration Time	250 ms
Camera Read Time	950 ms
1Wire Internal Temperature Sensors	2.5 s
Remaining Sensors	<1 ms
Write to Storage	1 ms

Total Time (with Camera)
Time: 3.75 s ± 30 ms

Total Time (without Camera)
Time: 2.6 s ± 30 ms

C&DH Timing: Conclusions

Item	Req.	Model	Actual
Science Data Cadence	60 s	1 s	2.6 s
Science Data Lag	2 s	13 ms	1 ms
Camera Image Cadence	60 s	60 s	60 s

Data LoS: 3

FR 3: The system shall return data.
DR 3.1.1 Science data shall be recorded once per minute.
DR 3.1.2 Science instrument measurements shall be recorded within 2 seconds.
DR 3.1.3 Camera images shall be recorded once per minute.

C&DH Capacity

Measurement	Model Total	Actual Total
Spectrometer	9.25 GB	3.63 GB
External temperature	4.6 MB	1.8 MB
Internal temperature	27.7 MB	5.3 MB
Humidity	4.6 MB	1.8 MB
Photodiode (x4)	36.9 MB	7.1 MB
Sun angle	4.6 MB	0 B
Total	9.4 GB	3.65 GB

Measurement	Model Total	Actual Total
Camera images	17.7 GB	3.63 GB
Other Data	9.4 GB	3.65 GB
Total	27.1 GB	7.28 GB

SLC Flash Drive

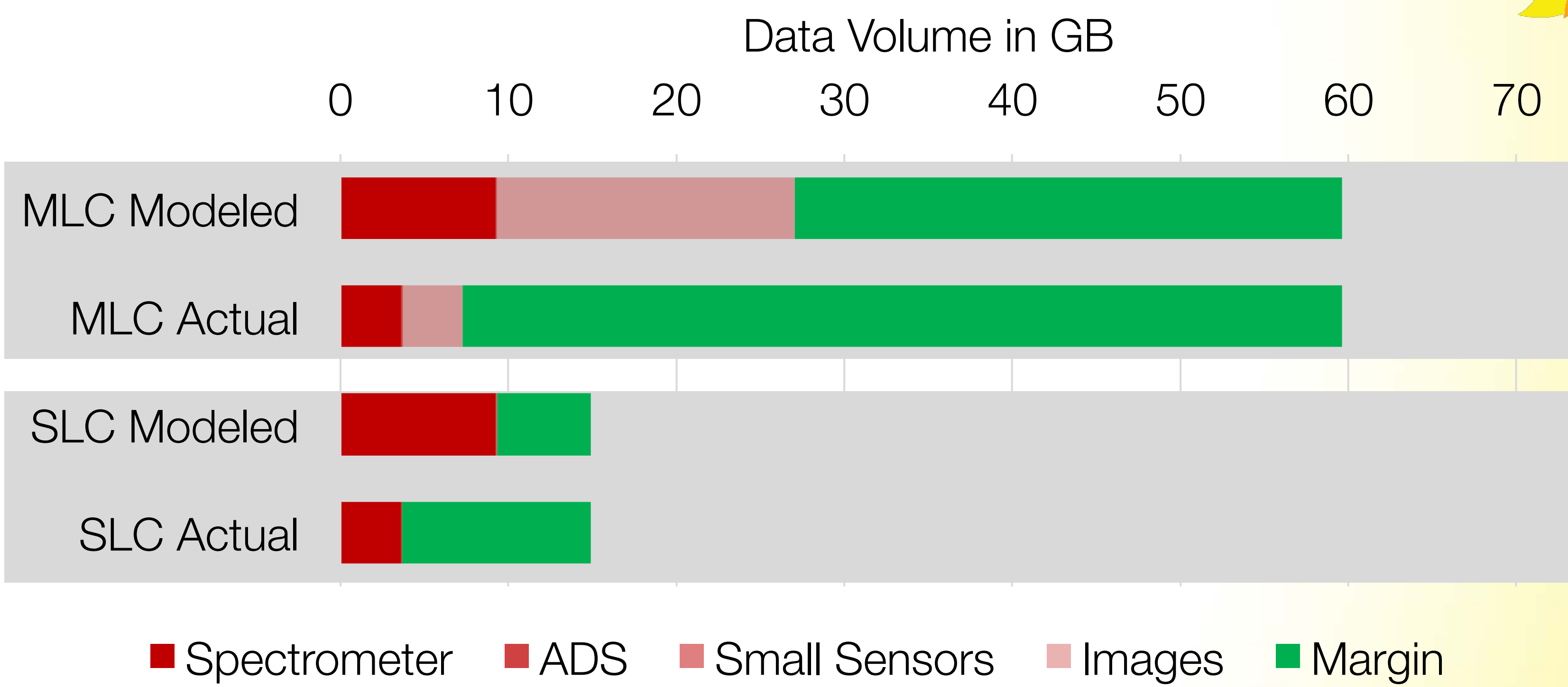
14.9 GB Capacity
Modeled Margin: 37%
Actual Margin: 76%

MLC Flash Drive (2)

59.6 GB Capacity
Modeled Margin: 55%
Actual Margin: 88%

Overall mission capacity uncertainty: ±10.7%

C&DH Capacity: Conclusions



FR 3: The system shall return data.
DR 3.1: The data shall be recorded.

Data LoS: 3

Power Budget: Model & Results

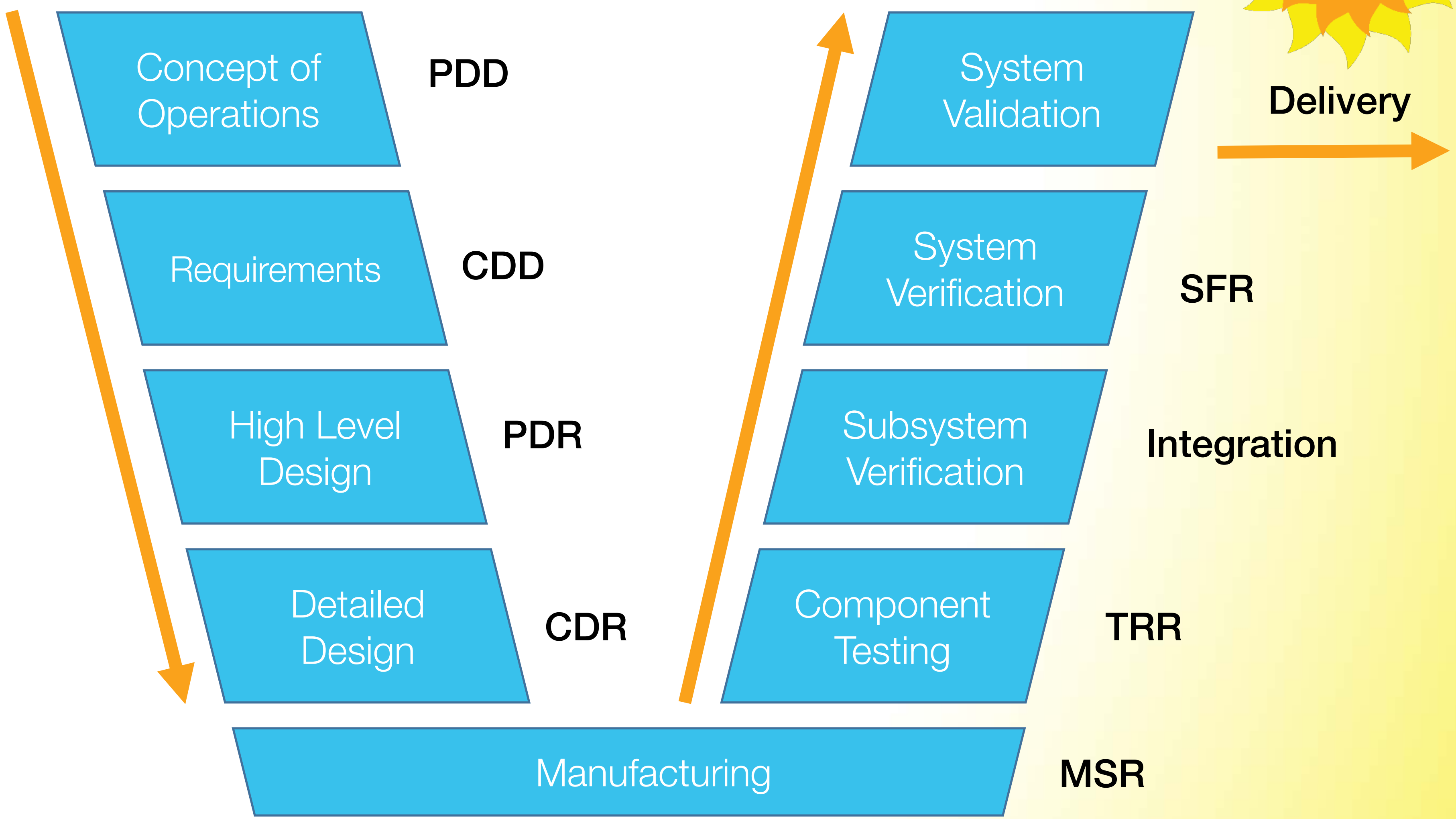
Component	Modeled Power Draw
Raspberry Pi	4.25 W
Spectrometer	1.25 W
Camera	0.7 W
Small Sensors	0.1 W
Flash Drives	1.4 W
Total (Cruise)	7.7 W
HiWind Power	15 W

Power LoS: 1

Measured Total Power Draw: 3.2 ± 0.5 W

Systems Engineering

Systems Engineering



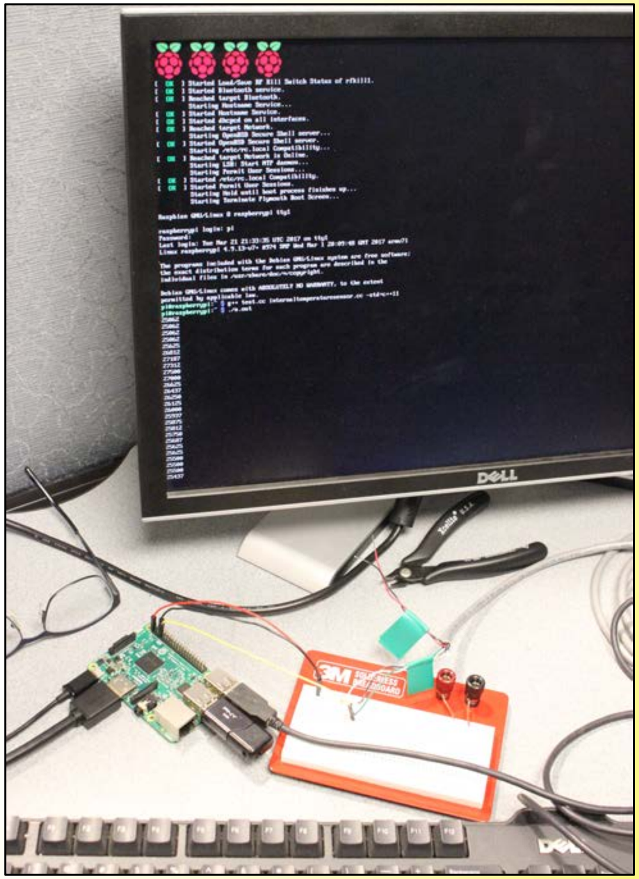
Component Test Mapping

Detailed Design ⟷ Component Testing

- Relate individual components to CDR level design and sub requirements
- Verify functionality of aspects such as ENV and HK sensors

Lessons Learned:

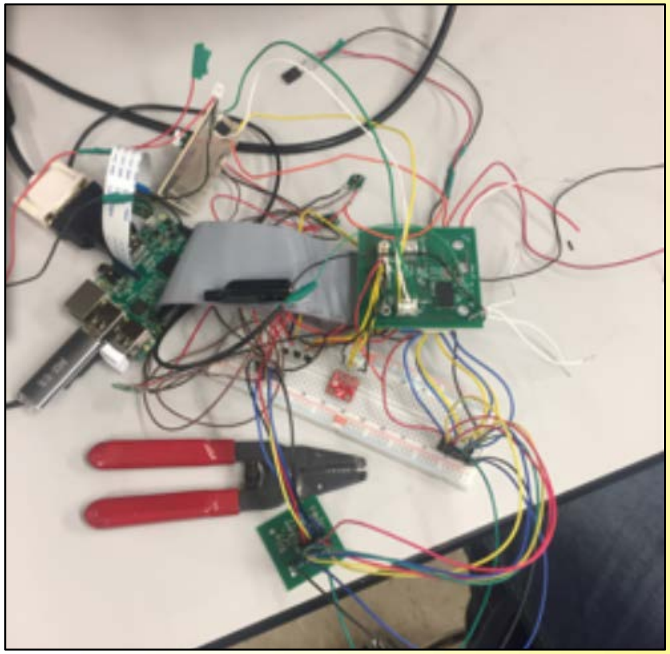
- "Components" still require integration
- Easy for issues to push schedule



Subsystem Integration

High Level Design ↔ Subsystem Verification

- Test functionality of system subsets
- Verify PDR level design aspects



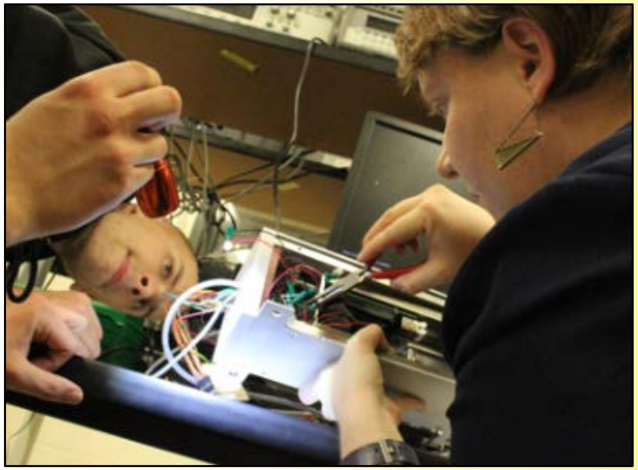
Lessons Learned:

- Wire design and harnessing is crucial

System Integration

Requirements ⟷ System Verification

Requirement	Completion
Solar irradiance	4/4 Verified
Environmental conditions	3/6 Verified
Data	2/2 Verified
Attitude	0/2 Verified
Interface	6/6 Verified
Imaging	3/3 Verified



Lessons Learned:

- Most issues occurred during this phase
- Budget time and money to fix issues that come up

Requirements: Solar Irradiance

Verified

- 1.1: Spectrometer derived requirements
  - 250 to 1000 nm, < 1.5 nm resolution, calibrated
- 1.2: Environmental sensor derived requirements
  - Measure temperature and humidity once per minute

To be verified:

- None!

Requirements: Environment

Verified

- 2.4: Humidity of 5% to 90%
- 2.5: Pressure of 0.20 kPa to 100 kPa
- 2.6: Resist radiation effects

To be verified:

- 2.1: Ground temperatures
- 2.2: Ascent temperatures
- 2.3: Cruise temperatures

To be verified in environmental testing by HAO

Requirements: Data

Verified

- 3.1: Data storage rate of once per minute and derived requirements
- 3.2: Data storage survives landing

To be verified:

- None!

Requirements: Attitude

Verified

- TBD

To be verified in SBO testing

To be verified:

- 4.1: Accuracy within one arcminute
- 4.2: Data storage rate of once per minute

Requirements: Interface

Verified

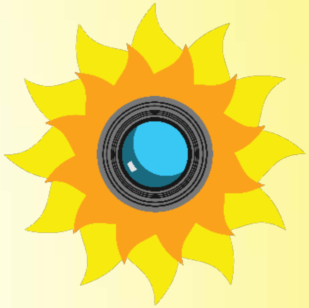
- 5.1: Dimensions of 32 cm x 10 cm x 10 cm
- 5.2: Sun facing plate is the 10 cm x 10 cm
- 5.3: Power interface and derived requirements
  - 15 W at 28-33 V
- 5.4: ICD compliance

To be verified:

- None!

ICD

- Created ICD for HiWind/RADIANCE Integration
- Defines structural, electrical interfaces
- Defines interface associated risks



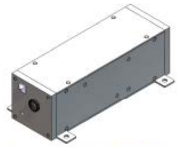


Figure 1: An image of the RADIANCE system.

1 Introduction

The purpose of this interface control document is to define the interface between RADIANCE and HiWind, which is a high-altitude balloon payload built by the High Altitude Observatory (HAO). This document will outline the general interface, assumptions, constraints, and risks of the interface, as well as the detailed requirements and qualification methods of the interface requirements.

HAO is a division of the National Center for Atmospheric Research (NCAR), which, among other scientific work, studies atmospheric science. Previously, HiWind was flown in June 2011 from Sweden on a 4-day flight to accomplish several scientific objectives. During that flight, HiWind's primary science objective was to measure summertime polar cap thermospheric neutral winds. Between November 2017 and February 2018, HiWind will be flown again from Antarctica for a 2-week circumpolar flight with a cruising altitude of approximately 40 km.

RADIANCE is a project of the University of Colorado Boulder Aerospace Engineering Science's senior projects course sequence, whose customer is NCAR/HAO. The science objectives of RADIANCE are to take solar irradiance measurements, to image the sun in the visual spectrum, and to record ambient atmospheric data during HiWind's flight. The RADIANCE system is a 3U-sized cubesat-style payload (each "U" is a 10cm x 10cm x 10cm cube) that houses all systems needed to support the science objectives. Solar irradiance data will be taken by a spectrometer in the range of 200 to 1100 nm, camera images will be taken through a neutral density filter, and the system will record ambient pressure, temperature, and humidity data. RADIANCE will be the first prototype developed for a future system that may consist of several space-grade on-orbit cubesats.

2 Overview

There are two critical areas of interface between HiWind and RADIANCE: the power and structural interfaces. These interfaces are outlined below, with the fundamental requirements of each interface.

2

Requirements: Imaging

Verified

- 6.1: Image storage on drives
- 5.2: Field of view of $5° \pm 3°$
- 5.3: Image cadence of once per minute

To be verified:

- None!

Projects Risk Matrix – Post CDR

Likelihood	Consequences					
	Risks easily mitigated	1 FR Failed	2-3 FRs Failed	3-4 FRs Failed	5-6 FRs Failed	
Certain	1					5
Likely						4
Moderate	1					3
Unlikely		4				2
Rare	1	4	1		1	1
	1	2	3	4	5	

Risk Status

Element	Value	Test	Current Status
Overheating	5	TVAC	Thermal Model Validated
Frost on optics	5	Acceptable Risk	
Heater failure	3	TVAC	No recorded failure
Drive hardware failure	4	Acceptable Risk	
Temporary power failure	3	Flatsat	Mitigated with batteries in Flatsat testing
Software data write failure	2	Flatsat	
Bit flip	2	Acceptable risk	
Drive connection failure	2	Acceptable risk	
Camera Oversaturation	2	SBO	Image taken
Pi Software failure	1	Flatsat	Pi restarts as expected

Risk Summary

Changes to risks

- Increased risk of heater failure in vacuum
  - QB50 team encountered issues, including recommended heater in path to space

Additional Risks

- Improper power cycling *may* cause SD card corruption
- Few software risks identified by CDR (mitigated during testing)
- Scheduling risks

Project Management

Management Approach

- Proactive efforts to build a positive, supportive team environment
  - Encouraged discussion from the start to work towards solutions
  - Every team member’s contribution is valuable and their perspective is valid
- “Leadership Through Service”

Success and Challenges

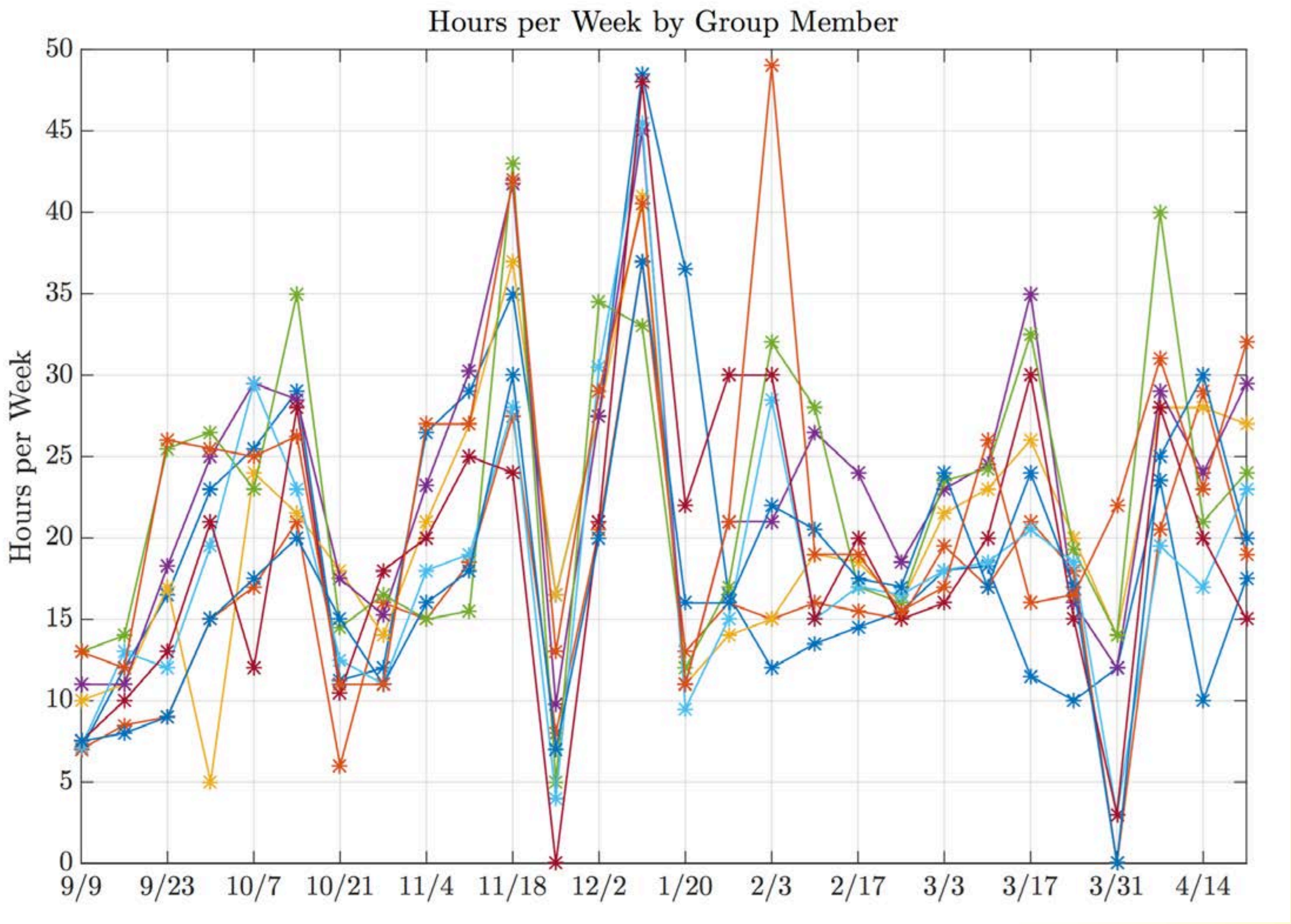
- Success: We all still like each other
- Success: Peer Reviews
- Challenge: Time management with other obligations (work, courses, etc.)
  - Needs of the project vs. needs of the team
- Sometimes it felt like…

Success and Challenges

Lessons Learned

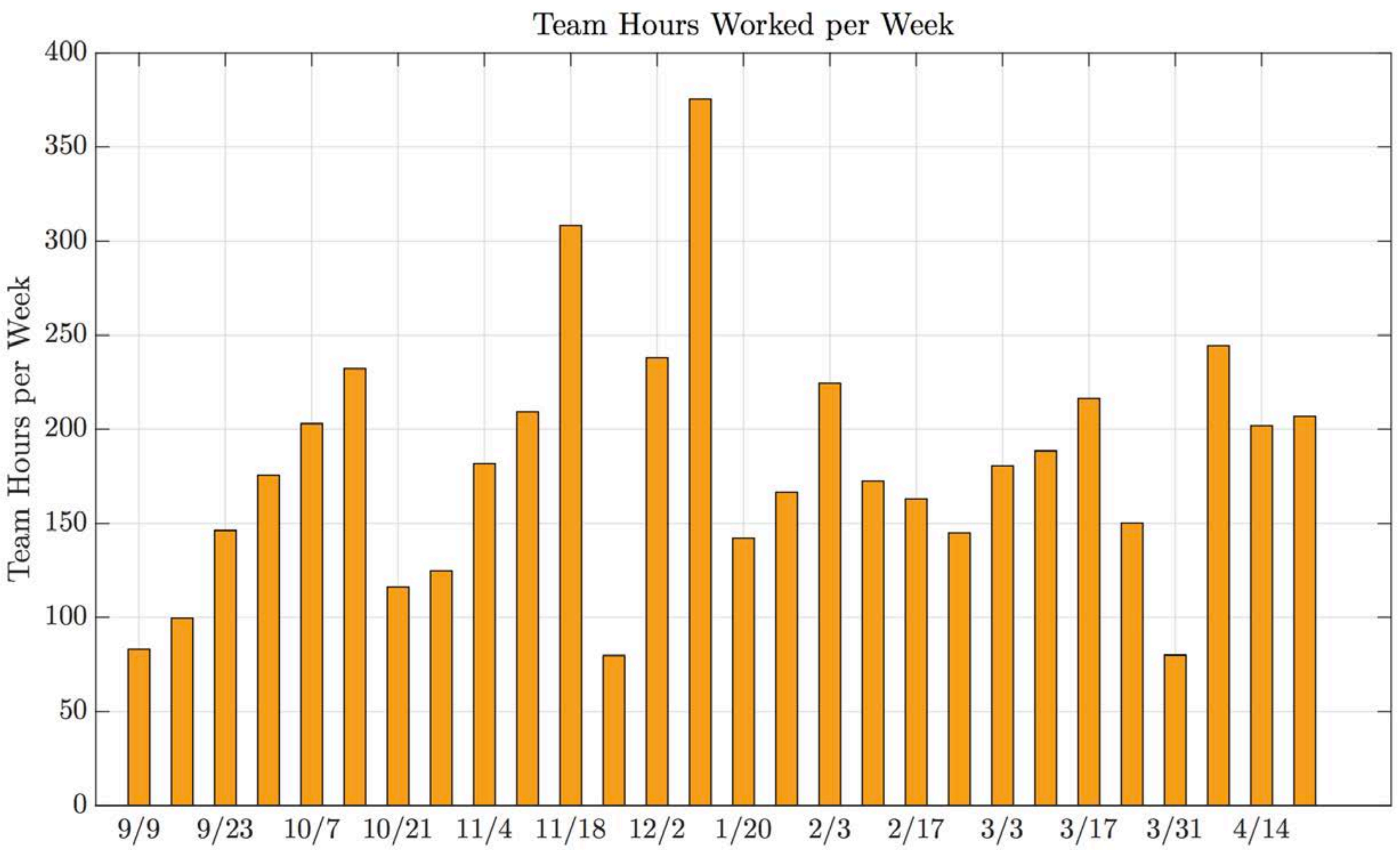
- Diverse project led to scattered focus at times → important to be aware of this
- 80/20 rule
  - Balance between when to go for the extra 20% and when to let it go
- Need to balance burn-out with productivity

Individual Hours Worked

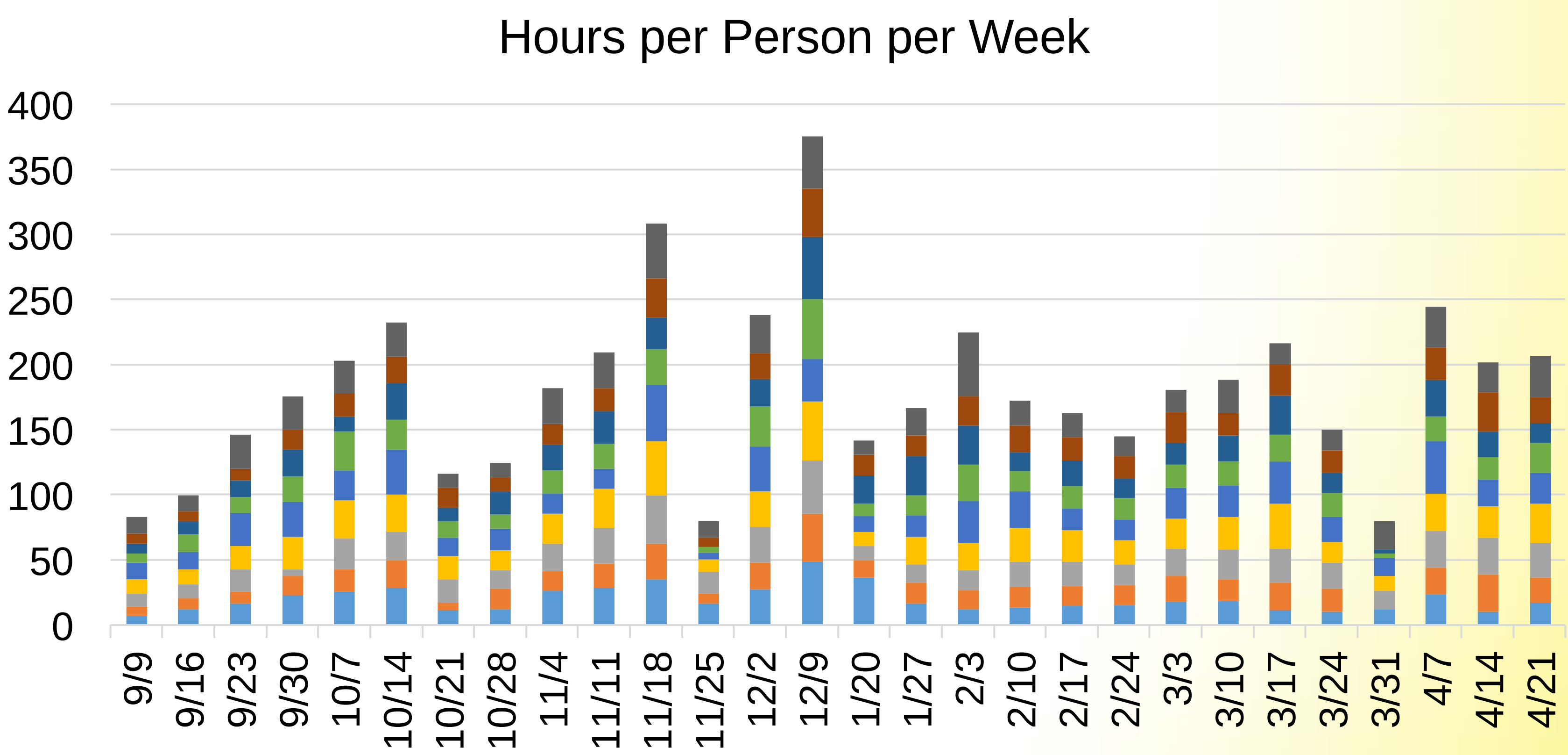


Purpose & Objectives | Design Overview | Test Overview | Test Results | Systems Engineering | Project Management

Team Hours Worked



Hours per Person per Week



Purpose & Objectives
Design Overview
Test Overview
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Project Management

Budget

Subsystem	Projected Cost	Procured	To be Procured	Margin (%)	Effect on Budget
C&DH	$ 167	$ 149	—	—	+$ 18
Sensors	$ 203	$ 127	—	—	+$ 76
Instrumentation	$2988	$3052	—	—	–$ 64
Power	$ 662	$ 615	$ 39	$ 8	–$ 50
PM	$ 84	$ 49	—	—	+$ 35
Structure	$ 418	$ 223	$ 4	$ 6	+$185
Testing	$ 250	$ 77	$ 16	$ 157	—
Thermal	$ 66	$ 36	—	—	+$ 30
TOTAL	**$4613**	**$4327**	**$ 59**	**$ 171 (290%)**	**+$230**

Equivalent Industry Cost

Estimate	Cost
CDR Estimate	$4920
MSR Estimate	$4634
TRR Estimate	$4613
SFR Estimate	**$4613**

Billable Item	Cost
5056 Hours	$157,997
Materials	$ 5,000
Overhead	200%
“Industry Cost”	**$478,991**

Acknowledgements

- Scott Sewell and Phil Oakley, HAO/NCAR
- Trudy Schwartz, CU Boulder
- Bobby Hodgkinson, CU Boulder
- Fabio Mezzalira, Sommers Bausch Observatory
- Andrew Dahir and Nicholas Rainville, QB50
- James Mason, MinXSS
- Steve McGuire, CU Boulder

MinXSS CubeSat

QBUS

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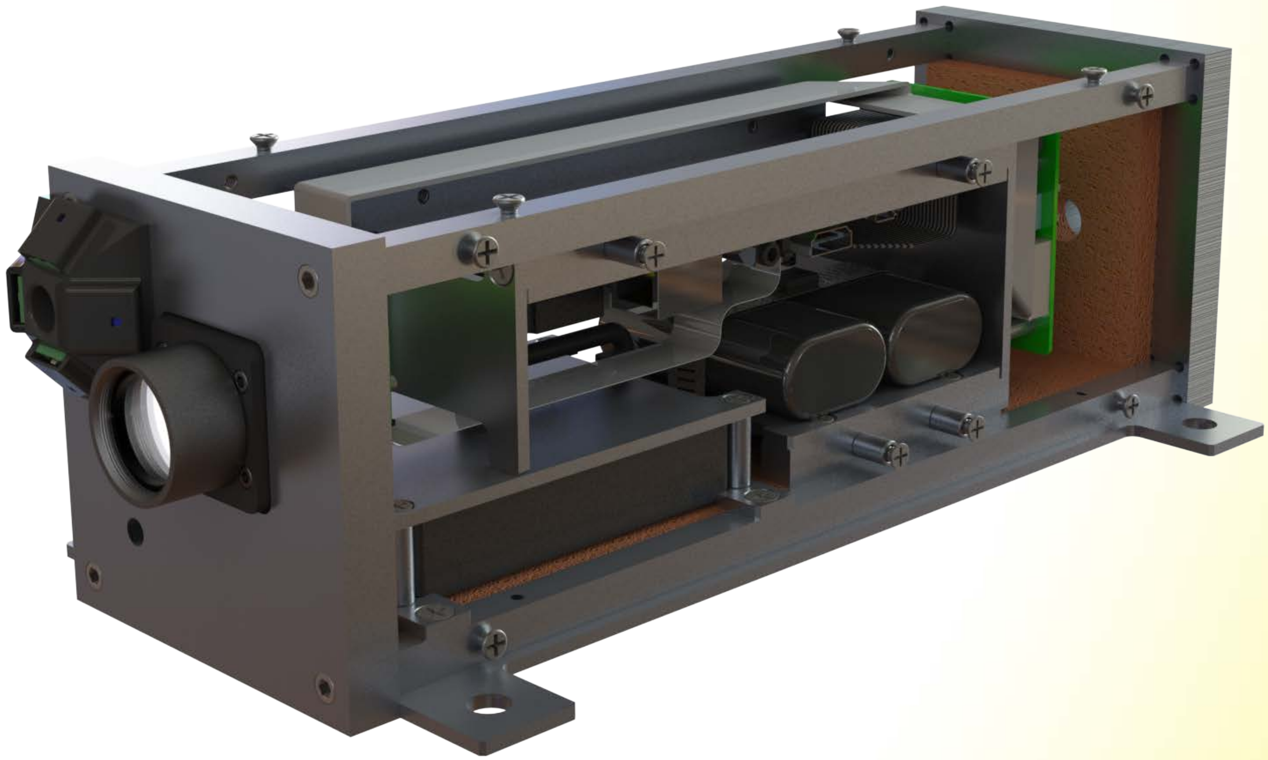
HAO

Ann and H.J. Smead
Aerospace Engineering Sciences
UNIVERSITY OF COLORADO **BOULDER**

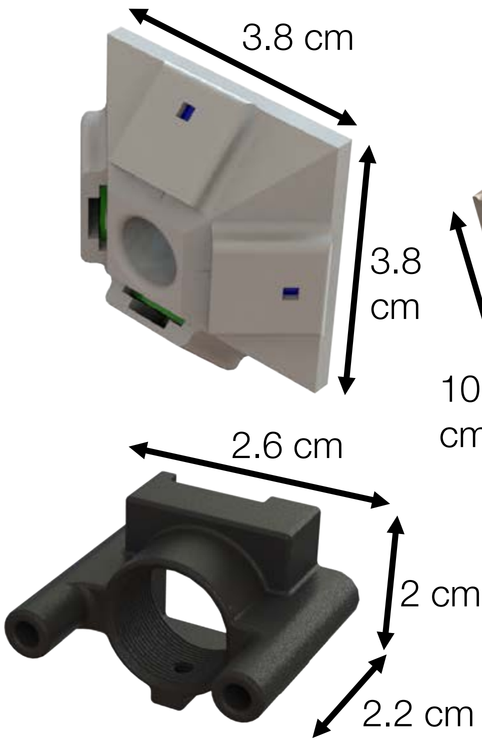
Thank you!

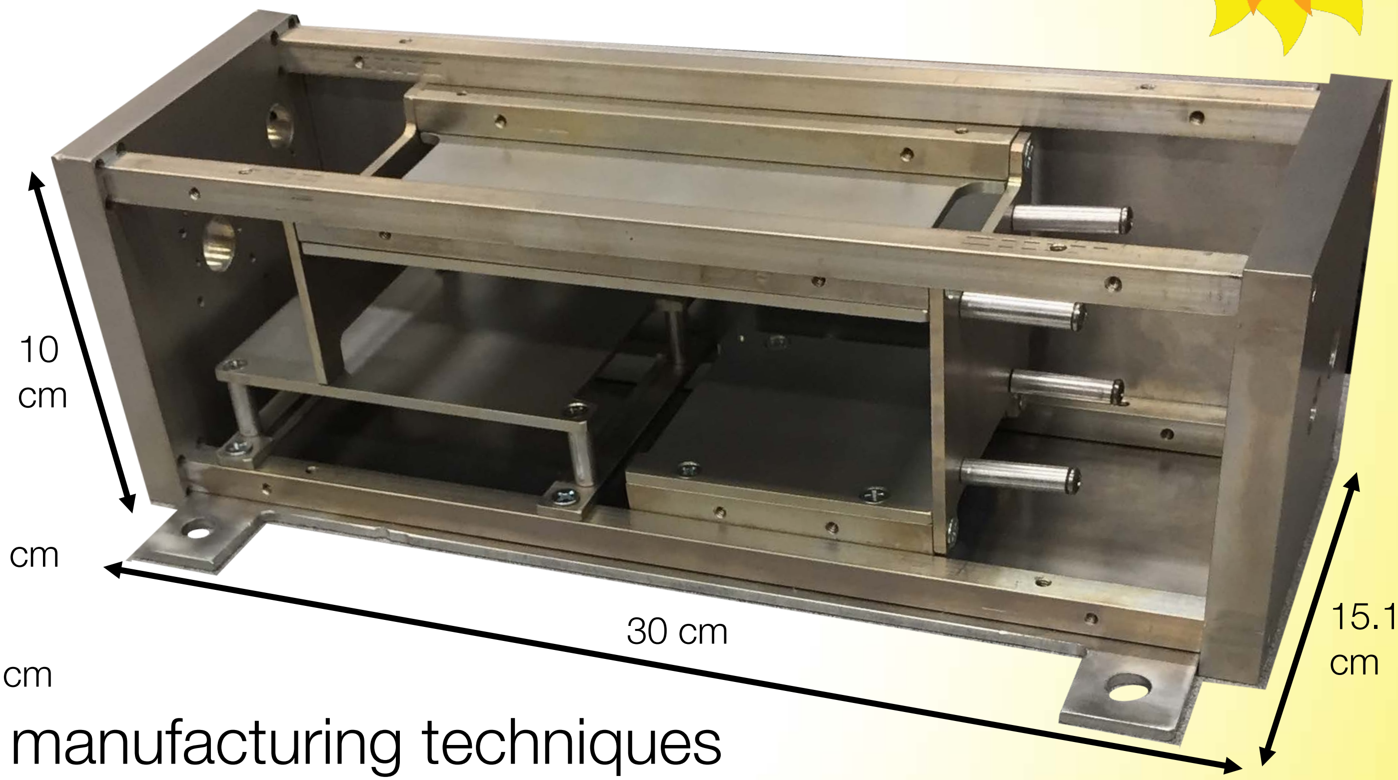
We welcome your questions!



BACKUP SLIDES

Manufacturing Process





- Conventional manufacturing techniques
- Only minor manufacturing issues
- 3D printed parts required several iterations

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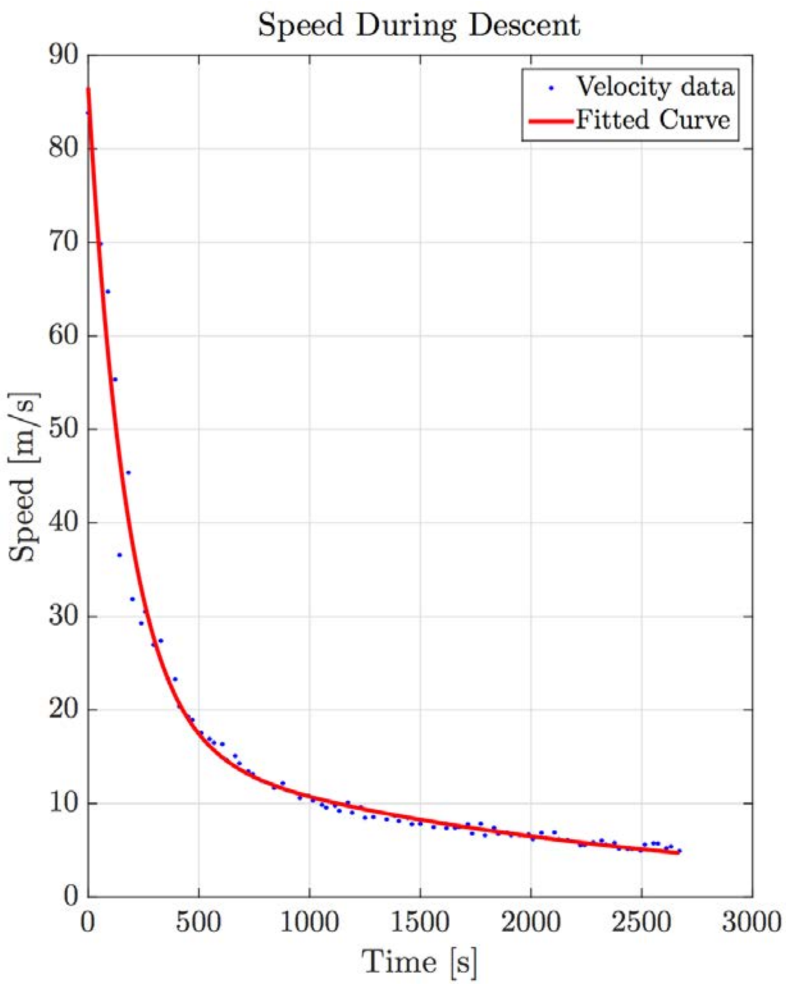
Structural Design Motivations



R3.2: Data storage shall survive landing

- Previous flight data: speed is 5.44 m/s at landing
- Equipped with parachute and crush pads
- Data only taken every ~30 seconds → must infer landing force using Δ in momentum

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Structural Design

From previous data:	$\Delta v = 5.44\ \frac{\text{m}}{\text{s}}$ $m = 2092\ \text{kg}$
Estimated crash duration:	$t_{\text{impact}} = 0.17\ \text{s}$

Duration determined based on height of crush pads and speed

Fundamental equations:
$$F = \frac{m\Delta v}{t} = \frac{(2092\ \text{kg})\left(5.44\ \frac{\text{m}}{\text{s}}\right)}{0.17\ \text{s}} = 67.75\ \text{kN}$$

$$G = \frac{F}{mg} = \boxed{3.30\ \text{Gs}}$$

Landing Impact
3.30 Gs

$\ll$

Flash Drive Rating
1500 Gs

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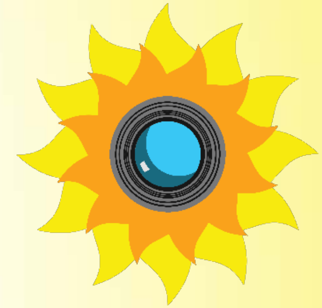


Camera

Field of View Calculation

Known parameters:

Default FOV $= 53.5^\circ$ $\quad h = 2.76$ mm

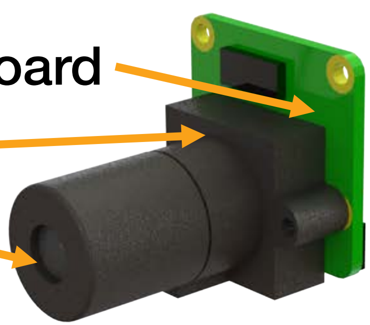
Sun $= 0.5^\circ$ $\quad f = 25$ mm

$$\text{FOV} = 2\tan^{-1}\left(\frac{h}{2f}\right) = \boxed{6.32^\circ}$$

Camera board

Mount

Lens



Neutral Density Filter Calculation

Flux on Ground $= 1050\ \frac{\text{W}}{\text{m}^2}$

Flux at 40 km $= 1200\ \frac{\text{W}}{\text{m}^2}$

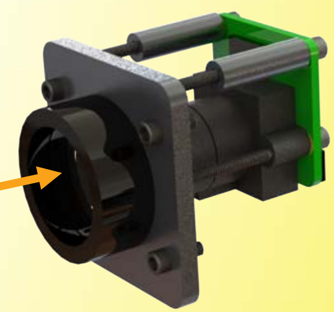
Using flux and size of the sun on the image sensor, find total power:

$$\begin{aligned} &\text{Power on Ground:} && 6.986 \times 10^{-7}\ \text{W} \\ &\text{Power at Cruise:} && 5.721 \times 10^{-5}\ \text{W} \end{aligned}$$

$$\frac{6.986 \times 10^{-7}\ \text{W}}{5.721 \times 10^{-5}\ \text{W}} = \boxed{1.22\%}$$

Result:

Choose filter with
96.875% attenuation
(OD of 1.5)



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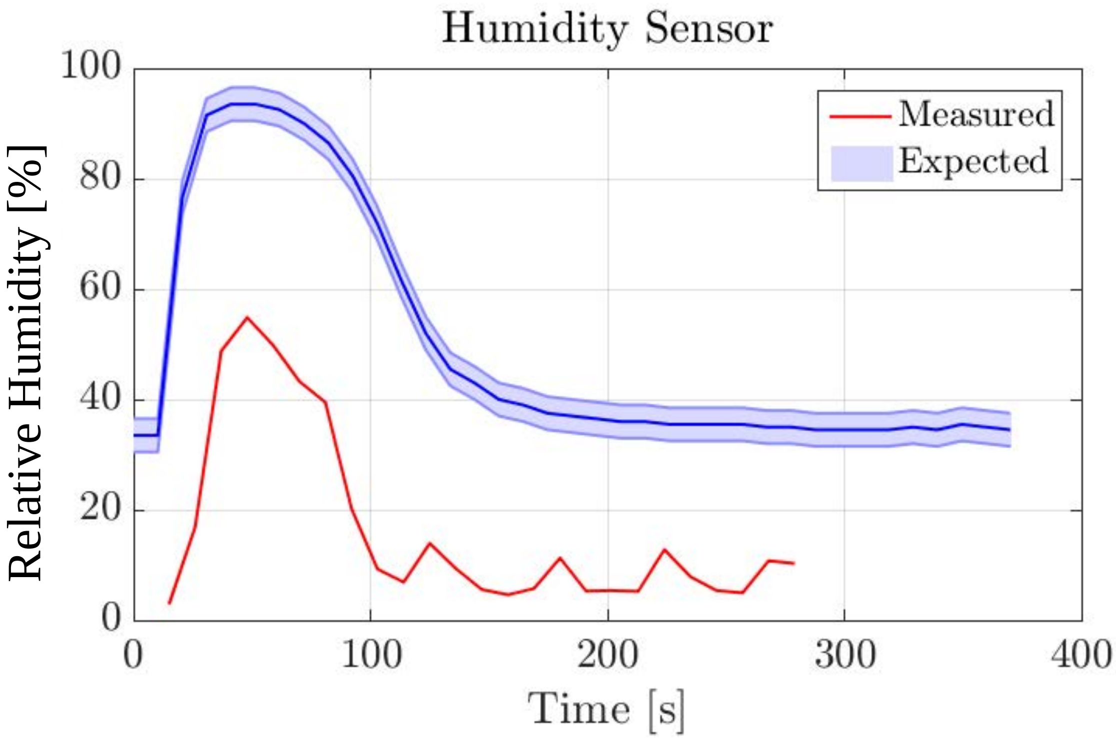
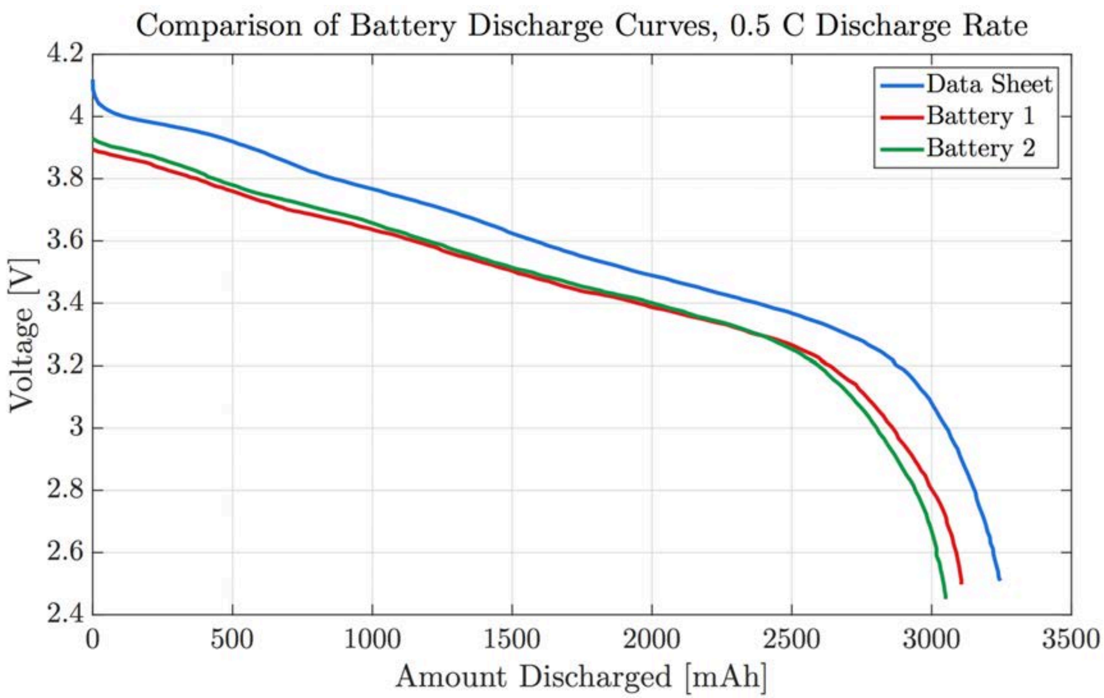
Humidity Sensor Calibration

- Systematic bias of ~36%
- Straightforward adjustment in software



DR 1.2 The system shall take environmental measurements.

Battery Capacity



- Battery trending between the two cells is in family
- Lower than published data, but within starting tolerance of 3.6 to 4.2 V; system noise is approximately 17 mV

C&DH Capacity: Model

Measurement	Data Point Size	Frequency	Total
Spectrometer	8.2 kB	1 s	9.25 GB
External temperature	4 B	1 s	4.6 MB
Internal temps (x6)	24 B	1 s	27.7 MB
Humidity	4 B	1 s	4.6 MB
Photodiode (x4)	32 B	1 s	36.9 MB
Sun angle	4 B	1 s	4.6 MB
Total	8.3 kB	--	9.4 GB

Measurement	Data Point Size	Frequency	Total
Camera images	920 kB	60 s	17.7 GB
Other Data	8.3 kB	1 s	9.4 GB
Total	936.5 kB	--	27.1 GB

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C&DH Capacity: Results

Measurement	Data Point Size	Frequency	Total
Spectrometer	8.19 kB	2.602 s	3.63 GB
External temperature	4 B	2.602 s	1.8 MB
Internal temps (x3)	12 B	2.602 s	5.3 MB
Humidity	4 B	2.602 s	1.8 MB
Photodiode (x4)	16 B	2.602 s	7.1 MB
Sun angle	0 B	2.602 s	0 B

Measurement	Data Point Size	Frequency	Total
Camera images	152 kB	60 s	3.63 GB
Other Data	8.24 kB	2.602 s	3.65 GB
Total	160.24 kB	--	7.28 GB

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Light Attenuation

Test	mA
Current without ND Filter	10.07
Current with ND Filter (Expected)	1.007
Current with ND Filter (Actual)	0.97

$$OD = \log_{10} \frac{I_0}{I}$$

Error = 3.6%