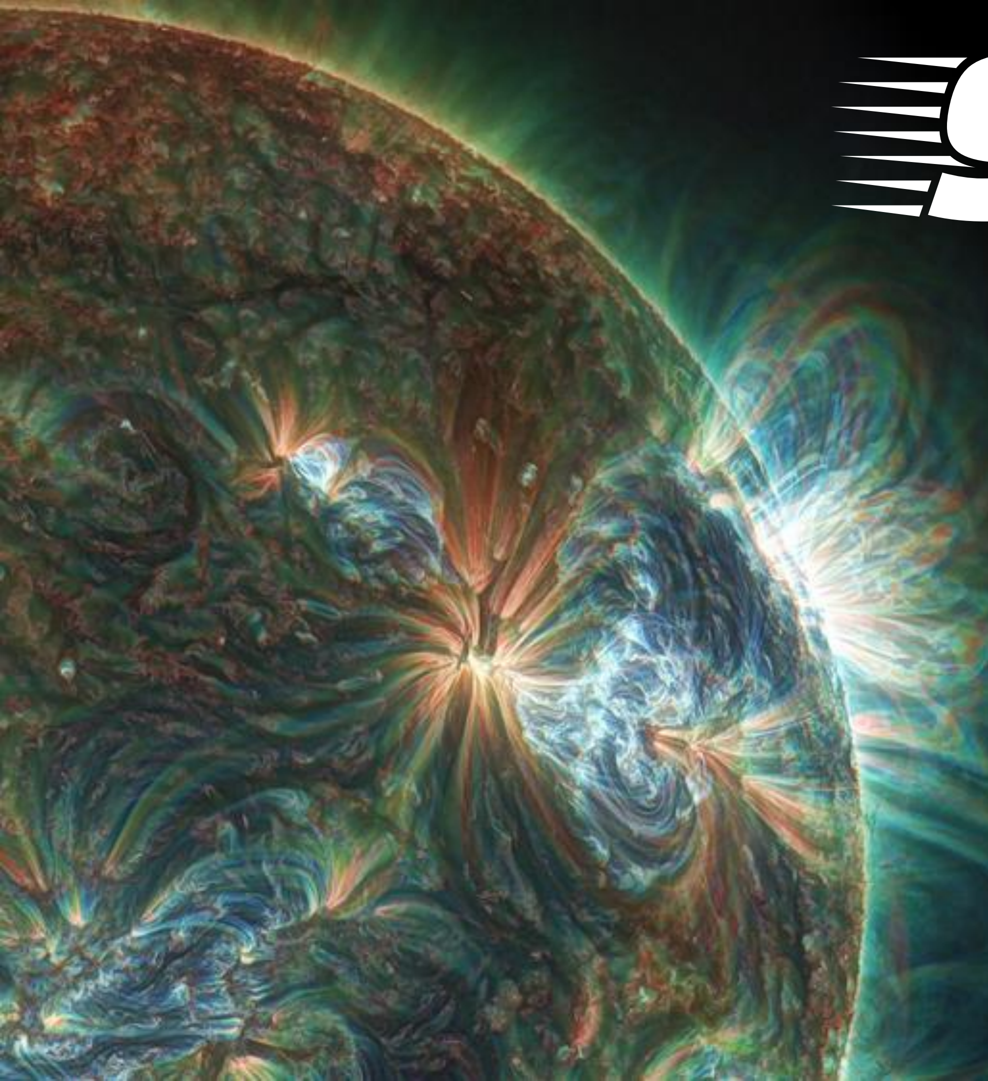


STOUT

Spectropolarimeter
Telescope
Observatory for
Ultraviolet
Transmissions

Presenters:

1. Andrew Arnold
2. Caleb Beavers
3. Darin Brock
4. Matt Funk
5. Ian Geraghty
6. Andrew Lux
7. Dawson Stokely

Advisor:
Francisco López Jiménez

Team Members:

1. Zach Allen
2. Joshua Bruski-Hyland
3. Ryan Lynch
4. Matthew Normile

Customer:
NCAR High Altitude Observatory

1. Phil Oakley
2. Scott Sewell

Project Purpose / Objectives

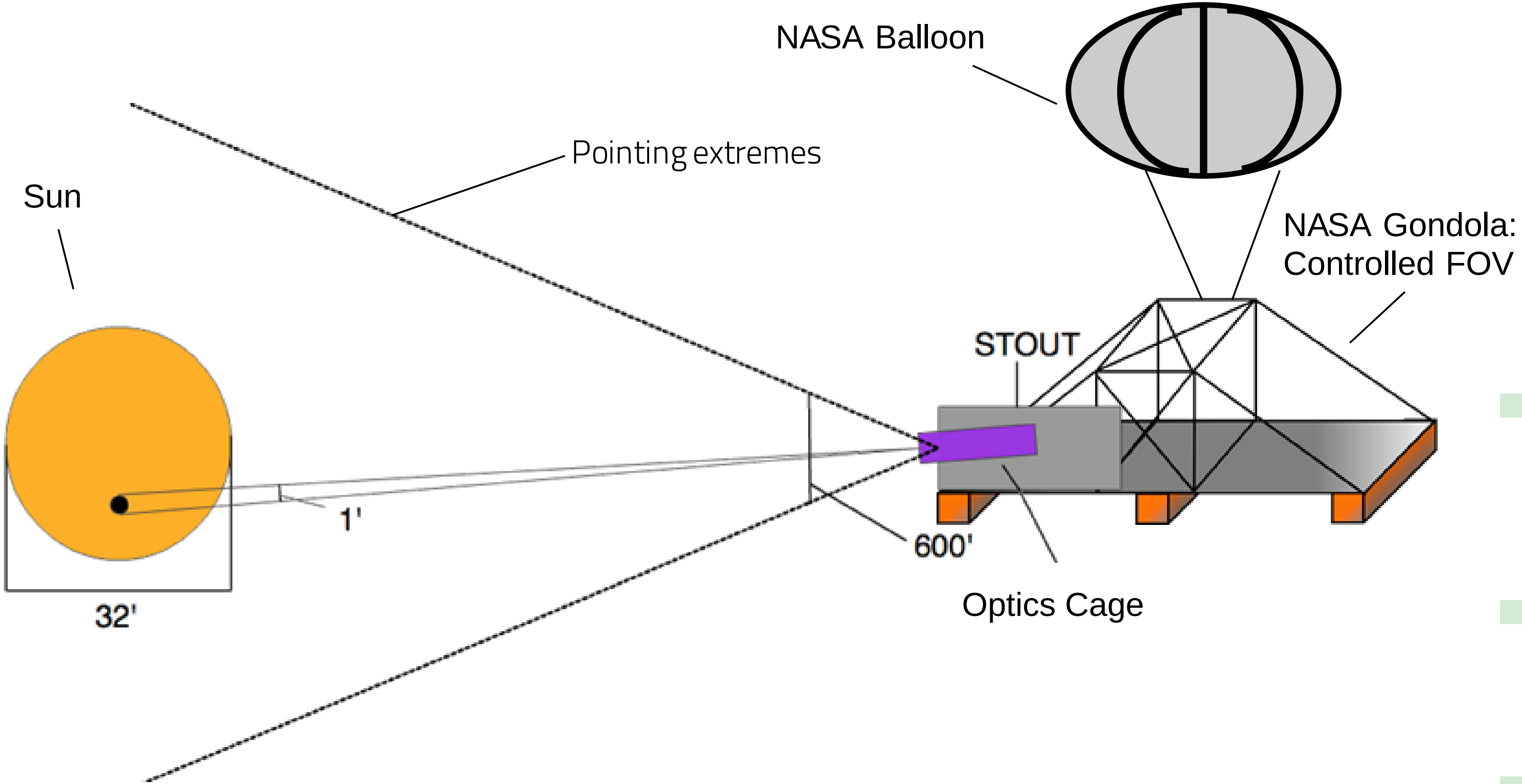
Motivation

- Solar phenomena present catastrophic risks to ground and space based systems
- Models can be used to determine preconditions in the magnetic structure that lead to solar phenomena
- Solar photosphere and transition region (solar atmosphere) emit UV light
- UV light passes through the sun's magnetic field and is polarized to align with the field vector
- Measurements of UV spectra at varying polarization angles can be used to model solar magnetic field structure

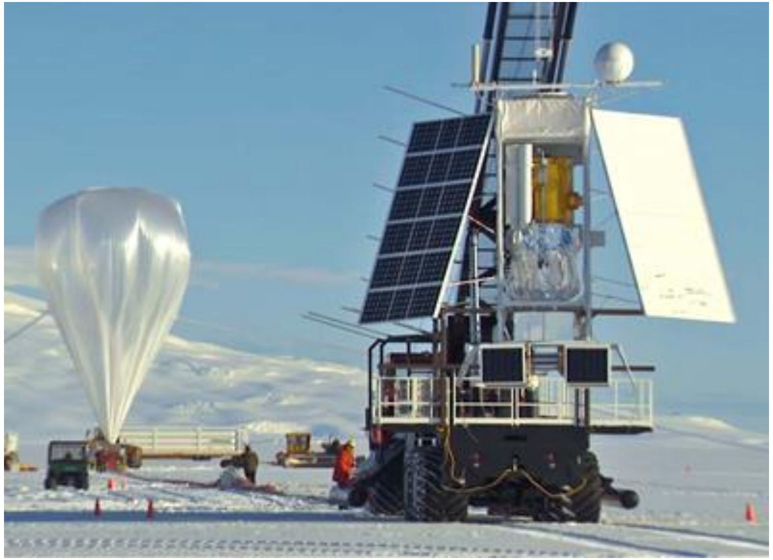
Mission Statement

STOUT will design and manufacture a 3U CubeSat-style payload capable of high-altitude balloon flight, which integrates with last year's RADIANCE project. The module will scan the body of the sun to measure sunlight intensity as a function of position on the sun, polarization angle, and wavelength. Ambient atmospheric data, pointing attitude information, and images will be recorded as well. The team will utilize a variety of ground tests that simulate the expected high altitude environment in order to calibrate the module’s data collection systems and verify the payload’s flight readiness.

Pointing Explanation



NASA Gondola



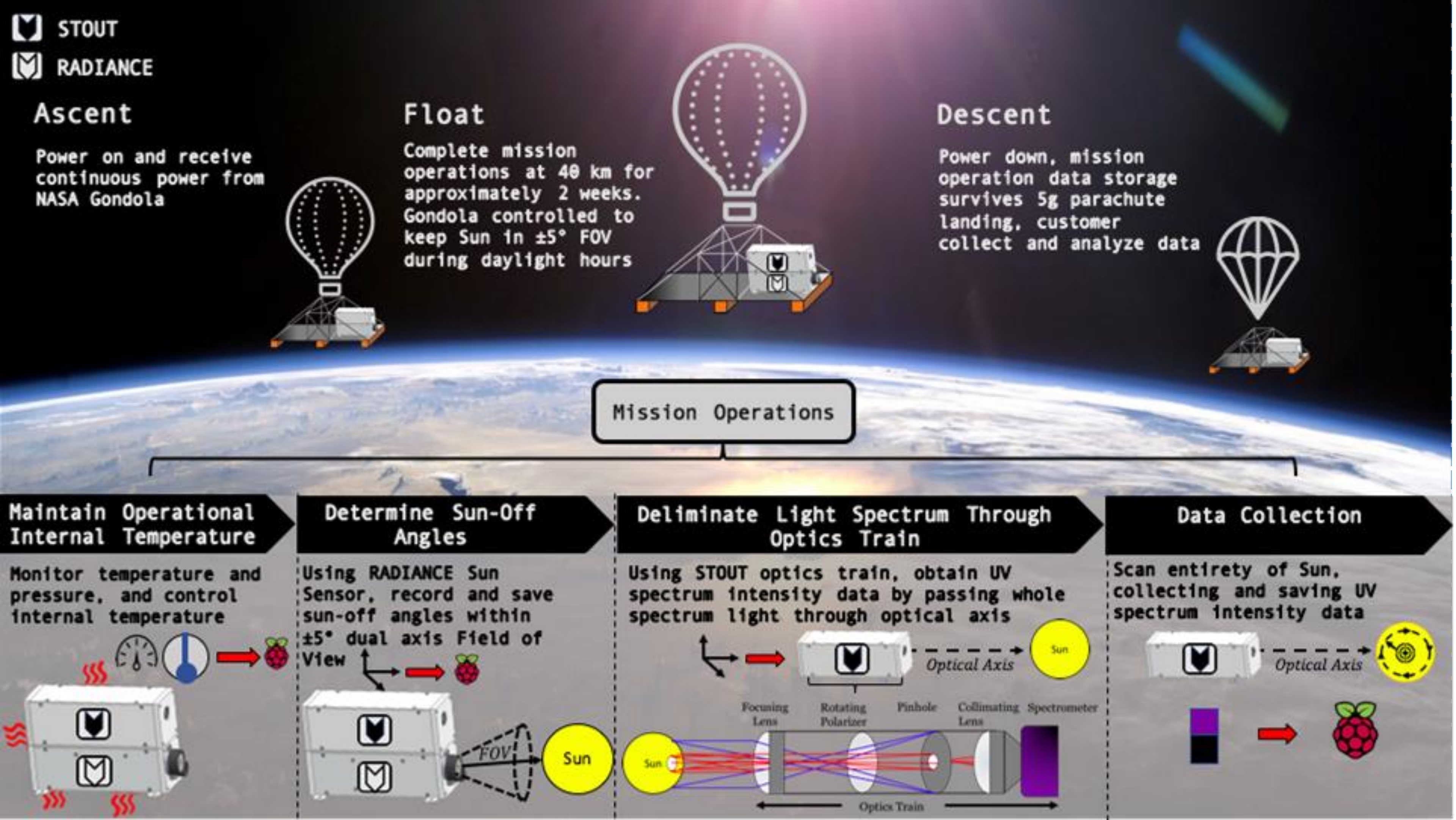
Mission

- Ground: 8 Hours
  - Powered on and systems check
- Ascent: 2 hours
  - Launched from NM or Antarctica
- Flight: 2 weeks at 40 km
  - Gondola platform puts the system FOV within +/- 5° of the Sun
  - Solar irradiance data collected
  - Polarized UV spectra collected
- Descent: 1 hr
  - Customer retrieves data

Project Objectives

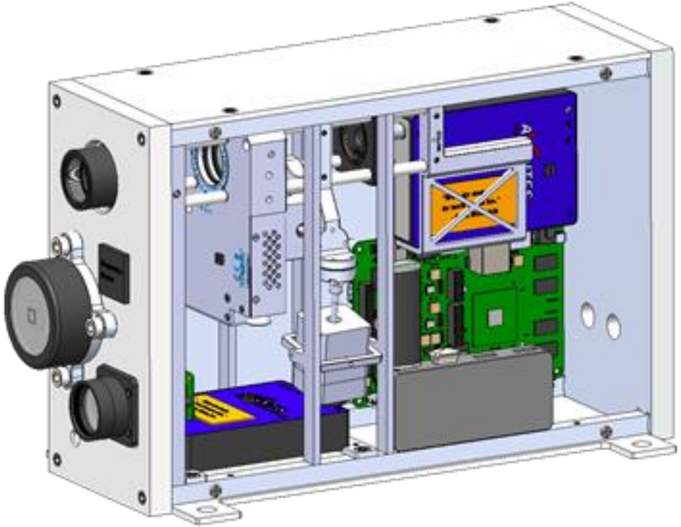
STOUT shall be capable of…

1. Integrating with RADIANCE module and NASA high altitude balloon gondola
2. Enduring and collecting data during the conditions of a 40 km high-altitude balloon flight
3. Determining its attitude relative to the sun
4. Collecting variable polarization UV spectra at various points on the sun's surface
5. Capturing images of the sun in the visible spectrum
6. Surviving a descent under parachute and impacting with the ground so data is retrievable by customer


STOUT
RADIANCE
Ascent
Power on and receive continuous power from NASA Gondola
Float
Complete mission operations at 40 km for approximately 2 weeks. Gondola controlled to keep Sun in ±5° FOV during daylight hours
Descent
Power down, mission operation data storage survives 5g parachute landing, customer collect and analyze data
Mission Operations
Maintain Operational Internal Temperature
Monitor temperature and pressure, and control internal temperature
Determine Sun-Off Angles
Using RADIANCE Sun Sensor, record and save sun-off angles within ±5° dual axis Field of View
FOV
Sun
Deliminate Light Spectrum Through Optics Train
Using STOUT optics train, obtain UV spectrum intensity data by passing whole spectrum light through optical axis
Optical Axis
Sun
Focusing Lens
Rotating Polarizer
Pinhole
Collimating Lens
Spectrometer
Optics Train
Data Collection
Scan entirety of Sun, collecting and saving UV spectrum intensity data
Optical Axis

Design Solutions

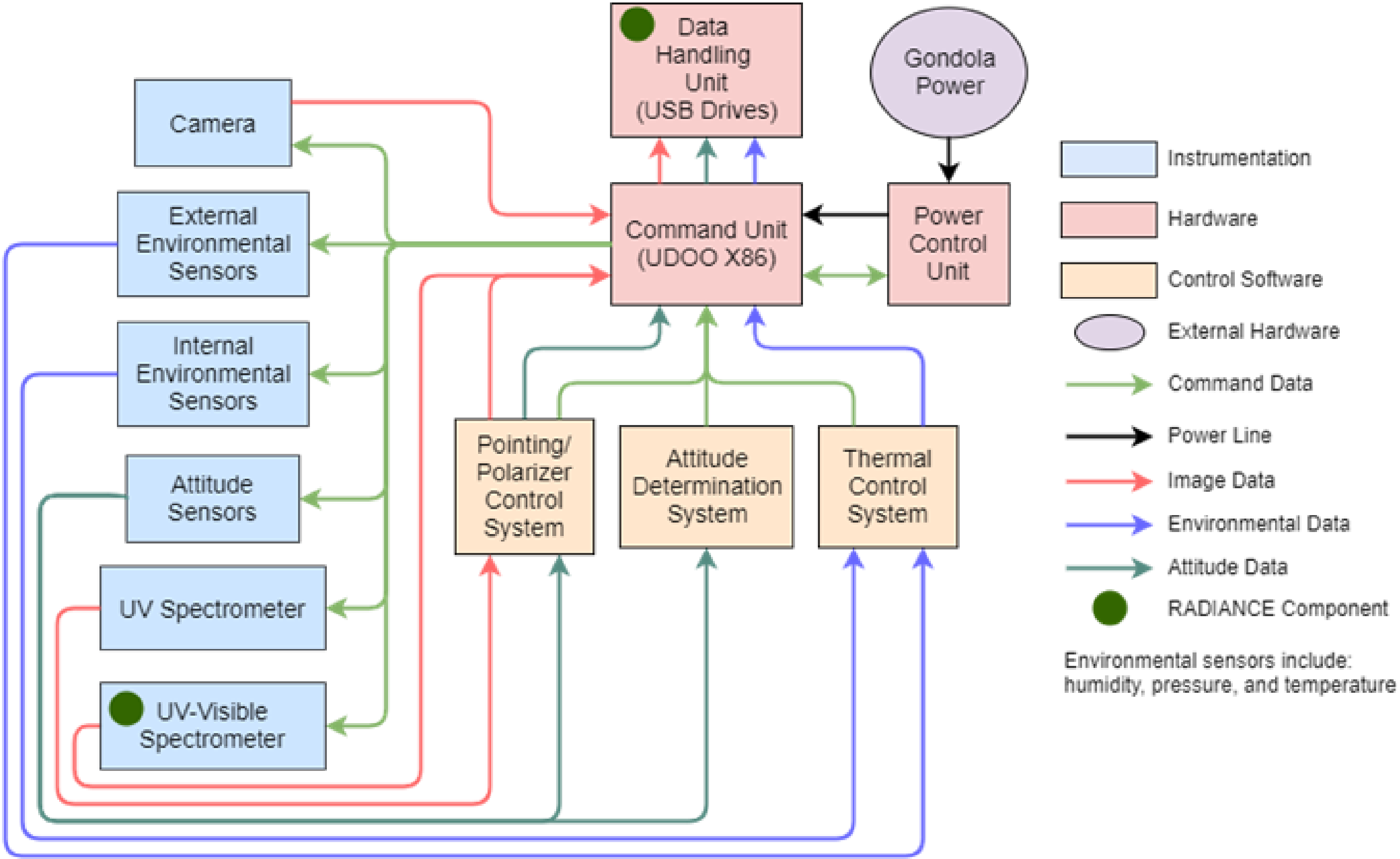
System Overview



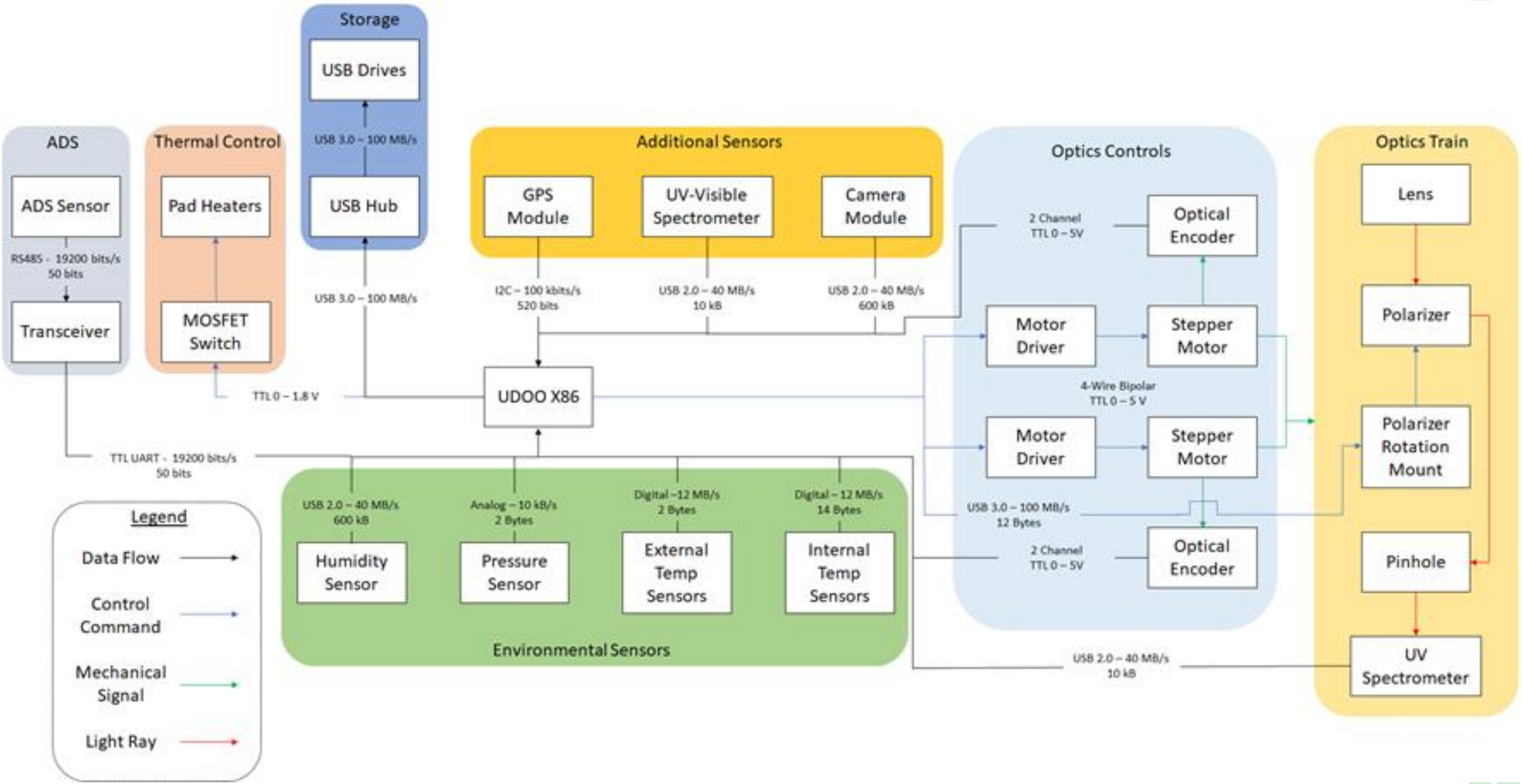
Summary

Parameter	Values
Dimensions	10x20x30 cm
Mass	4.4 kg
Power Consumption	74.5 W
Flight Environment	-70℃ - 20℃
Materials	Aluminum 6061 (Structure) Polyisocyanurate (Insulation)

Functional Block Diagram

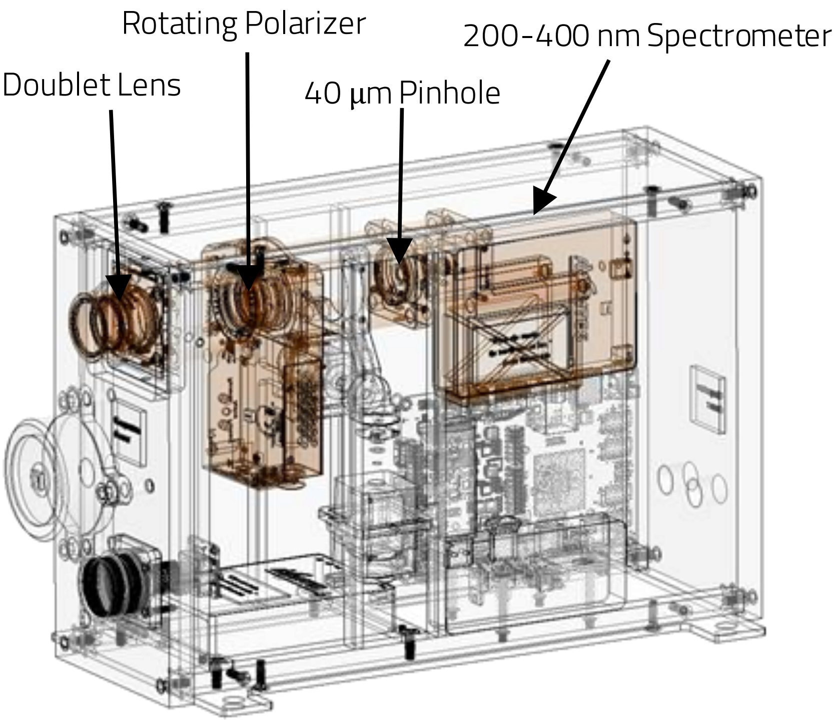


Hardware Architecture Diagram



Design Solutions

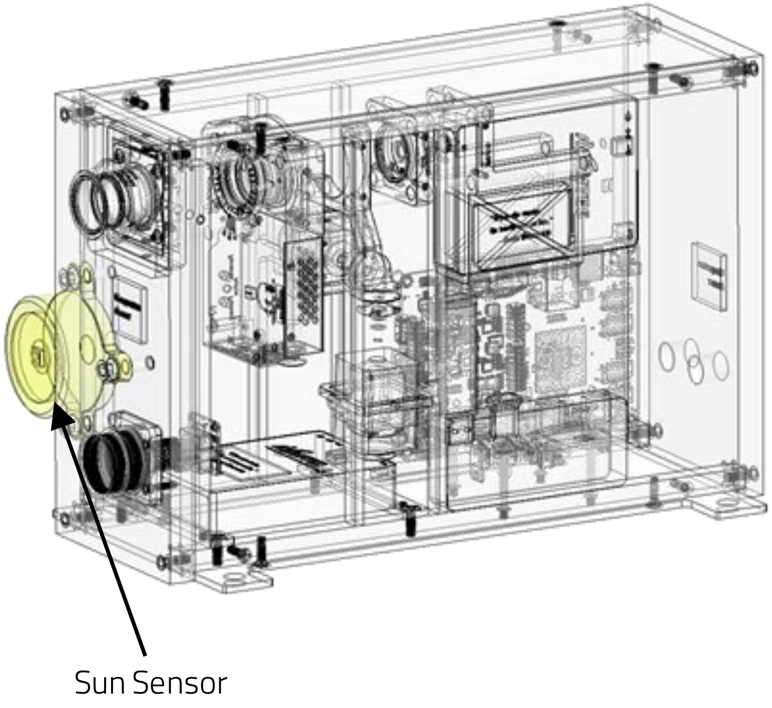
Optics



Components

- Thorlabs UV Doublet Lens: Focus light in UV spectrum
- Thorlabs Mounted Wire Grid Polarizer: Control input light polarization angle
- Thorlabs Precision Pinhole: Isolate spot on Sun
- Avantes Collimating Lens: Feed light into spectrometer
- Avantes Spectrometer: Measure light intensity as function of wavelength
- Thorlabs Optics Cage: Mount and align optical components

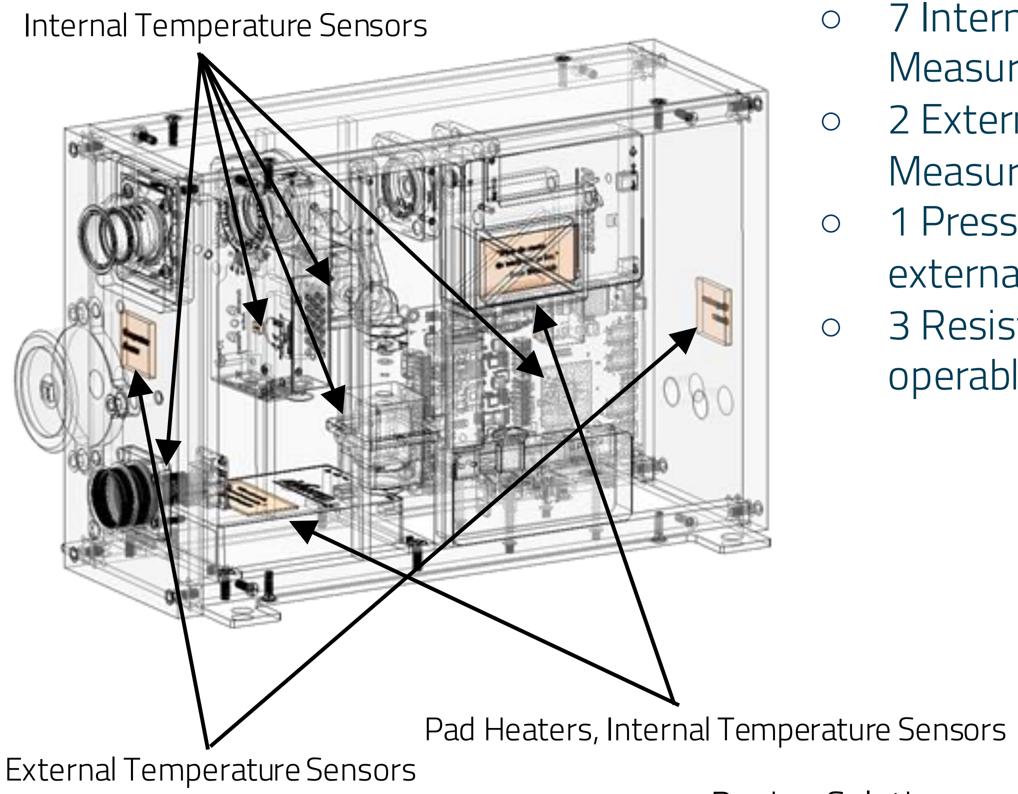
Attitude Determination System



Components

- Solar Mems Sun Sensor: Determines Sun's position in the system's FOV
- Quadrant photodetector used to measure off-sun angles from generated photocurrents

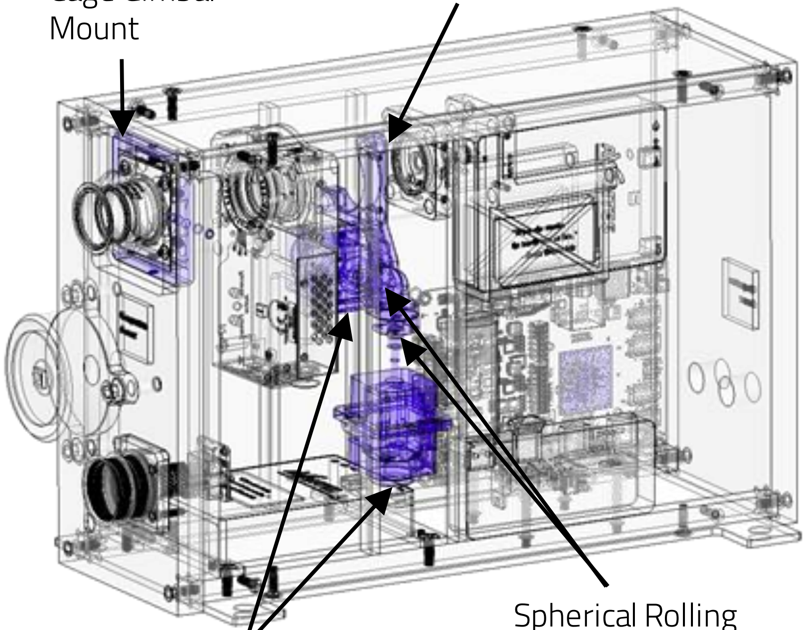
Environmental Monitoring & Control System



Components

- 7 Internal Temperature Sensors: Measure internal temperature
- 2 External Temperature Sensors: Measure External Temperature
- 1 Pressure Sensor: Measure external pressure
- 3 Resistive Pads: Keep module at an operable temperature

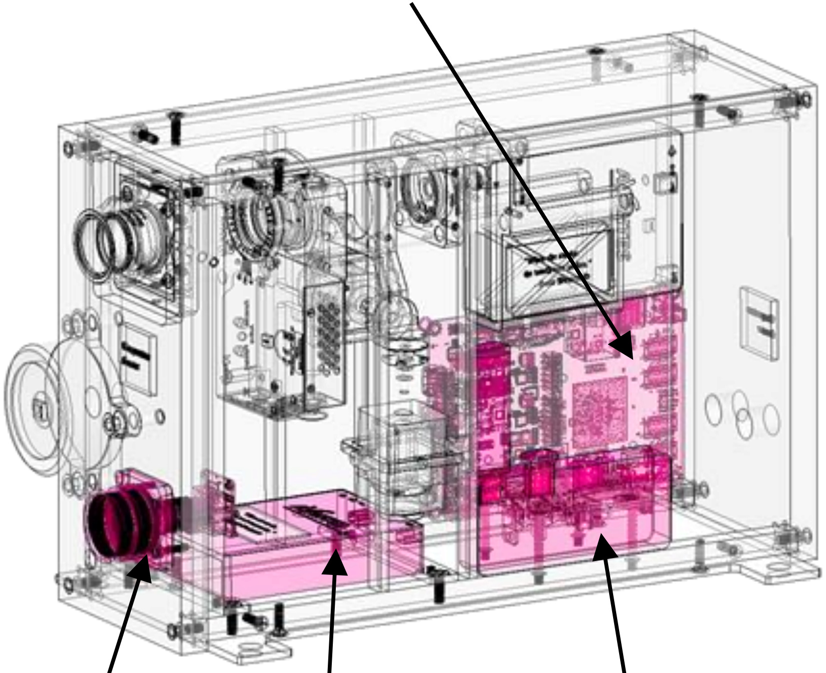
Pointing Controls



Components

- Custom Cage System Gimbal Mount
- 2 Haydon Kerk Pittman Hybrid Stepper Motor Non Captive Linear Actuator
- Custom Motor Casings
- Custom Motor Gimbal Mounts
- Custom Cage System Pusher Arm
- Hephaist Spherical Rolling Joints

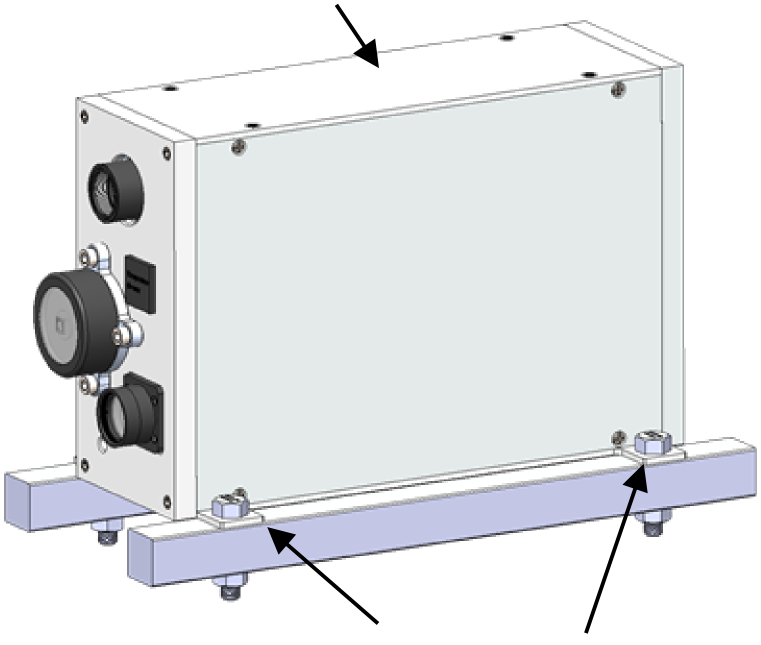
CPU and Data Acquisition



Components

- UDOO x86 Ultra
  - 2.56 GHz Quad Core processor for control computation
  - Intel Curie Microcontroller for motor control
  - USB 3.0 for fast write rates
- USB Thumbdrives for data storage
  - One MX-ES Ultra 64 GB
  - One Samsung Fit 64 GB
- Sabrent 4 Port USB 3.0 Externally Powered Hub
- RADIANCE Spectrometer
- 2 MP Visible Camera

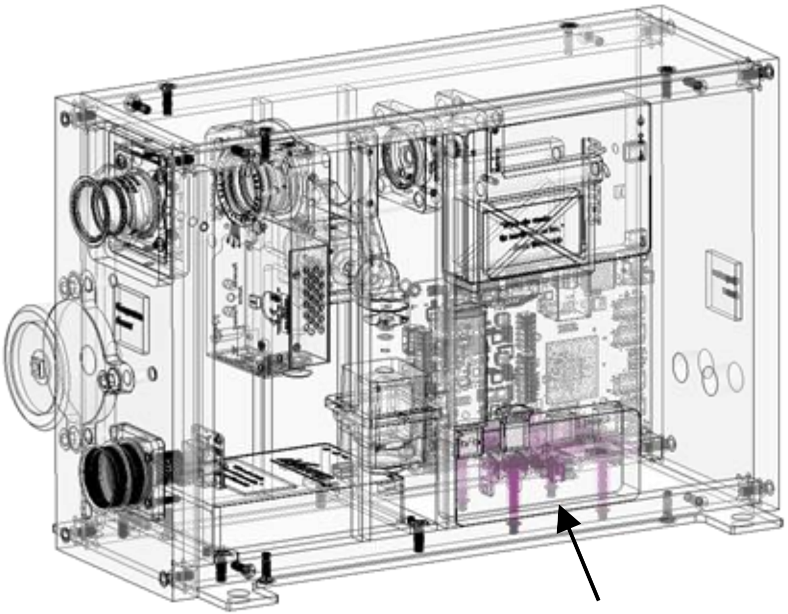
Structure



Components

- Aluminum 6061: Exterior plates and interior struts
- Tabs attach to balloon gondola

Electrical Power System



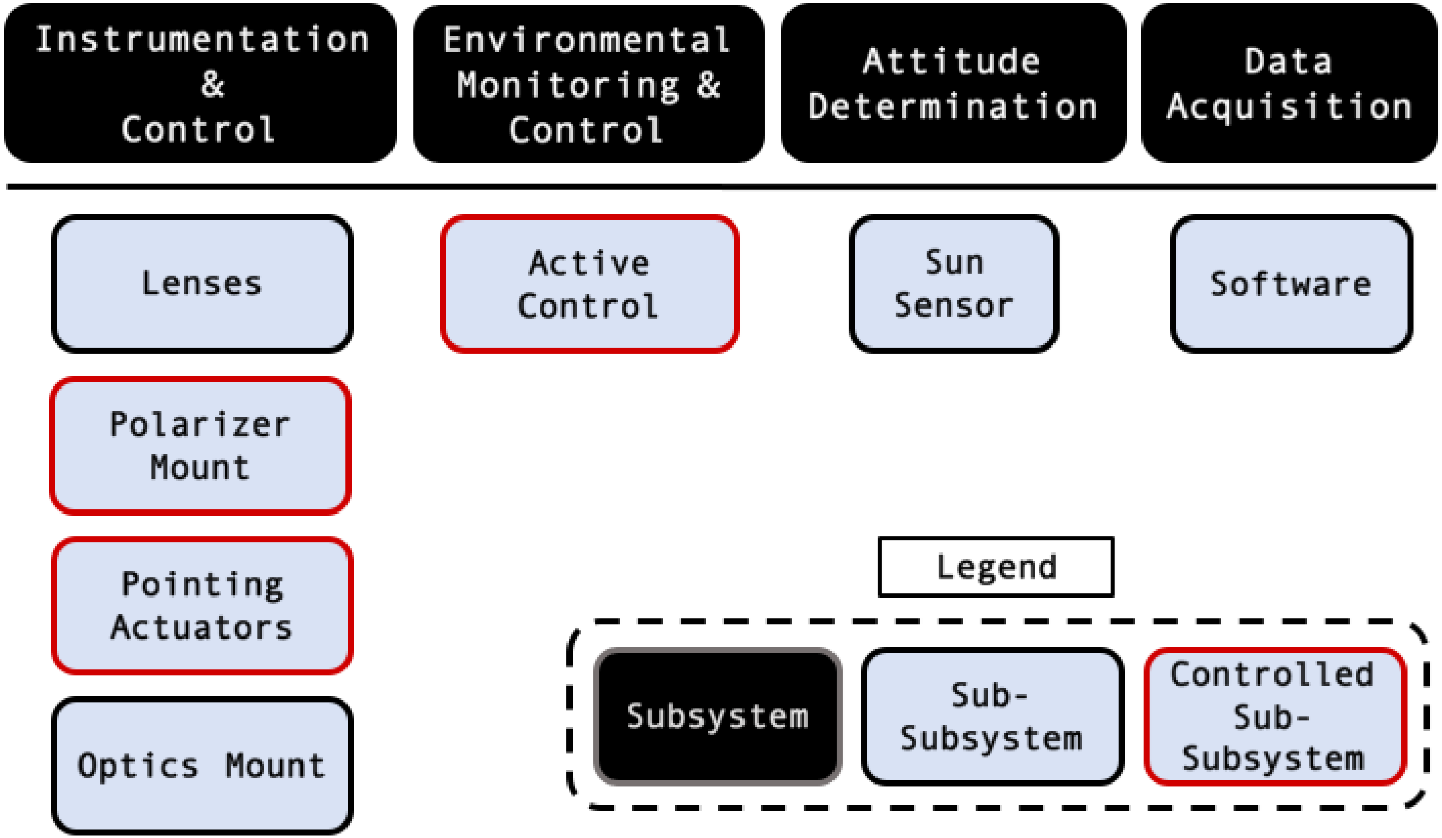
Printed Circuit Board

Components

- Custom PCB to distribute power to subsystems

Critical Project Elements

Critical Project Elements



Design Requirements and Their Satisfaction

Functional Requirements

- **FR 1:** The system shall integrate with RADIANCE module
- **FR 2:** The system shall take variable polarized UV spectrum measurements at various points on the sun's surface
- **FR 3:** The system shall determine its attitude
- **FR 4:** The system shall take environmental measurements
- **FR 5:** The system shall survive the environmental conditions of a high altitude balloon flight to 40 km
- **FR 6:** The system shall record data
- **FR 7:** The system shall interface with the NASA balloon gondola

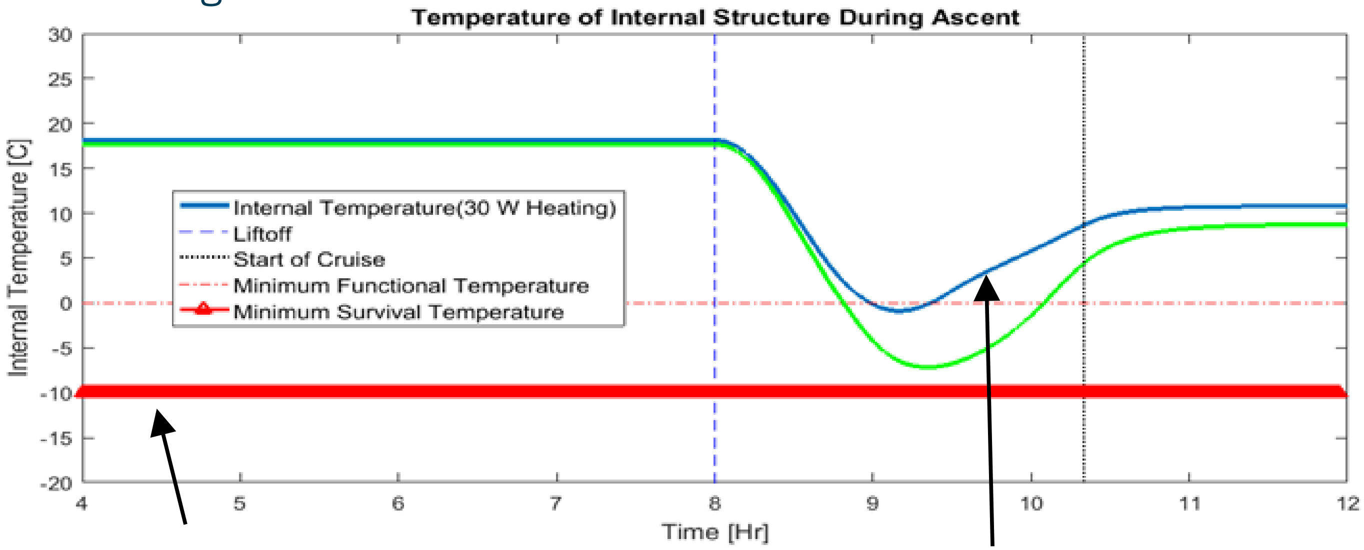
EMCS Requirements

FR5: The system shall survive the conditions of a high altitude balloon flight up to 40km

Requirement	Description
5.1	During ascent and descent the system shall survive external temperatures ranging from -65°C to 20°C
5.2	During cruise the system shall operate under external temperatures ranging from -25°C to -15°C
5.3	The system shall operate at pressure values of 100 kPa to 10 Pa

EMCS Requirements

- EMCS proven valid during cruise and descent, however ascent operational temperature margins were too close to validate through 1D model



Survival temperature determined by spectrometer survivability temperature

Internal Temperature (20 W Heating)

Design Requirements: EMCS

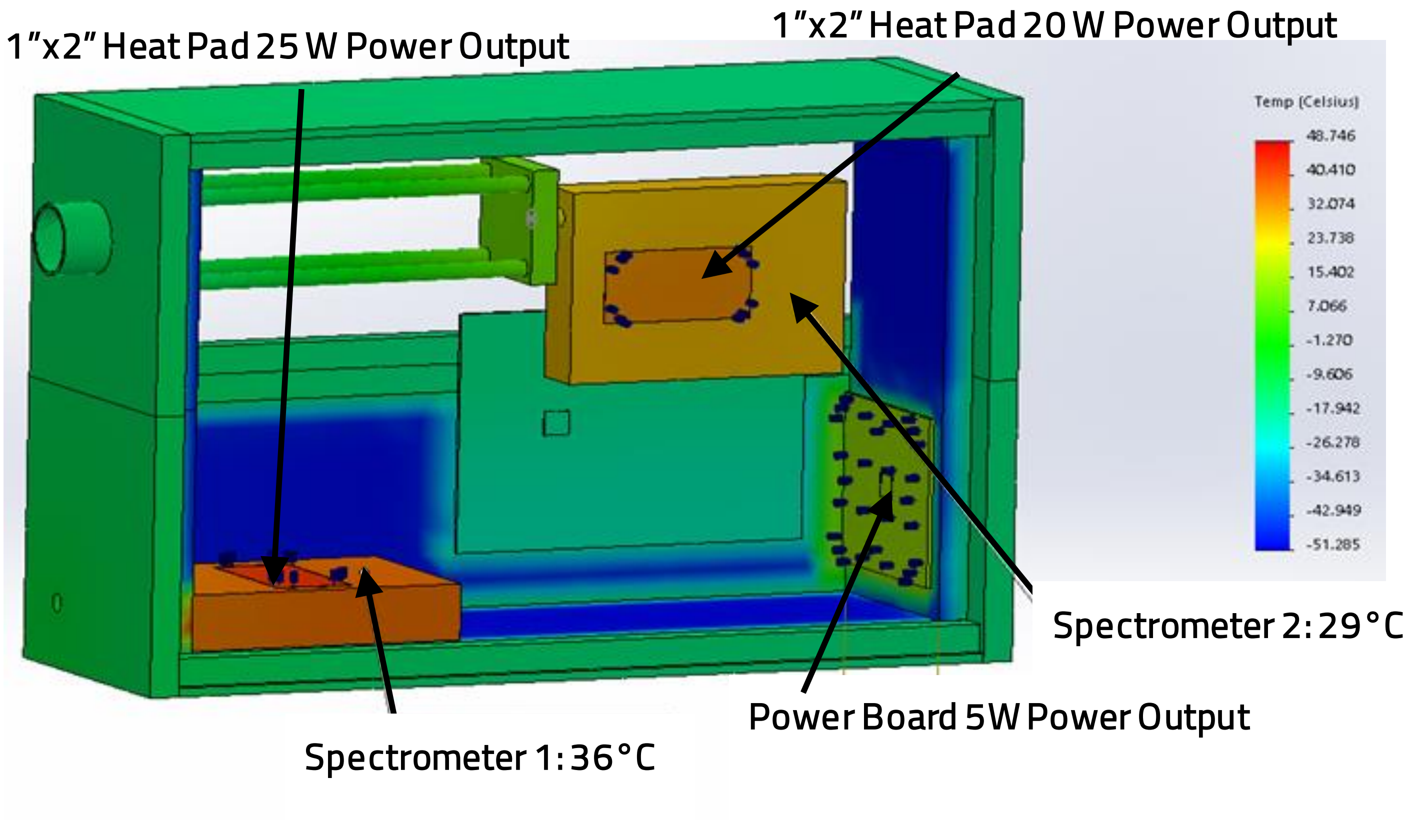
Solidworks 3D Thermal Modeling

- Partial transient model simulated at harshest ascent condition of approximately -65°C at 16 km altitude
- Assumptions
  - Perfect thermal conduction through bonded contacts
  - Convection, conduction and radiation accounted for
  - Power board, and heat pads are only notable heat sources (all other systems not operating during ascent)

Initial Conditions

Item	Value
STOUT Internal Temp.	15°C (STD sea level)
Ambient Temperature	-65°C (Lower temperature limit of ascent)
Air Convective Heat Transfer Coefficient (External and Internal)	~5 W/m^2K

Expected Spectrometer Temperatures at -65°C Environment



Design Requirements: EMCS

Future EMCS Development

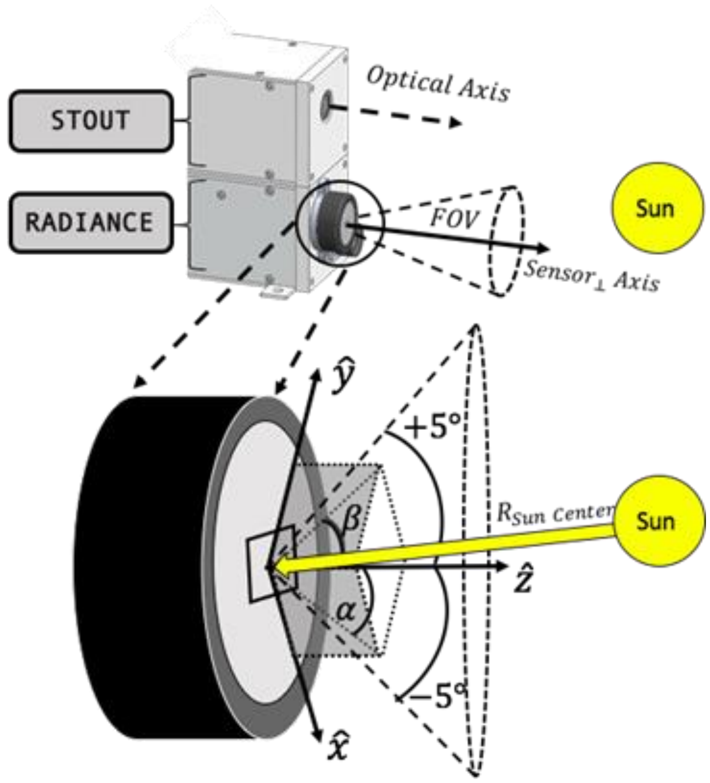
- Develop Full transient model of ascent, cruise, and descent of mission flight
  - Allows for optimization of EMCS (i.e. resistive pad placement and size, total power usage through various flight phases, etc.)
- Verification of EMCS
  - TVAC chamber testing to verify thermal system is suitable for STOUT flight
  - Possible use of environmental chamber for harsher conditions

Attitude Determination Requirements

FR3: The system shall determine its attitude relative to the Sun center

Requirement	Description
3.1	The off-light source angle attitude shall be determined to within 3′ (0.05°) of light source center
3.2	Attitude data shall be recorded synchronously with instrument data
3.3	Attitude data shall be interfaced with instrumentation pointing control

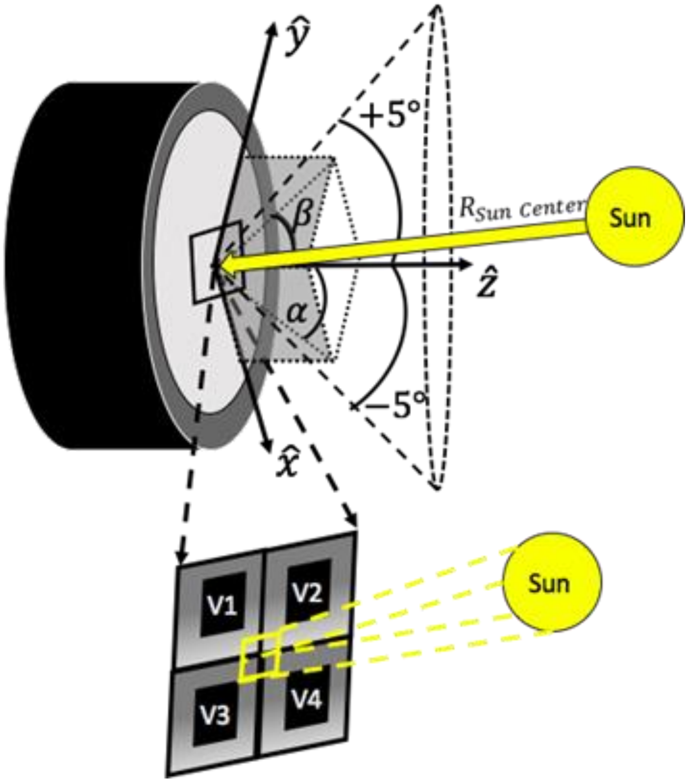
Attitude Determination System



Solar Mems Sun Sensor

- Quadrant photodetector used to measure off-sun angles from generated photocurrents for optics pointing control
- Field of View: dual axes ± 15°
- Accuracy: ± 0.02°
- Serial RS 485 Communication
- Output in Hex
- Requires calibration in conjunction with optical axis

Attitude Determination System



$$x_1 = V_3 + V_4 \qquad y_1 = V_1 + V_4$$

$$x_2 = V_1 + V_2 \qquad y_2 = V_2 + V_3$$

$$F_x = \frac{x_2 - x_1}{x_2 + x_1} \qquad F_y = \frac{y_2 - y_1}{y_2 + y_1}$$

$$\alpha = arctan(C * F_x) \qquad \beta = arctan(C * F_y)$$

Parametric Value (C)
∗ Dependent on Sensor ∗

Sun Off-Angles (α & β)

- Communicates the sun's position relative to field of view to the system
- Data saved and used in optics controls

Optical System Requirements

FR2: Take variable polarization angle UV spectrum of multiple points on the Sun

Requirement	Description	Level Met
2.1	Isolation of <= 1′ (0.0167°) spot in the FOV	1
2.2	Take spectrum measurements over the 270 - 400 nm range	3
2.3	Rotate polarizer with <= 0.5° accuracy	2
2.4	Pointing capabilities of +/- 1° in azimuth and +/- 5° in elevation	1

Optical System

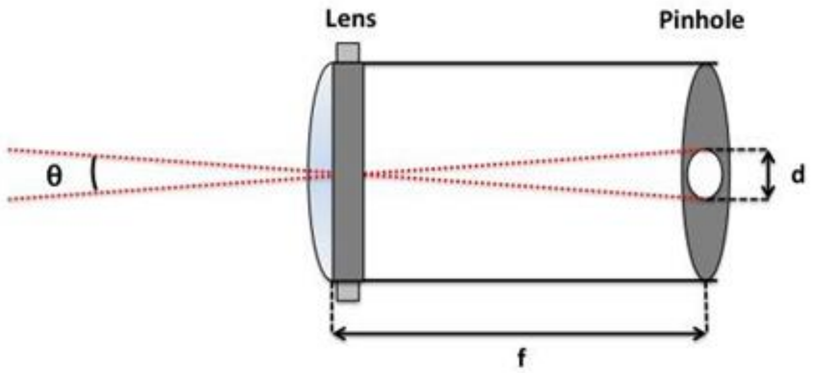
FR 2.1: Isolation of <= 60" (0.0167°) spot in FOV

- **Relevant Components**
  - Thorlabs ACA254-UV lens with a 150 mm focal length
  - Thorlabs Precision Pinhole with a 40 μm diameter
- **Sources of Error**
  - Manufacturing error of lens focal length (+/- 1.5 mm)
  - Human error in placing the pinhole directly in the focal plane of the lens (+/- 1 mm)
  - Manufacturing error of pinhole diameter (+/- 3 μm)

Pinhole Diameter: d = 40 +/- 3 μm
Lens Focal Length: f = 150 +/- 1.8 mm

Isolated Spot Size

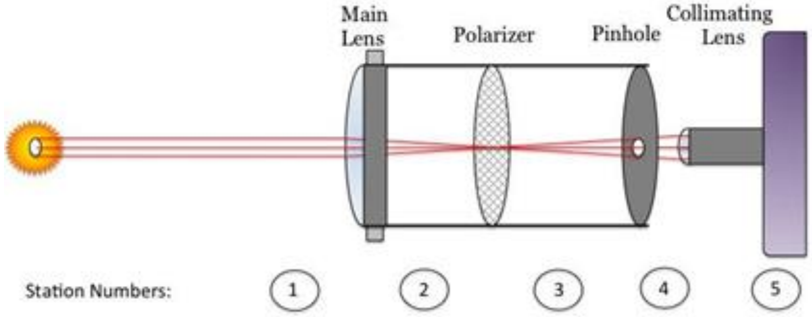
$\theta = 2\tan^{-1}(d/2f) = 55 +/- 7$ "



Optical System

FR 2.2: Take spectrum measurements over the 270 - 400 nm range

- **Relevant Components**
  - Avantes AvaSpec Mini 2048 Spectrometer with a 200-400 nm grating
  - Avantes COL-UV/VIS Collimating Lens
  - Thorlabs Precision Pinhole with 40 µm diameter
  - Thorlabs ACA254-UV Lens
  - Thorlabs Ultrabroadband Wire Grid Polarizer



Power at Station 5 used to test system to set an appropriate spectrometer exposure time

200 - 400 nm Flux Budget

Station	Total Power
1	41.8 mW
2	38.7 mW
3	23.7 mW
4	19.5 µW
5	18.1 µW

Design Requirements and Satisfaction

Optical System

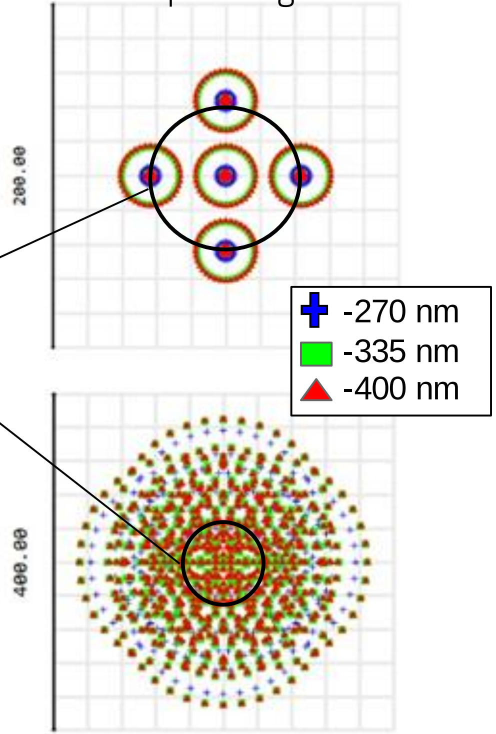
➢ Improper placement of the pinhole relative to the lens degrades focusing quality

60" Spot Diagrams

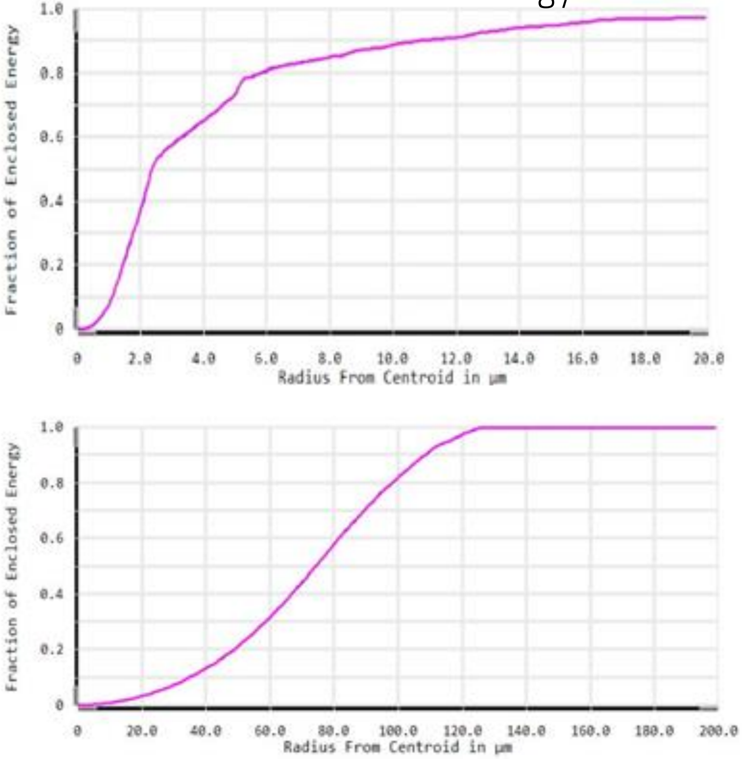
Perfectly in focal plane

40 µm Pinhole Diameter

Including manufacturing and human error (+/- 1.8 mm)



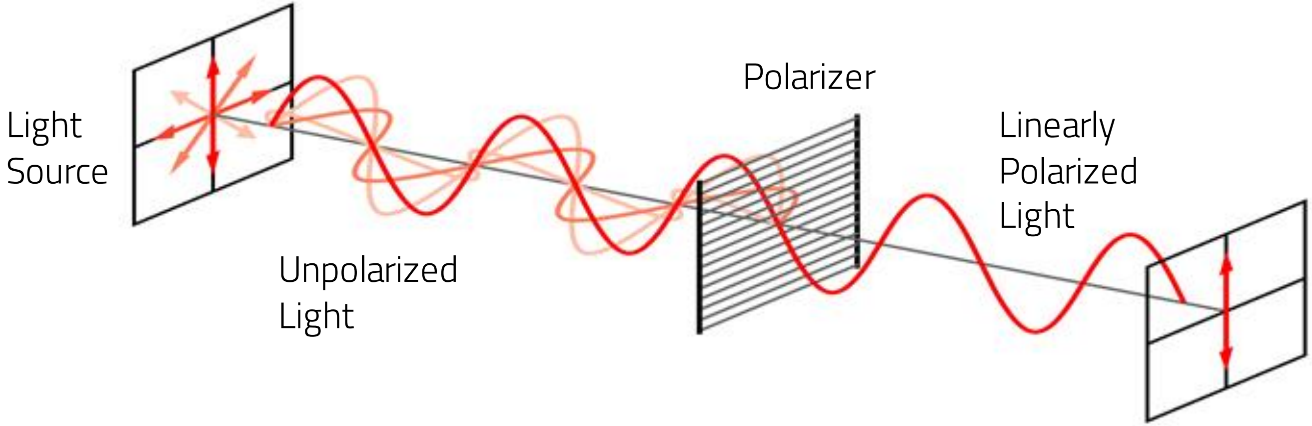
60" Enclosed Energy



Optical System

FR 2.3: Rotate polarizer with <= 0.5° accuracy

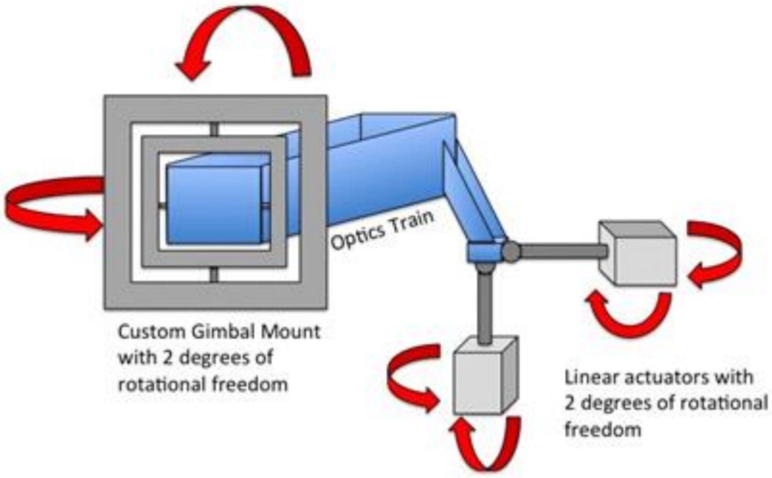
- **Relevant Components**
  - Thorlabs Stepper Motor Rotation Mount
    - Provides 360° rotation of the polarizer at a speed of 10 °/s with an accuracy of +/- 0.14°



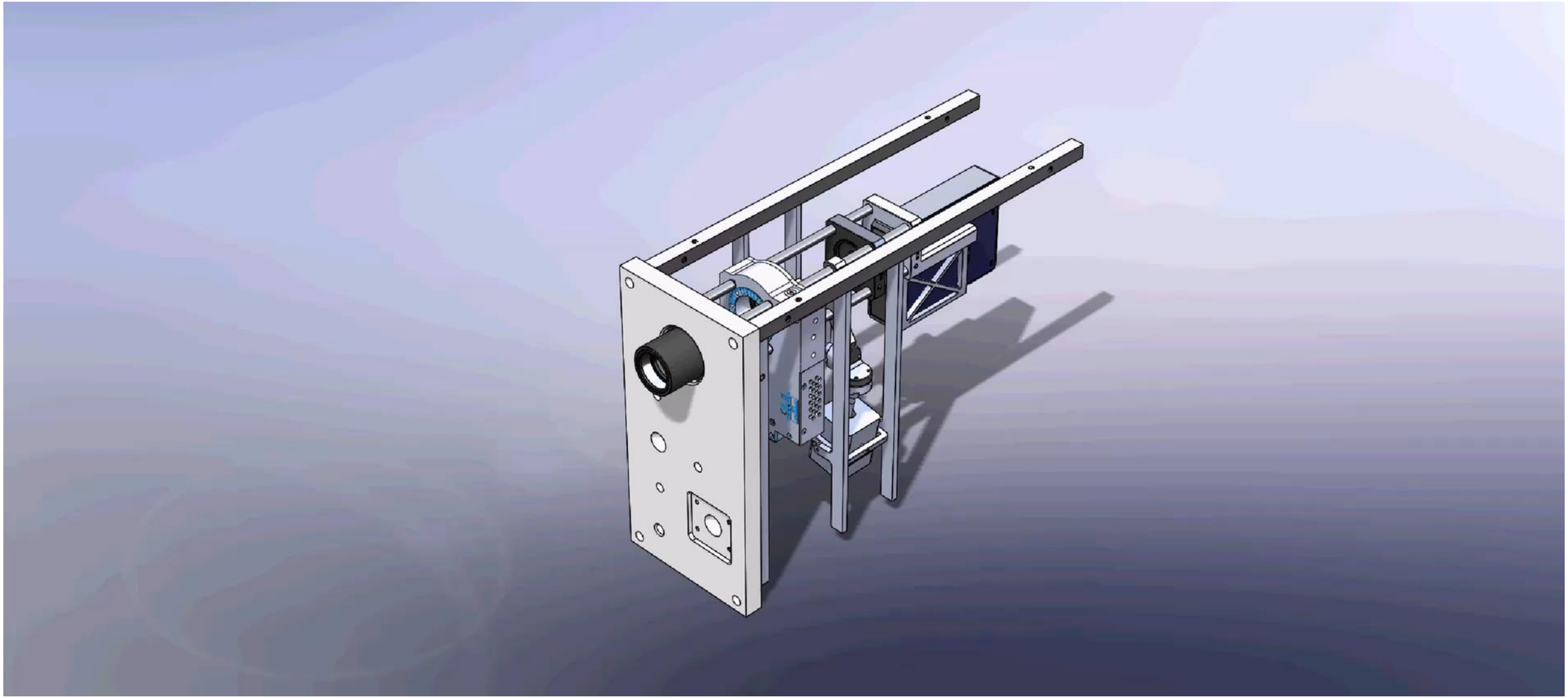
Optical System/Pointing Control

FR 2.4: Pointing capabilities of +/- 5° in azimuth and +/- 1° in elevation

- **Relevant Components**
  - Thorlabs 30mm Cage System
  - Custom Cage System Gimbal Mount
  - Haydon Kerk Pittman Hybrid Stepper Linear Actuator with encoder
  - Hephaist Spherical Ball Joints
  - Custom Gimbal Motor Mounts
- **Sources of Error**
  - Manufacturing error of the alignment of Thorlabs Cage System (+/- 180 μm)
  - Slack in ball joints (+/- 2 μm)
  - Slack in gimbal mounts

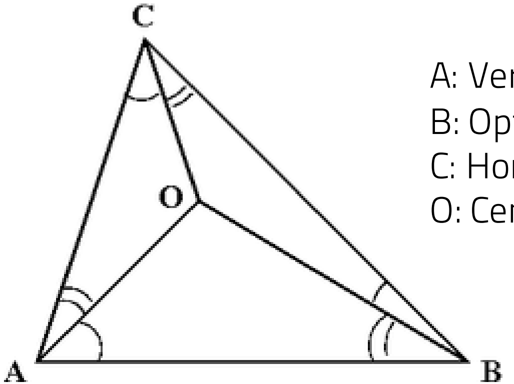


Pointing Control: Animation



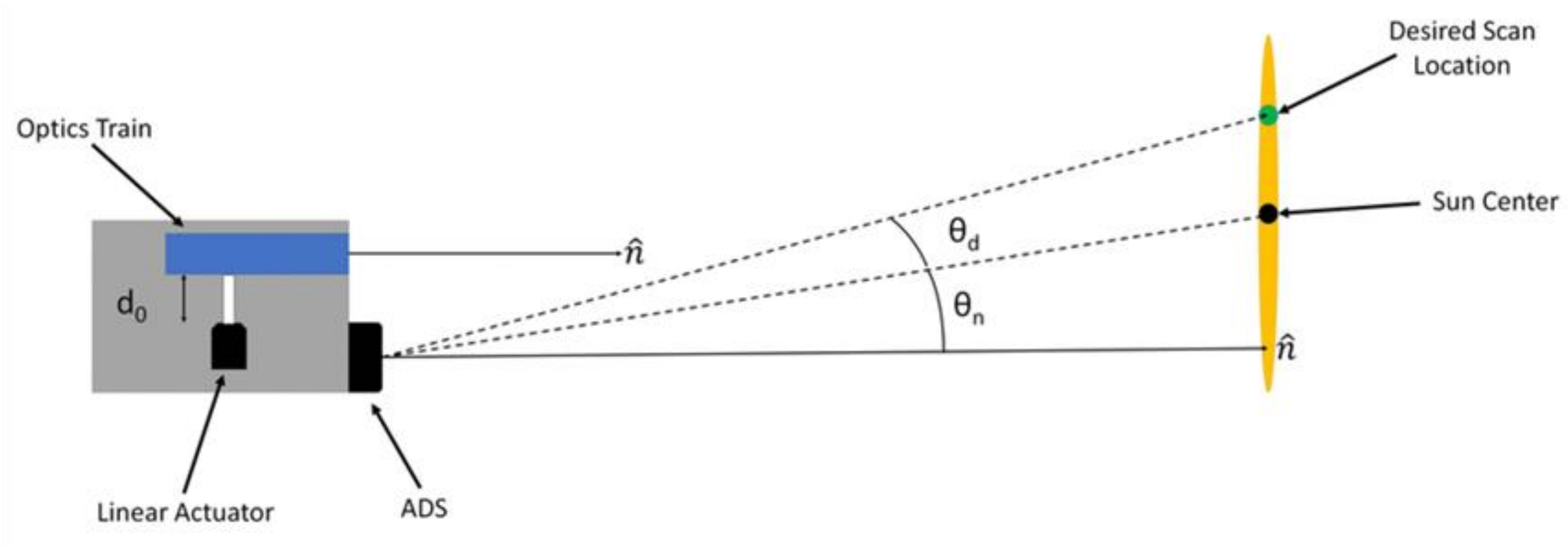
Pointing Algorithm

- **Needed Values:** Stepper motor extensions needed for a desired pointing angle
- **Known/Fixed Values**
  - Position of actuators
  - Position of front of optics cage
  - Distance between actuators
  - Distance between actuators and front of optics cage
- **Governing Principles:** Geometry of a tetrahedron
- **Summary**
  - Desired pointing angle can be used to calculate the extension of each motor head
  - Library of 788 different pointing angles needed for a full sun scan will be programmed into the onboard CPU



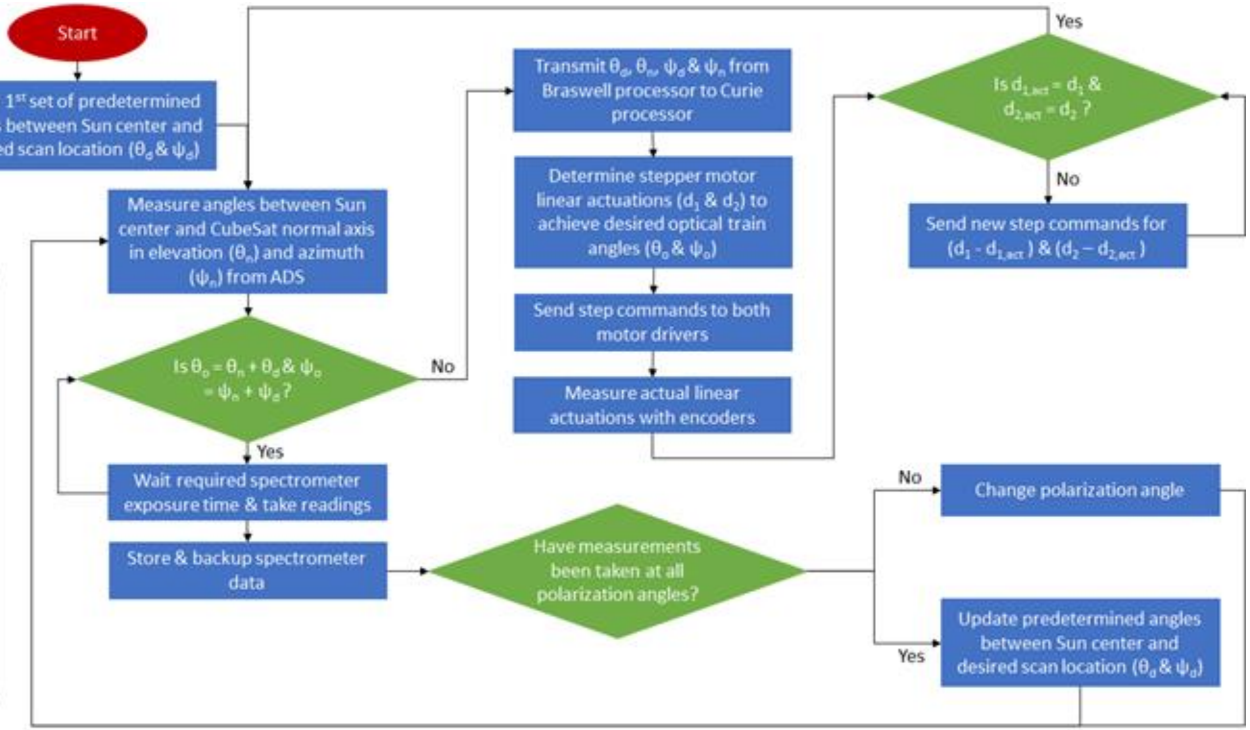
A: Vertical actuator center
B: Optics cage gimbal center
C: Horizontal actuator center
O: Center of actuator pushing plane

Pointing Control: Angle Explanation



Not to Scale

Pointing Control: Software Flow

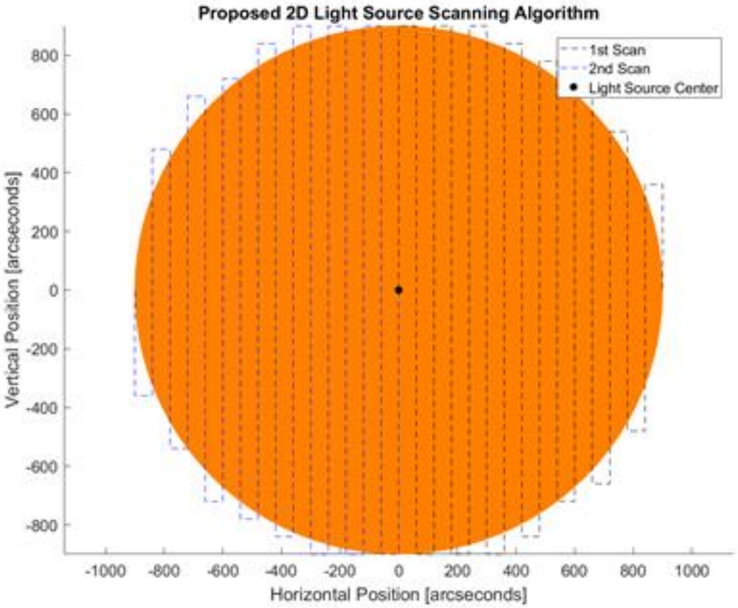


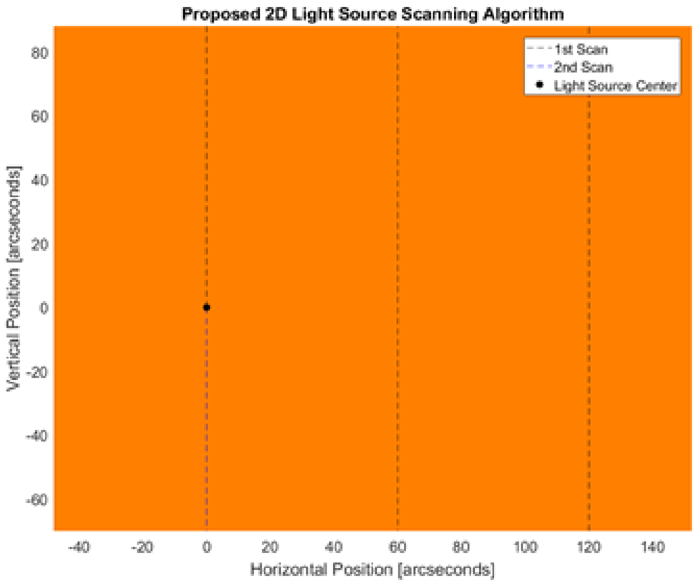
Legend

- θ: Elevation angles
- ψ: Azimuth angles
- d: Actuator displacements
- x_d: Angles b/t Sun center & desired scan location
- x_n: Angles b/t Sun center & CubeSat normal axis
- x_o: Angles b/t optical axis & CubeSat normal axis
- x_{act}: Actual, measured value

Light Source Scanning Algorithm

- 1′ between scan points
- 788 scan points: 1.1 days to scan entire surface at each needed polarization angle

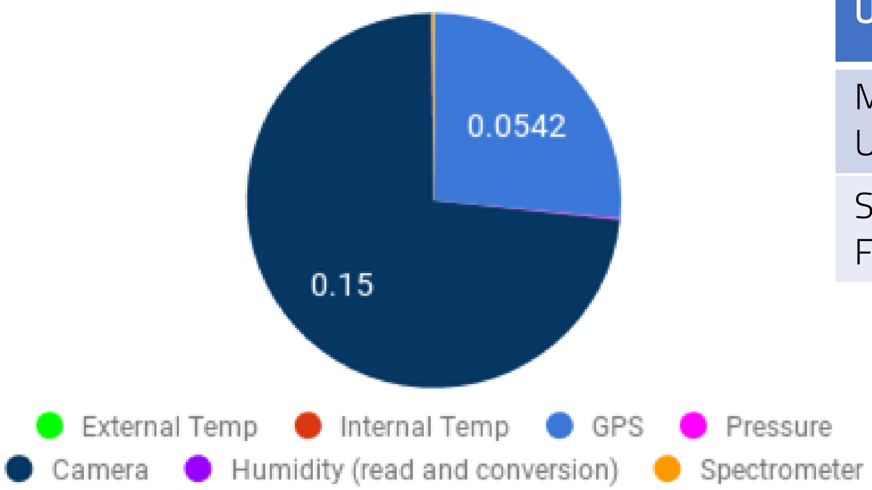




Data Acquisition

- Required environmental sensor measurement cadence: 1 Hz

Sensor Read Time [s]



Total Read Time: 0.2068 s

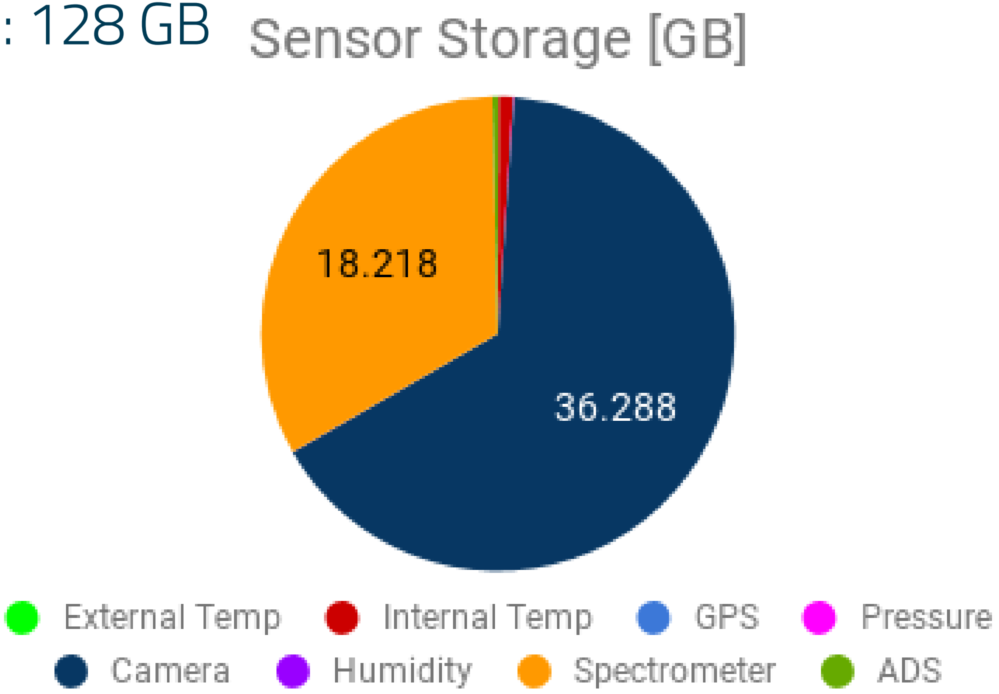
Write Times

USB Type	Message Time	Write Rate	Write Sub Total
MX-ES Ultra	620.08 KB	26.7 MB/s	0.023 s
Samsung Fit	620.08 KB	42.12 MB/s	0.014 s

Total Time/Worst Case Write: 0.23 s

Data Storage

- Total Storage Required For Entire Flight: 55.34 GB
- Storage Available: 128 GB

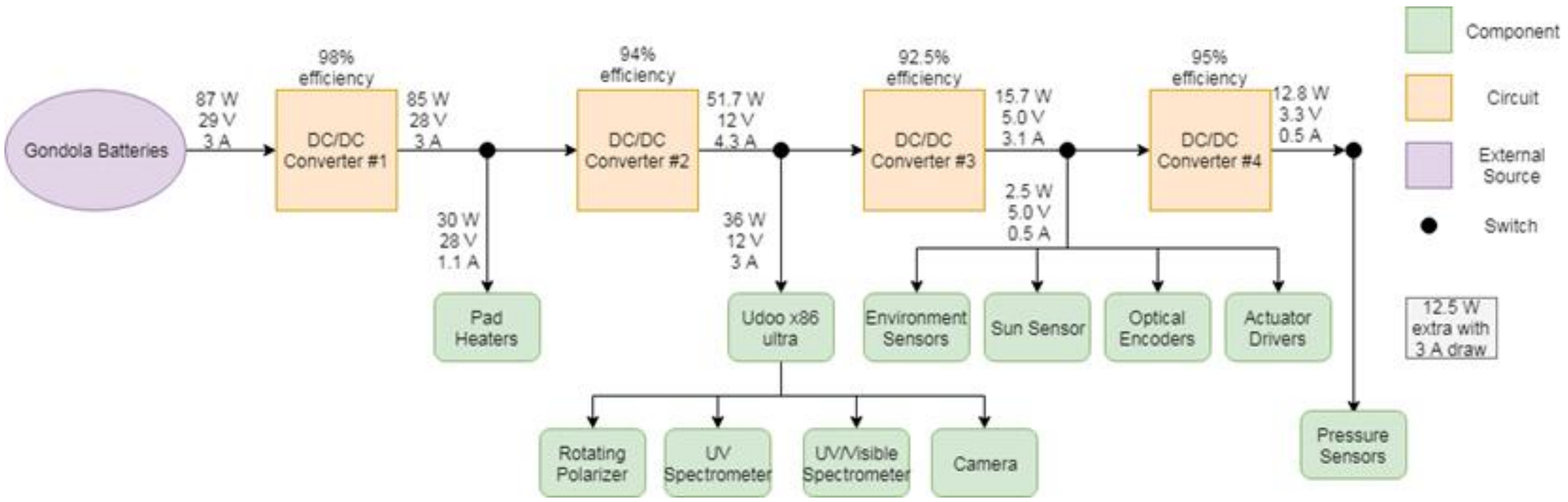


*Data from both spectrometers and the ADS is saved twice for redundancy

Power Budget

Component	Wattage (W)	Voltage(V)
Udoo x86 ultra (DAQ)	36	12.0
Linear Actuators	2.45	5.0
Pad Heaters	40.0	28.0
Sun Sensor	0.045	5.0
Total	68.5	-
Converter Efficiency	0.8101	-
Needed Supply	74.5	28.0
Supply	87 W @ 3.0 A draw	29.0
Margin	16.7%	3.5%

Power Flow


Gondola Batteries
87 W
29 V
3 A
98% efficiency
DC/DC Converter #1
85 W
28 V
3 A
30 W
28 V
1.1 A
Pad Heaters
94% efficiency
DC/DC Converter #2
51.7 W
12 V
4.3 A
36 W
12 V
3 A
Udoo x86 ultra
Rotating Polarizer
UV Spectrometer
UV/Visible Spectrometer
Camera
92.5% efficiency
DC/DC Converter #3
15.7 W
5.0 V
3.1 A
2.5 W
5.0 V
0.5 A
Environment Sensors
Sun Sensor
Optical Encoders
Actuator Drivers
95% efficiency
DC/DC Converter #4
12.8 W
3.3 V
0.5 A
Pressure Sensors
Component
Circuit
External Source
Switch
12.5 W extra with 3 A draw

Project Risks

Risk Summary

Risk	Risk Description	Pertaining Functional Requirement
R1	Software Data Write Failure	FR 2, FR 3, FR 4, FR5
R2	Software Bit Flip	FR 2, FR 3, FR 4, FR5
R3	Under-heating of CubeSat Internal Components	FR 1, FR 2, FR 4, FR5
R4	Over-heating of CubeSat Internal Components	FR 1, FR 2, FR 4, FR5

		Severity				
		1	2	3	4	5
Likelihood	5				R8	
	4				R7	
	3			R3	R4	
	2			R2	R1/R6	
	1				R5	

Project Risks

Risk Summary

Risk	Risk Description	Pertaining Functional Requirement
R5	Operation Failure "Freeze" of UDOO X86	FR 1, FR 2, FR 4, FR5
R6	Loss of Attitude Determination Calibration	FR 3, FR 4
R7	Manufacturing/Calibration/Test Delays	FR 1-5
R8	Manufacturing creates optical precision errors	FR2, FR4

		Severity				
		1	2	3	4	5
Likelihood	5				R8	
	4				R7	
	3			R3	R4	
	2			R2	R1/R6	
	1				R5	

Project Risks

High Risk Mitigation

Risk	Risk Description	Risk Mitigation
R8	Manufacturing creates pointing precision errors	• High precision machined gimbal mounts • Calibrate errors out in software & machine shop • Contact with AES machining faculty
R7	Manufacturing/Calibration/Test Delays	• Utilize machining, testing and staff resources • Finalize test plans early in Spring Semester • Follow hard timeline
R4	Over-heating of CubeSat Internal Components	• Conduct thorough thermodynamic analysis • Explore use of peltier devices

Types of Risks

- [X] Budget
- [X] Technical
- [ ] Safety
- [X] Schedule

		Severity				
		1	2	3	4	5
Likelihood	5				R8	
	4				R7	
	3				R4	
	2					
	1					

Project Risks

Medium Risk Mitigation

Risk	Risk Description	Risk Mitigation
R1	Software Data Write Failure	• Watch Dog methodology
R3	Under-heating of CubeSat Internal Components	• Conduct thorough thermodynamic analysis
R6	Loss of Attitude Determination Calibration	• Allow larger calibration time in schedule • Transport safety plan

Types of Risks

- [X] Budget
- [X] Technical
- [ ] Safety
- [ ] Schedule

		Severity				
		1	2	3	4	5
Likelihood	5					
	4					
	3			R3		
	2				R1/R6	
	1					

Project Risks

Verification and Validation

Verification and Test Plan

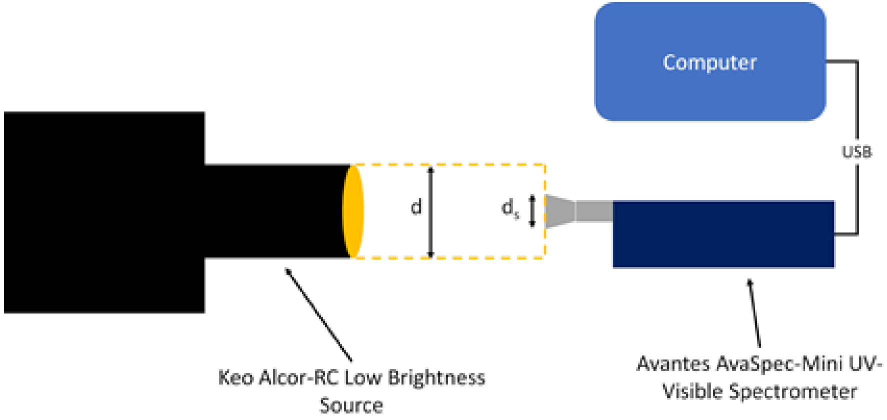
Component Selection	Component Testing	Subsystem Testing	Integration Testing
- Operational & Survival Conditions - Resolution - Read/Write Speeds - Control Requirements Size	- Motors - Polarizer Mount - DAQ/CPU - Powerboard circuit Breadboard - Heaters & Thermocouples -Spectrometers -Sun Sensor	- Optics Train - Udoo Board & Storage Devices - Power Board - EMCS -RADIANCE Systems -ADS	- ADS/Pointing Integration and Calibration - FlatSat - TVAC
Completed	Jan 16 - Jan 26	Jan 26 - Feb 27	Feb 27 - Apr 16

Functional Requirements	Requirements Tests
Take variable polarization angle UV spectrum measurements at various points on the sun	Sommers-Bausch Campaign, Integration Time Test, Focal Length Determination Test
Determine its attitude relative to the Sun	Sommers-Bausch Campaign
Operate and collect data during the environmental conditions of a 40km high altitude balloon flight	FlatSat, TVAC

Verification and Validation

Integration Time Test

- **Purpose:** Determine the spectrometer exposure time needed to take high SNR measurements
- **Procedure**
  - Use Keo *Alcor* Remote Controlled Low Brightness Source (provided by Dr. Marshall) to simulate the expected power input of the spectrometer of 18.1µW
  - Use spectrometer software to optimize the exposure time using RADIANCE spectrometer with 200 - 1100 nm grating since the light source produces light in the visible spectrum



$P_{expected} = 18.1\ \mu W$
$d = 100\ mm$
$d_s = 6\ mm$
$A_{light\ source} = \pi * (d_s/2)^2 = 785.4\ mm^2$
$A_{spectrometer} = \pi * (d/2)^2 = 28.3\ mm^2$

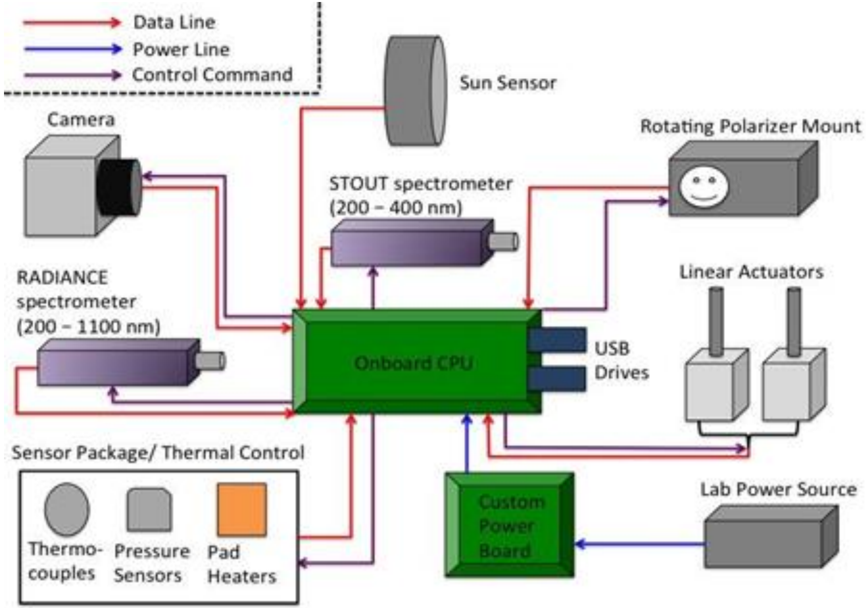
$P_{output,needed} = P_{expected} * (A_{light\ source}/A_{spectrometer})$

$= 0.5\ mW$

FlatSat Test

- **Purpose:** Determine that all of the components integrate and operate functionally
- **Procedure**
  - Integrate STOUT and RADIANCE electronics outside of the CubeSat structure
  - Verify expected voltages and currents with a multimeter
  - Calculate and verify expected power draws

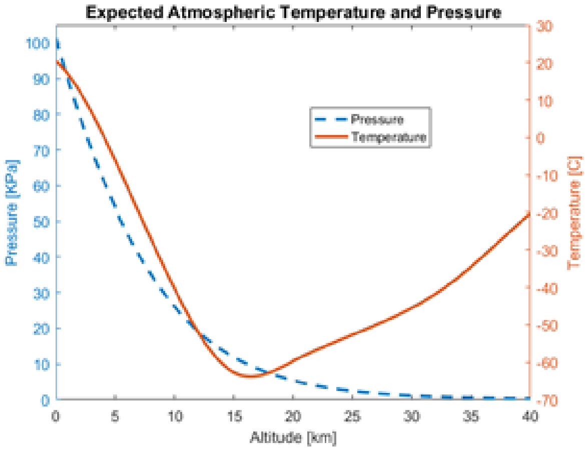
<u>Simplified FlatSat Test Connections</u>
*Note that the custom power board distributes power to each different component



Thermal Vacuum Chamber (TVAC) Test

- **Purpose:** Validate EMCS operation and thermal model during the temperature conditions of the high altitude balloon ascent and cruise phases
- **Procedure:** Use TVAC (provided by Phil Oakley at HAO) chamber to put STOUT module through the ascent phase temperature profile and 3 hours of the expected steady state operating temperature
  - Test 1: Structure and EMCS only
    - Post-process data used to verify the module remains at operable temperatures
  - Test 2: Entire module

*Temperature and pressure profile for proposed flight out of Fort Sumner, NM

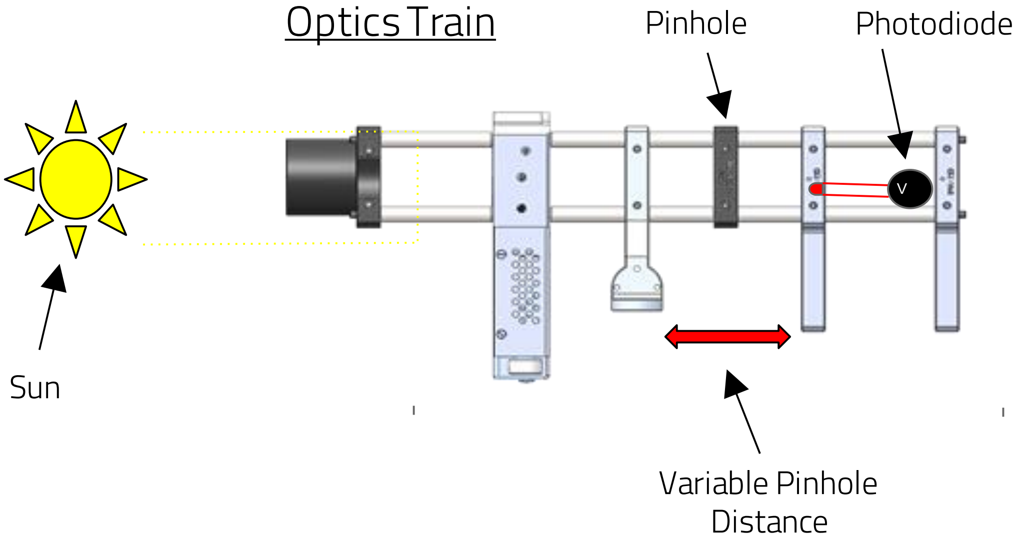


HAO Thermal Vacuum Chamber

Verification and Validation

Focal Length Determination Test

- **Purpose:** Experimentally determine the focal point of the main lens
- **Procedure:** Point optics train at Sun and use photodiode to verify pinhole placement within the optics train
  - Maximum voltage potential occurs across the photodiode when pinhole is located in the focal plane and Sun image is focused
  - Move pinhole incrementally until max photodiode voltage occurs



Sommers-Bausch Testing Campaign

Problem

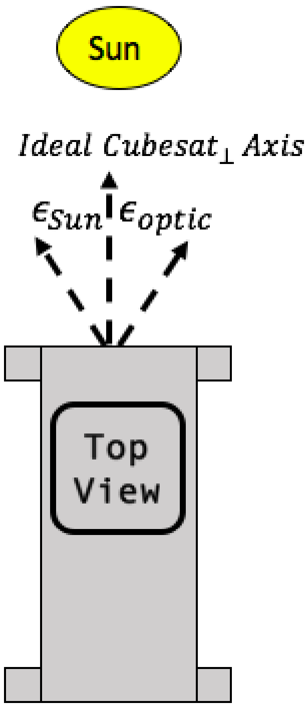
- Manufacturing and mounting errors lead to optical axis and sensor normal axis misalignment

Sun Sensor Calibration Principles

- Sensor outputs off-sun angles so long as sun is within +/- 5° FOV
- Maximum ADS photocurrent generation occurs when sensor normal axis is aligned with sun center

Solution

- Use Sommers-Bausch Telescope (provided by Fabio Mezzalira) for alignment to validate outputted off-sun angles, and calibrate angles relative to telescope mount for optics calibration

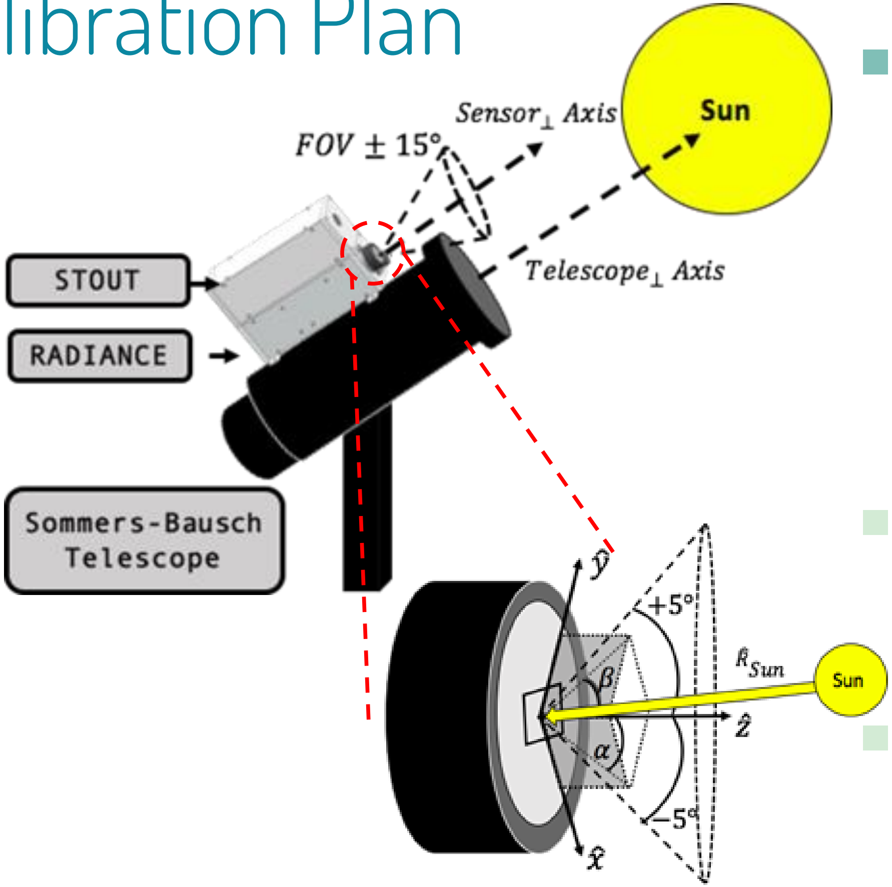


ADS Verification/Calibration Plan

Specifications

- Sommers-Bausch telescope has accuracy > 20 " ~ 0.0055°
- Accuracy of Sun sensor:
- 18" ~ 0.02°
- Total accuracy: 75.6" ~ 0.021°

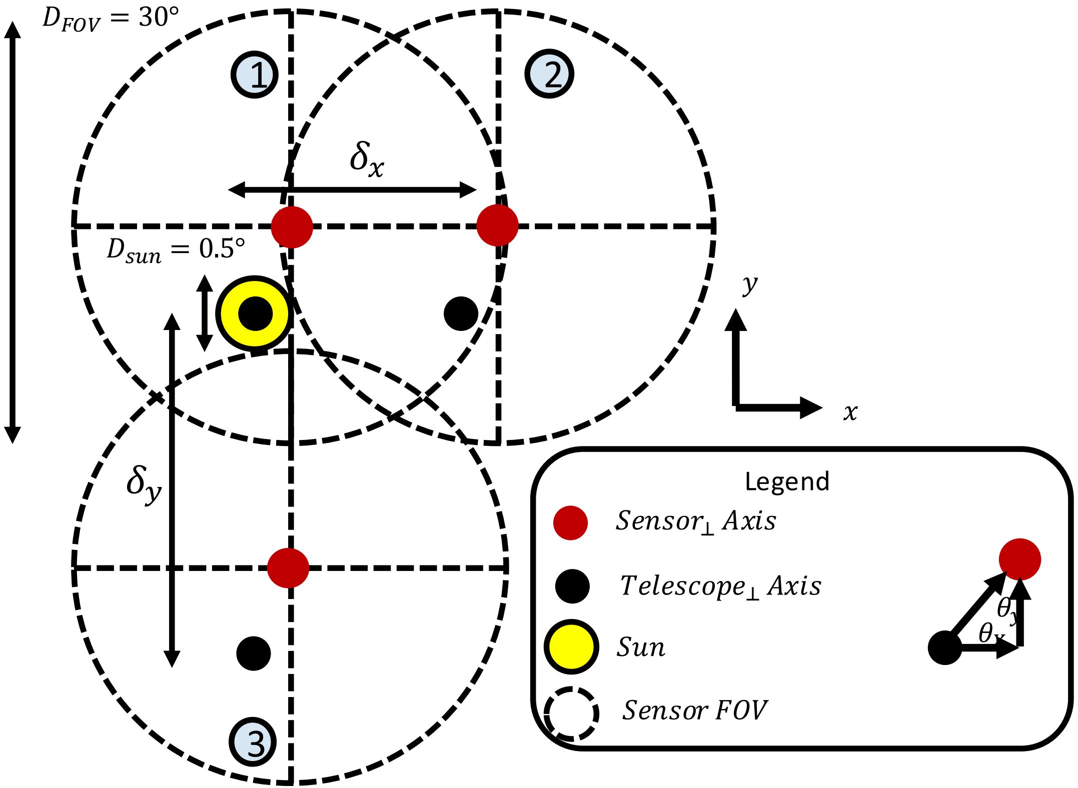
RADIANCE/Telescope Mount



ADS Verification Plan

Verification Procedure

- Point telescope at Sun center
  - Save sensor off-sun angles
- Deviate telescope normal axis and measure deviations between sensor normal axis and sun center using sensor FOV
- Repeat process for multiple nodes to ensure accuracy
- Compare sensor off-sun angles to experimentally determined off-sun angles



Sensor measured off-sun angles | **Experimentally determined off-sun angles**

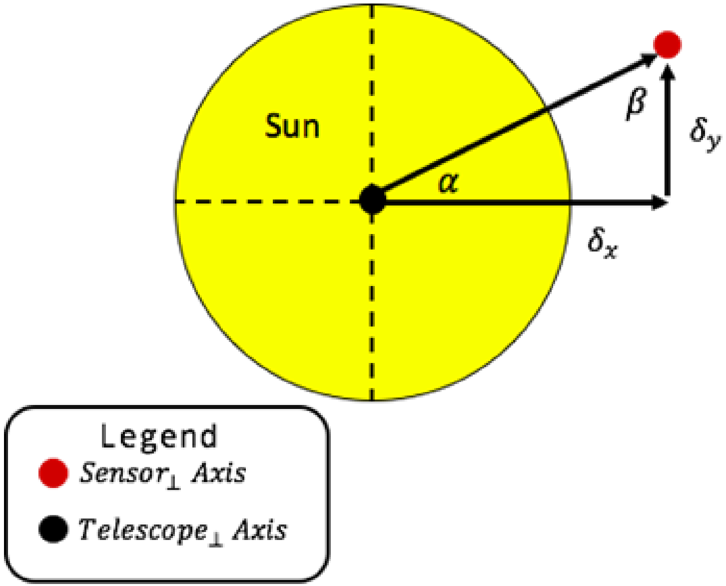
$$\alpha \approx \theta_{X-Offset} = \tan^{-1}\frac{\delta_y - 5°}{\delta_x - 5°}$$

$$\beta \approx \theta_{y-Offset} = \tan^{-1}\frac{\delta_x - 5°}{\delta_y - 5°}$$

ADS Calibration Plan

Calibration Procedure

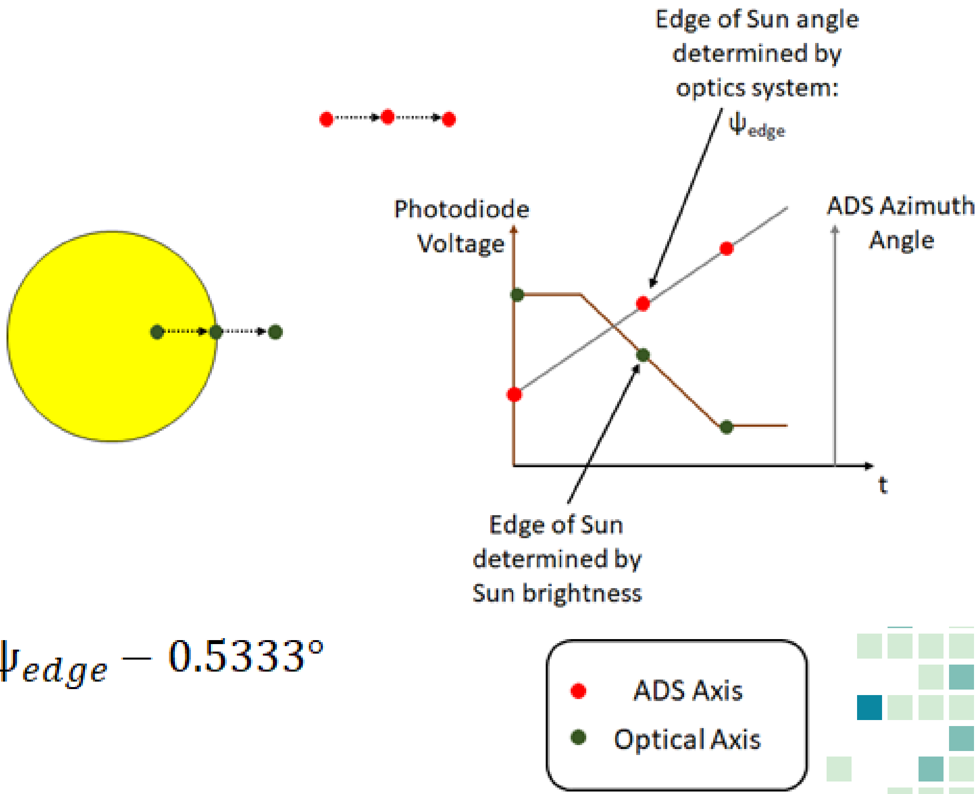
- Point Telescope at Sun center
- Record off sun angles
- Program deviation values in telescope software for optics calibration
- ADS now calibrated to Telescope mount
- Proceed with Optics Calibration



Optics Calibration Plan

Calibration Procedure

- Mount photodiode behind pinhole & verify optics train is pointed at the Sun
- Actuate telescope horizontally to move across edge of Sun
- Read photodiode voltage & ADS off-Sun angles as a function of time during movement
- Repeat for vertical actuation
- Post process data to determine offset between optics and ADS axes (dψ & dθ)

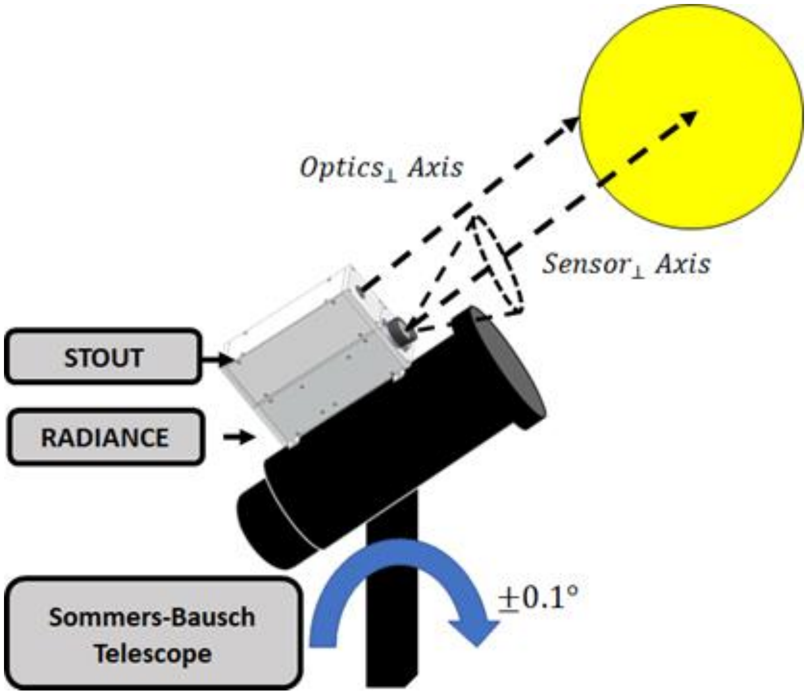


$$\delta\psi = \psi_{edge} - r_{Sun} = \psi_{edge} - 0.5333°$$

Pointing Control Verification Plan

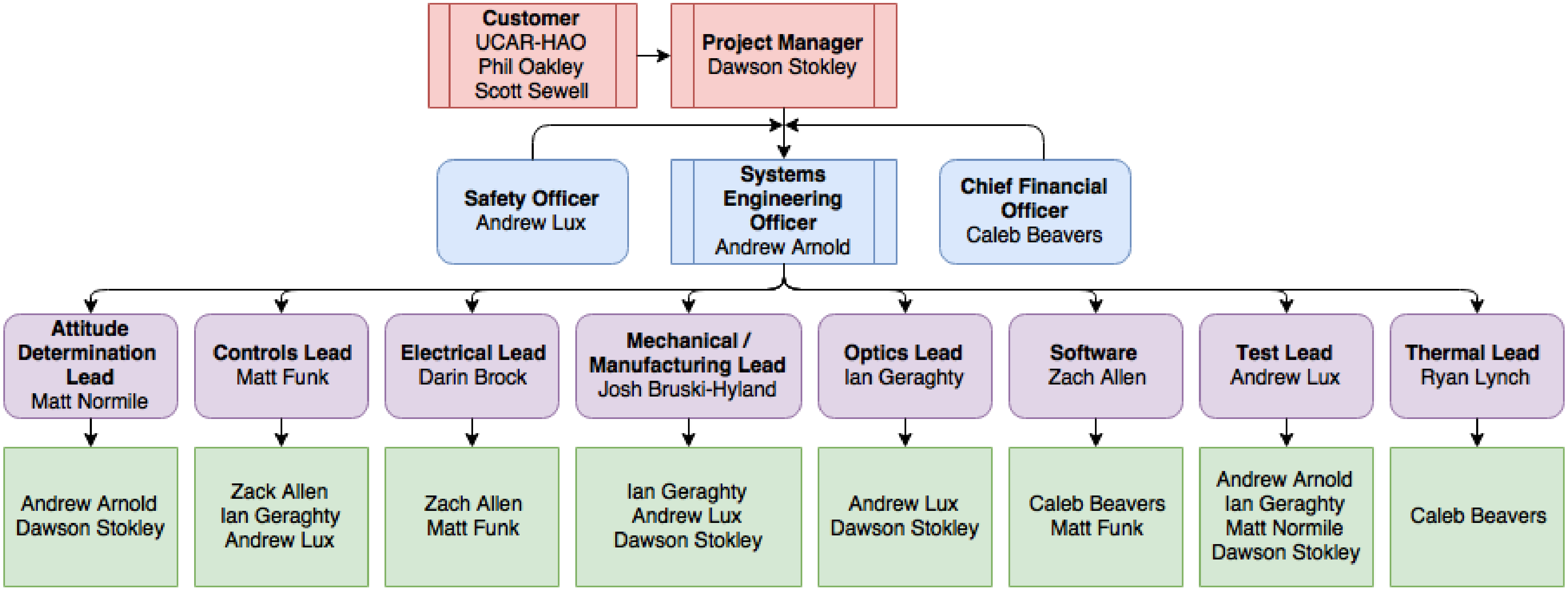
Verification Procedure

- After ADS & Optics calibration are accounted for in software, functionality of pointing control can be verified
- Center Sun in ADS FOV using telescope
- Actuate optics system to the edge of the Sun
- Program telescope to move in pendulum motion to simulate gondola
- Control system will maintain constant photodiode voltage if the pointing system accurately accounts for movement

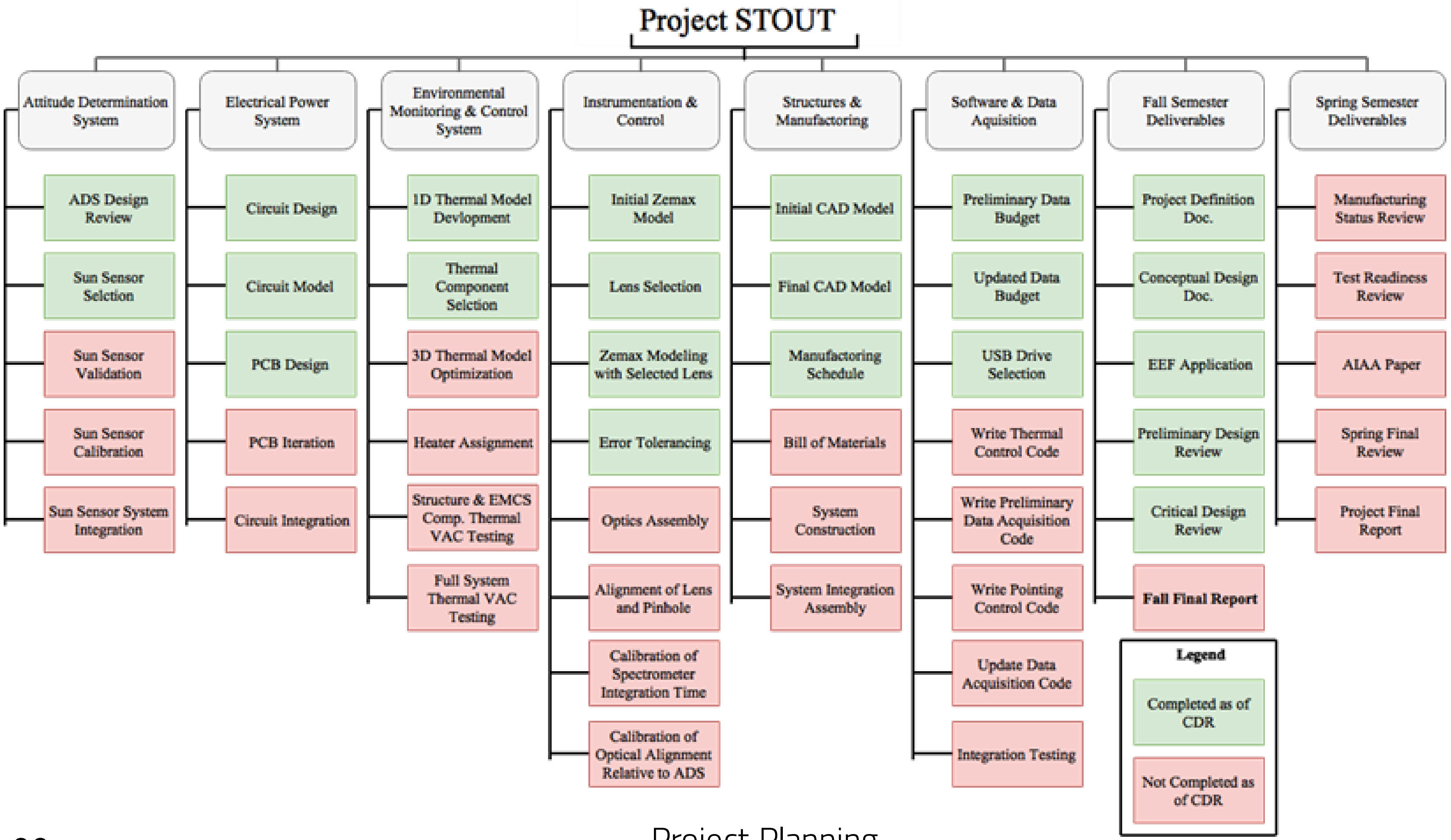


Project Planning

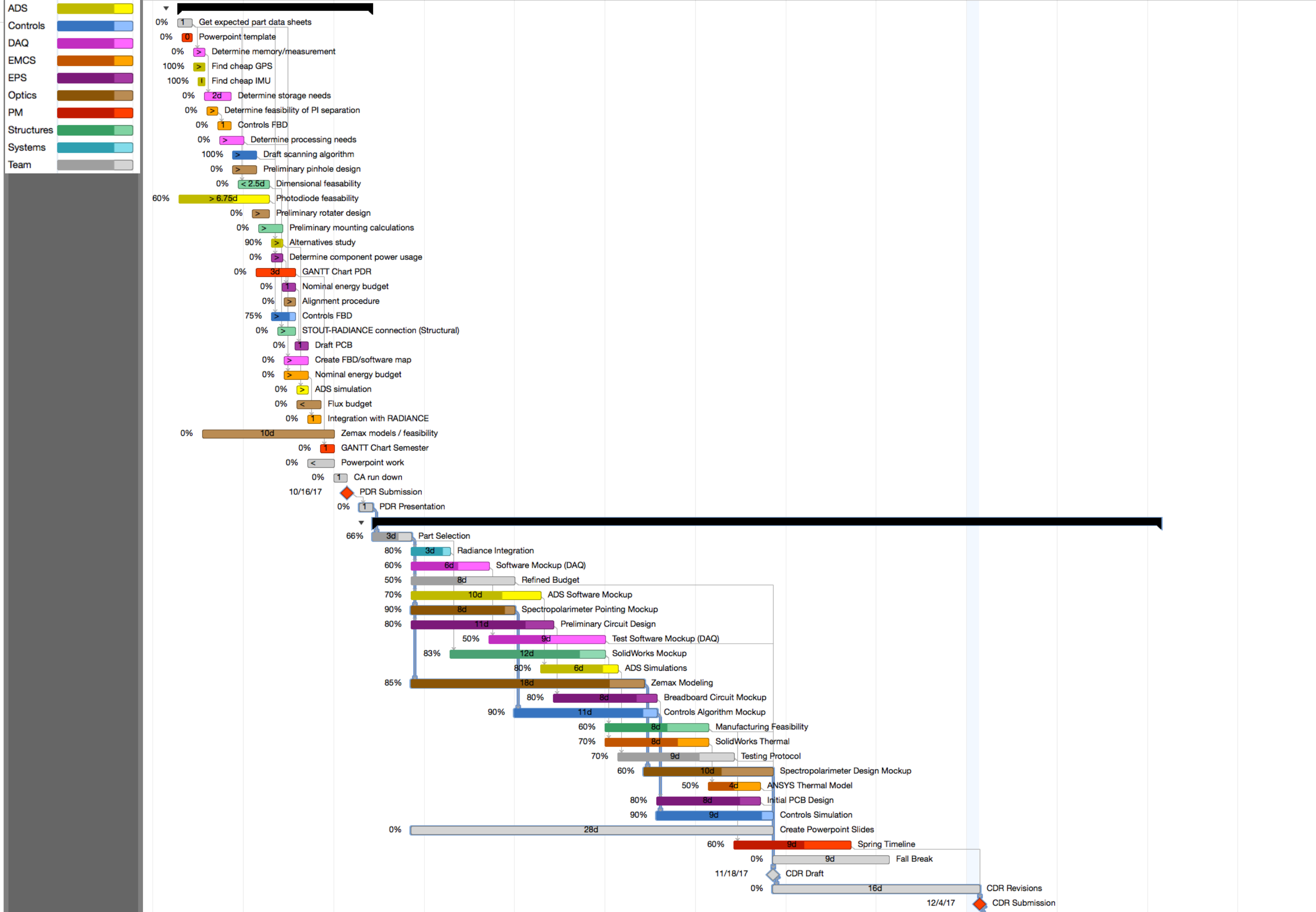
Organizational Chart



Work Breakdown Structure



Title	Planned Start	Planned End
▼ PDR	10/2/17	10/17/17
• Get expected part data sheets	10/2/17	10/3/17
• Powerpoint template	10/3/17	10/3/17
• Determine memory/measurement	10/4/17	10/4/17
• Find cheap GPS	10/4/17	10/4/17
• Find cheap IMU	10/4/17	10/4/17
• Determine storage needs	10/5/17	10/6/17
• Determine feasibility of PI separation	10/5/17	10/5/17
• Controls FBD	10/6/17	10/6/17
• Determine processing needs	10/6/17	10/7/17
• Draft scanning algorithm	10/7/17	10/8/17
• Preliminary pinhole design	10/7/17	10/8/17
• Dimensional feasability	10/7/17	10/9/17
• Photodiode feasability	10/3/17	10/9/17
• Preliminary rotater design	10/8/17	10/9/17
• Preliminary mounting calculations	10/9/17	10/10/17
• Alternatives study	10/10/17	10/10/17
• Determine component power usage	10/10/17	10/10/17
• GANTT Chart PDR	10/9/17	10/11/17
• Nominal energy budget	10/11/17	10/11/17
• Alignment procedure	10/11/17	10/11/17
• Controls FBD	10/10/17	10/11/17
• STOUT-RADIANCE connection (Structural)	10/10/17	10/11/17
• Draft PCB	10/12/17	10/12/17
• Create FBD/software map	10/11/17	10/12/17
• Nominal energy budget	10/11/17	10/12/17
• ADS simulation	10/12/17	10/12/17
• Flux budget	10/12/17	10/13/17
• Integration with RADIANCE	10/13/17	10/13/17
• Zemax models / feasibility	10/4/17	10/14/17
• GANTT Chart Semester	10/14/17	10/14/17
• Powerpoint work	10/13/17	10/14/17
• CA run down	10/15/17	10/15/17
• PDR Submission	10/16/17	10/16/17
• PDR Presentation	10/17/17	10/17/17
▼ CDR/FFR	10/18/17	12/18/17
• Part Selection	10/18/17	10/20/17
• Radiance Integration	10/21/17	10/23/17
• Software Mockup (DAQ)	10/21/17	10/26/17
• Refined Budget	10/21/17	10/28/17
• ADS Software Mockup	10/21/17	10/30/17
• Spectropolarimeter Pointing Mockup	10/21/17	10/28/17
• Preliminary Circuit Design	10/21/17	10/31/17
• Test Software Mockup (DAQ)	10/27/17	11/4/17
• SolidWorks Mockup	10/24/17	11/4/17
• ADS Simulations	10/31/17	11/5/17
• Zemax Modeling	10/21/17	11/7/17
• Breadboard Circuit Mockup	11/1/17	11/8/17
• Controls Algorithm Mockup	10/29/17	11/8/17
• Manufacturing Feasibility	11/5/17	11/12/17
• SolidWorks Thermal	11/5/17	11/12/17
• Testing Protocol	11/6/17	11/14/17
• Spectropolarimeter Design Mockup	11/8/17	11/17/17
• ANSYS Thermal Model	11/13/17	11/16/17
• Initial PCB Design	11/9/17	11/16/17
• Controls Simulation	11/9/17	11/17/17
• Create Powerpoint Slides	10/21/17	11/17/17
• Spring Timeline	11/15/17	11/23/17
• Fall Break	11/18/17	11/26/17
• CDR Draft	11/18/17	11/18/17
• CDR Revisions	11/18/17	12/3/17
• CDR Submission	12/4/17	12/4/17



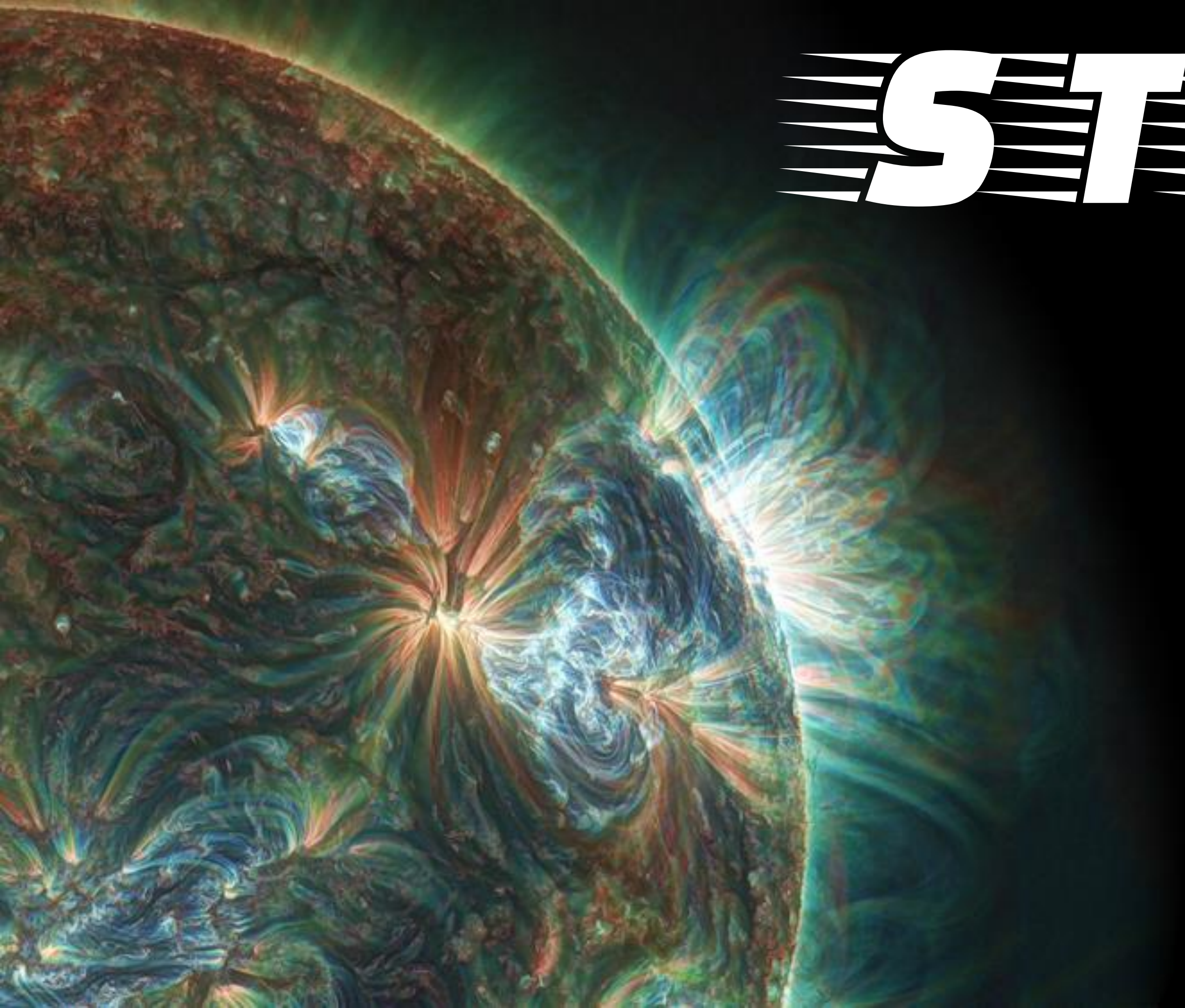
Cost Plan

System	Part	Price ($)	Shipping	Quantity	Total
ADS	Solar Mems Sun Sensor	$900.00	$0.00	1	$900.00
	UDOO RS-485 Shield	$9.95	$0.00	1	$9.95
Optics	Main Lens	$969.00	$10.00	1	$979.00
	Polarizer Mount	$1,289.00	$0.00	1	$1,289.00
	40 um Pinhole	$67.50	$0.00	1	$67.50
	Lens/Pinhole Mounts	$23.20	$0.00	2	$46.40
	Cage Rods 2 inch	$23.18	$0.00	1	$23.18
	Cage Rods 6 inch	$32.21	$0.00	1	$32.21
	Lens tubes	$14.10	$0.00	2	$28.20
	Avantes COL-UV/VIS Collimating lens	$140.00	$10.00	1	$150.00
	Photodiode for Testing	$100.00	$0.00	1	$100
TCS	Internal Temp Sensor	$3.95	$0.00	4	$15.80
	External Temp Sensor	$10.00	$0.00	2	$20.00
	Pressure Sensor	$59.95	$0.00	1	$59.95
	Resistive pad heaters	$130.00	$0.00	1	$130.00
	Humididty sensor	$16.95	$0.00	1	$16.95
	Amplfier board	$14.95	$0.00	2	$29.90
System	GPS	$45.00	$11.00	1	$56.00
Structure	Aluminum	$118.27	$20.00	1	$138.27
	Spherical roller bearings	$400.00	$20.00	2	$820.00
	Test Mounting Structure	$75.00	$0.00	1	$75.00
EPS	Converters	$2.50	$0.00	1	$2.50
	PCB	$80.00	$0.00	2	$160.00
Various	Printing	$100.00	$0.00	1	$100.00
Controls	Stepper Motor	$237.35	$20.00	2	$494.70
	Motor controllers	$14.95	$0.00	2	$29.90
DAQ	Camera	$45.99	$0.00	1	$45.99
	USB Hub	$16.99	$0.00	1	$16.99
	USB Drives	$50.00	$0.00	1	$50.00
	Logic level converters	$2.95	$0.00	10	$29.50
	UDOO x86 Ultra	$267.00	$20.00	1	$287.00

System	Cost	Cost w/15% Margin
ADS	$909.95	$1046.44
Optics	$2715.49	$3122.81
TCS	$272.60	$313.49
Systems	$56.00	$64.40
Structure	$1033.27	$1188.26
EPS	$162.50	$186.88
Various	$100.00	$115.00
Controls	$524.60	$603.29
DAQ	$429.48	$493.90
Total	**$6203.89**	**$7134.44**

Engineering Excellence Fund

Budget Increased to $73



STOUT

Thank you for listening! We appreciate your feedback.

Are there any questions?

References

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- Measuring Humidity on a High Altitude Balloon - http://www.societyofrobots.com/space_balloon_humidity_test.shtml
- Pad Heaters - https://www.omega.com/pptst/KHR_KHLV_KH.html
- Peltier Device - https://www.digikey.com/product-detail/en/cui-inc/CP60240/102-1676-ND/1747368
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- Battery Configuration Characteristics - ftp://apollo.ssl.berkeley.edu/pub/jolson/COSI_final_report/Final_report/CSBFGondolaDesignRecommendations%20newer%20version.pdf
- Ext Temp Sensor - https://www.adafruit.com/product/1727, https://www.adafruit.com/product/270
- Int Temp Sensor - https://www.sparkfun.com/products/245
- Actuator Supplier - http://www.haydonkerkpittman.com
- Pressure Sensor - https://www.sparkfun.com/products/9569
- Testing Photodiode - https://sglux.de/en/product/sg01s-18-en/

Table of Contents

Backups

Customer

HAO

High Altitude Observatory

NCAR

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

Design Requirements: EMCS

Solidworks 3D thermal modeling

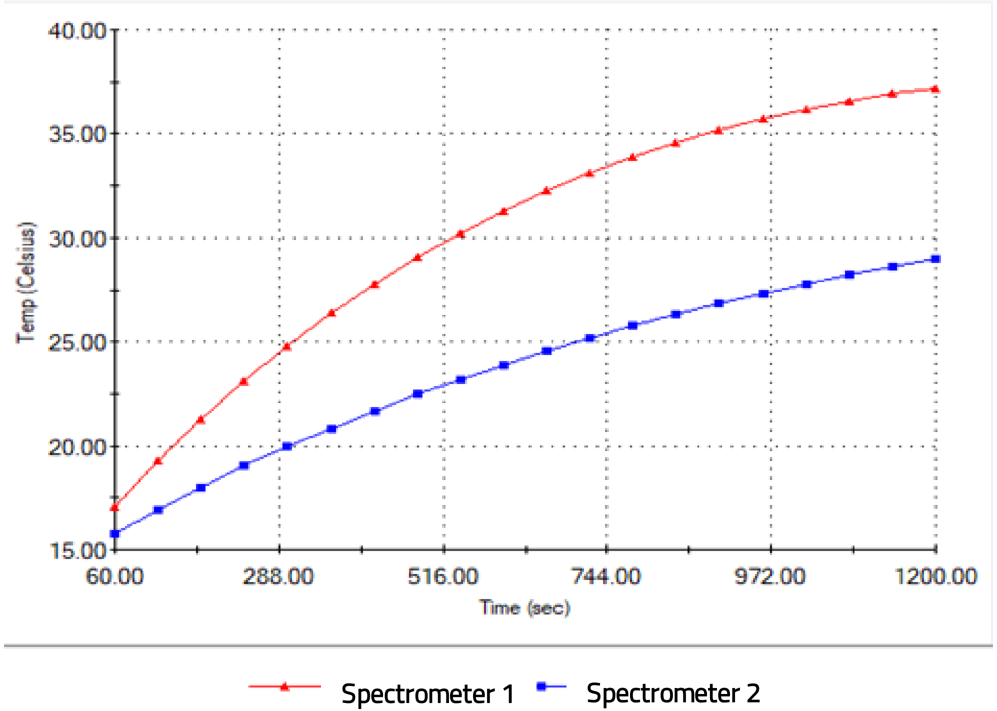
- Purpose
  - Verify validity of baseline EMCS design through more robust model, alleviating bulk temperature assumptions of matlab model
  - Allows for further development and optimization of design
- Reasoning
  - Accessible program
  - Baseline knowledge within team and implementation of existing CAD model
- Methodology
  - Create highly simplified CAD model consisting of main instruments
  - Conduct partial transient thermal model at harshest environmental conditions

Solidworks Result

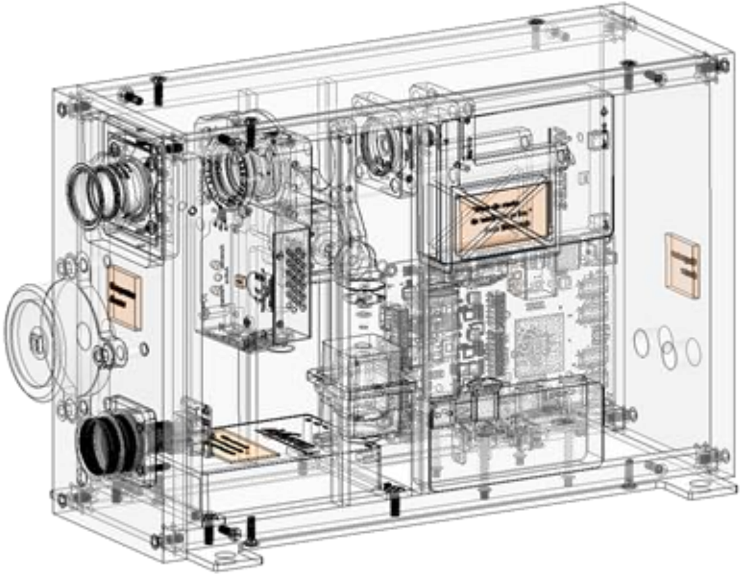
Partial Transient Time Profile

- 30 minute stimulation
- 60 second time interval

Spectrometer Temperature VS Time



Environmental Monitoring & Control System



Instrumentation

- 7 DS18B20 Temperature Sensors to measure the module's internal temperature
- 2 K-Type Thermocouples w/ Amplifier Boards to measure external environmental temperature
- MS5803-14BA Pressure Sensor to measure external environmental pressure
- HIH-4030 Humidity Sensor to measure environmental humidity
- 2-3 Kapton Resistive Pad Heaters to keep the interior of the module at an operable temperature

Relevant Thermal Equations

Radiated Heat

$$\sigma = 5.67 \times 10^{-8} \frac{W}{m^2 \cdot K^4}$$

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

Convection

$$Nu(Ra,Pr) = \frac{g C_p \rho (T_s - T_\infty) L_c^3}{K\nu}$$

$$h = \frac{k}{L_c} Nu$$

Absorbed Heat

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

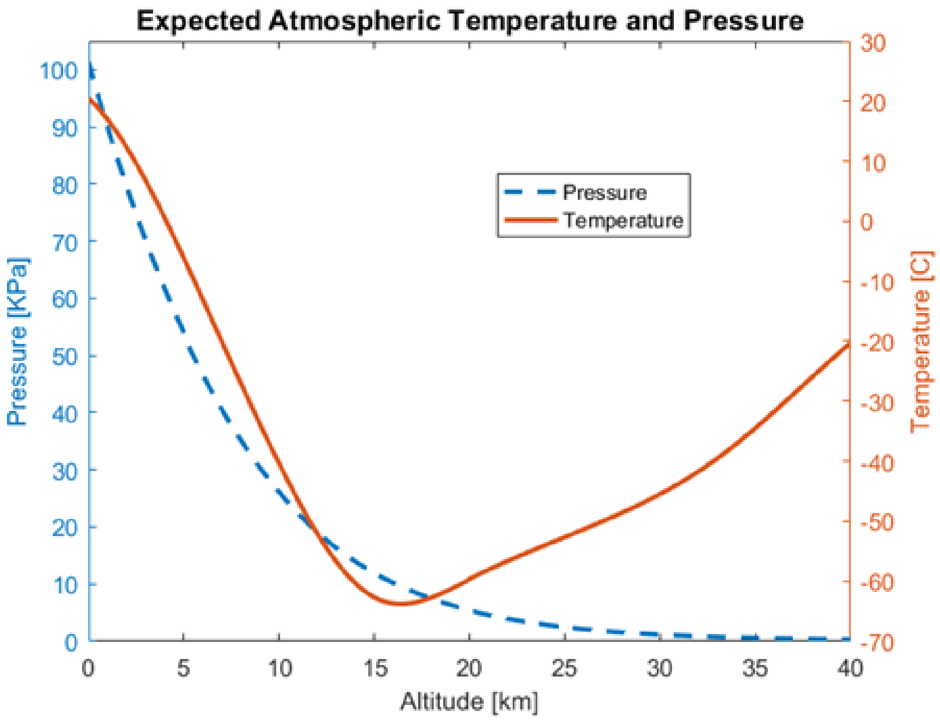
$$\dot{Q}_{Ground} \approx 1050 [W/m^2]$$

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

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

Atmospheric Model

- ➢ Flight conditions for Fort Sumner, NM launch
- ➢ Based on 2001 US Navy Model (temperature) & COESA Model (Pressure)

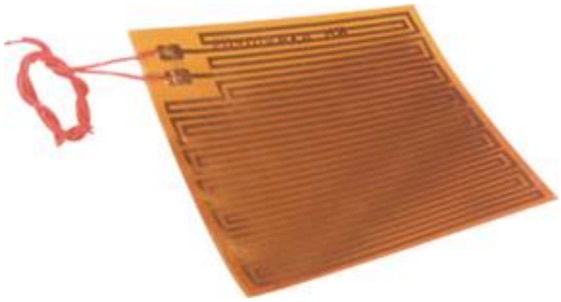


EMCS Feasibility: Pressure

Component	Minimum Pressure Rating (Pa)
Actuators	0.1
Polarizer Mount	0.133
ADS Sensor	5
Pressure Sensor	0

EMCS Feasibility: Pad Heaters

- **Omega Polyimide Film Insulated Flexible Heaters**
  - 28 V supply voltage, 0.357 A max supply current
  - 10 x 2.5 x 0.025 cm dimensions
  - 0-10 W evenly distributed heat output each

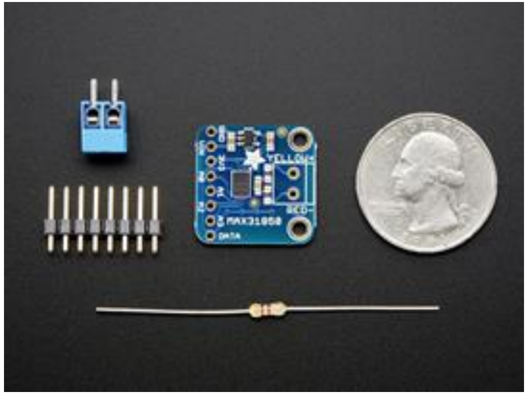


EMCS Feasibility: Temperature Sensors

- External Temperature:
  K-type thermocouples
  w/ amplifier boards

- Internal Temperature:

  7x DS18B20 One Wire Digital Temperature Sensors (Same as RADIANCE)



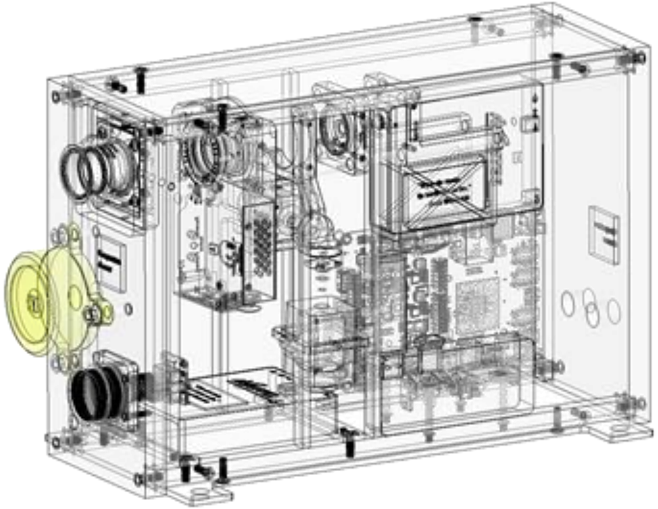
EMCS Feasibility: Pressure Sensor

- **Sparkfun MS5803-14BA**
  - 0 to 1400 kPa operating pressure
  - 1.8 to 3.6 V operating voltage
  - I2C interface

EMCS Feasibility: Humidity Sensor

➢ **Sparkfun HIH-4030**
  - 0 to 100% relative humidity measurement
  - 4 - 5.8 V supply voltage
  - Analog output

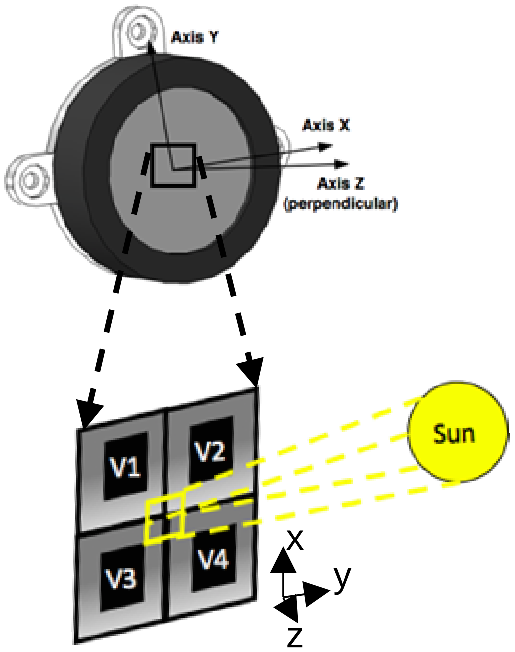
System Overview



Sun Sensor

- Determines Sun's position in the system FOV for optics control
- Photocurrent generation to determine off-sun angles
- Field of View: dual axes ± 5°
- Accuracy: ± 0.005°
- Serial RS 485 Communication
- Bit Rate: 19200 bps
- 0.05 mbar certified
- -40 to 85 °C operating temperature

Attitude Determination Feasibility



Solar Mems Sun Sensor

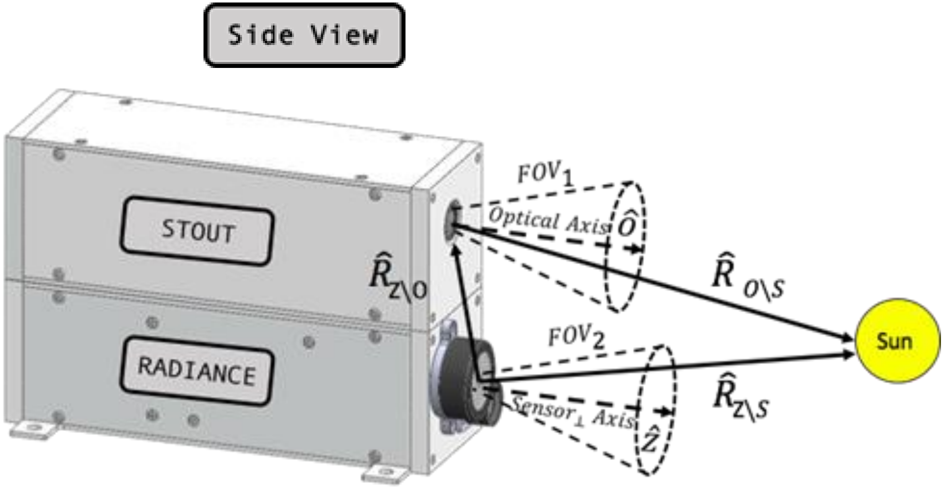
- Measures Incident Angle
- Uses Quadrant photodetector
- Photocurrents generated
- Field of View: Dual Axes ± 15°
- Accuracy: ± 0.02°

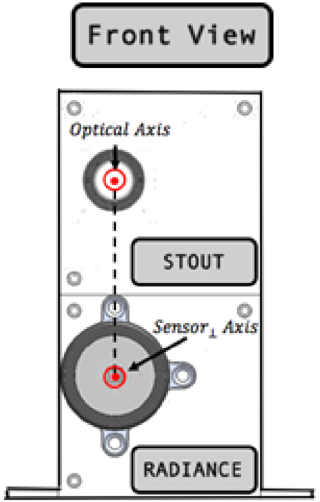
Calibration

- Telescope w/ high-precision sidereal tracking
- Control telescope to get max power generation
- Determine off sun angle, program as zero degree position

Attitude Determination Thermal Expansion

Purpose: Solve Off-Sun Angles





Assumptions

Sun within ± 15° of optical axis
(given by customer)

Given

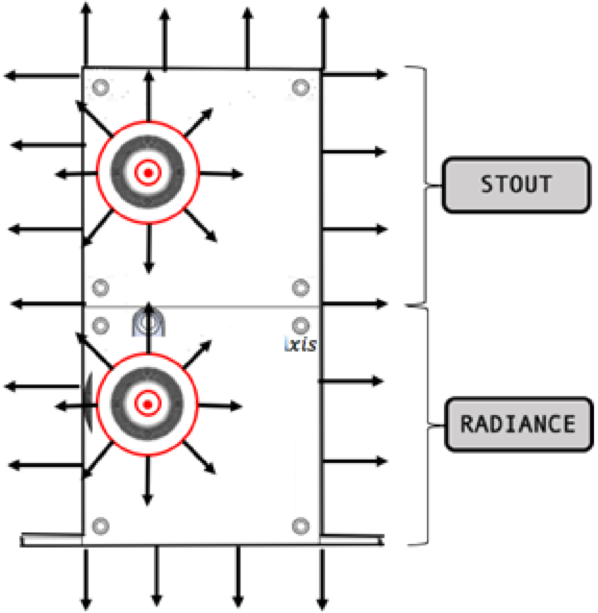
$\hat{o} = \hat{z}, \; \hat{R}_{O\backslash S}, \hat{R}_{Z\backslash S} >> \hat{R}_{S\backslash O}$

- $\hat{R}_{O\backslash S} = \hat{R}_{Z\backslash S}$

Conclusion

Sun off-angles relative to Sun Sensor axis is equal to that of the optical axis

Attitude Determination Thermal Expansion



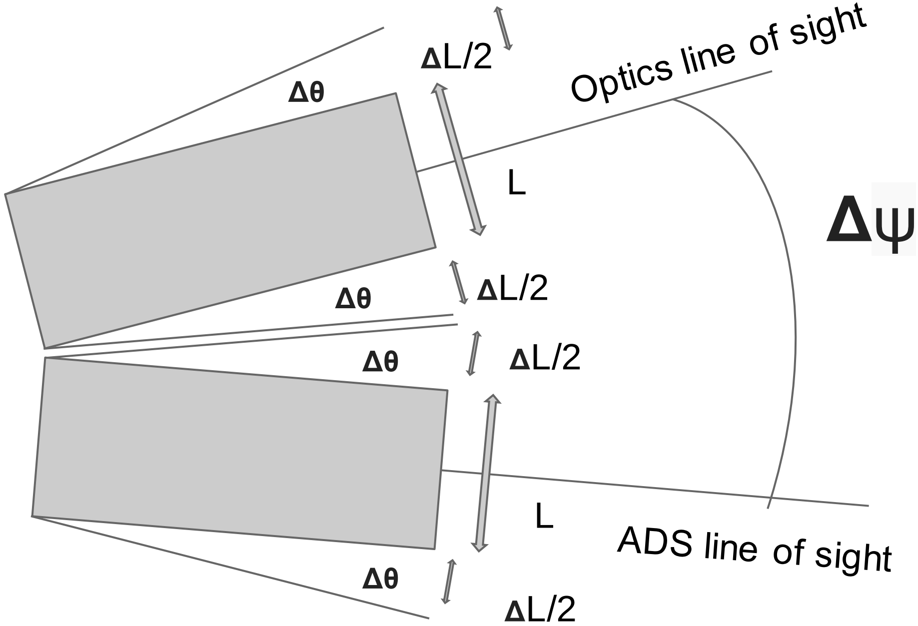
Thermal Expansion

- Expanding material assumed uniform
- Sun Face is assumed as flat plate
- Every linear dimension increases by the same percentage with a change in temperature, including holes.

Conclusion

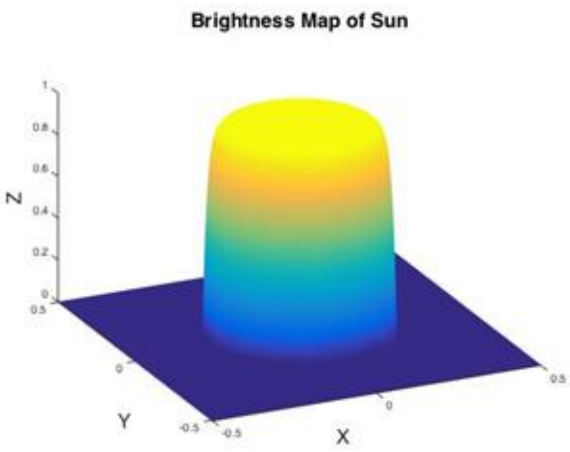
- Expansions assumed negligible so long as linear expansion and no bending (Explained on next slide)

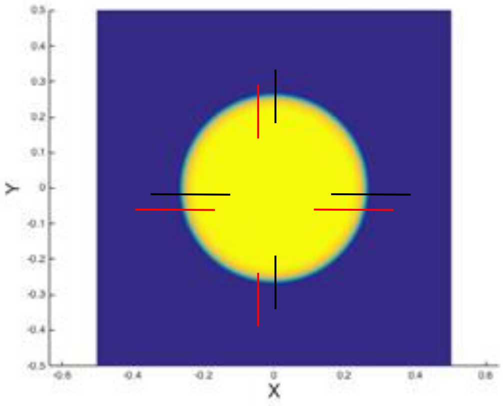
Attitude Determination Thermal Expansion

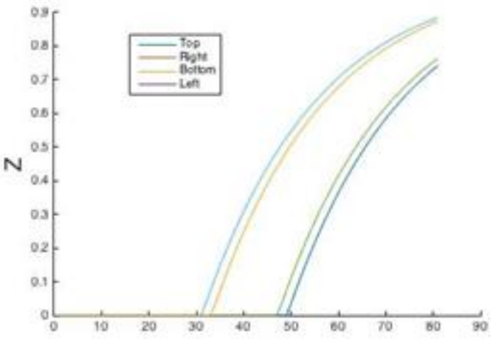


At an extreme variation in temperature where the front sun facing side is 20° K warmer than back side, the difference in optics and ADS line of sight will only be Δψ =0.00886°

ADS Calibration Plan Model







Model Process

- Build mock brightness map of the Sun in MATLAB, value of 1 at center and drop sharply to zero at edges
- Sample line of data at top, bottom, left, and right edges of Sun (black lines) with offset in X and Y coordinates (red lines, represent what optical axis “sees”)
- View functions from sample lines and find offset from these functions
- Vary model to account for various decreases in brightness and add more outward radial sample lines

Should Sun's Ellipticity be Accounted for?

Diameter of Sun from viewing point in degrees [Data from SunPy]

D = 149,559,787 km (distance from Sun to Earth)

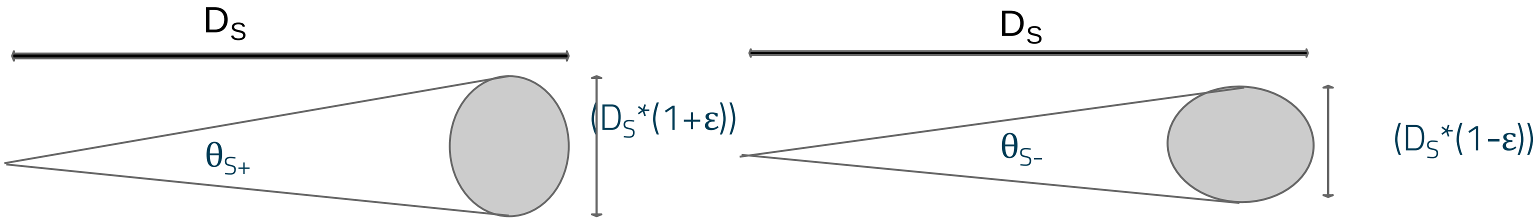
D_S = 1,391,016 km (Diameter of Sun)

ε = 5e-05 (ellipticity of Sun)

$\theta_{S+} = \tan^{-1}((D_S*(1+\varepsilon))/D) = 0.532904°$

$\theta_{S-} = \tan^{-1}((D_S*(1-\varepsilon))/D) = 0.532851°$

$\Delta\theta = |\theta_{S+} - \theta_{S-}| = 5.3e\text{-}05° =$ <u>0.00318</u> arc minutes

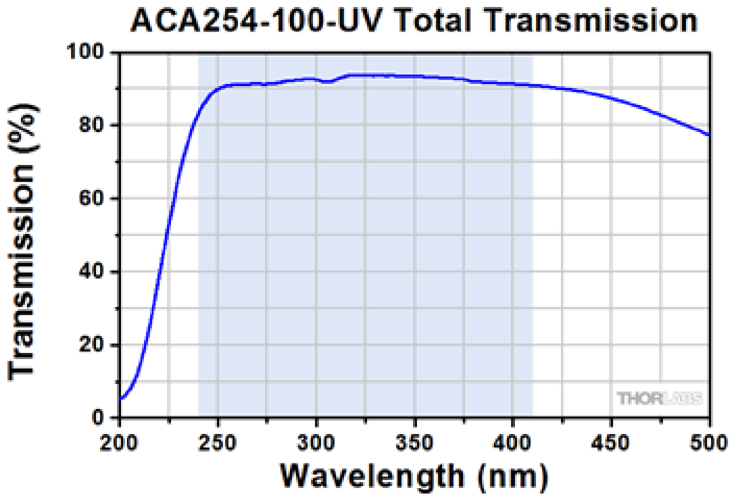


No, we can assume a perfect circle

Lens Baseline Design

Thorlabs ACA254-UV-150

- Air-Spaced Doublet to correct for chromatic aberrations

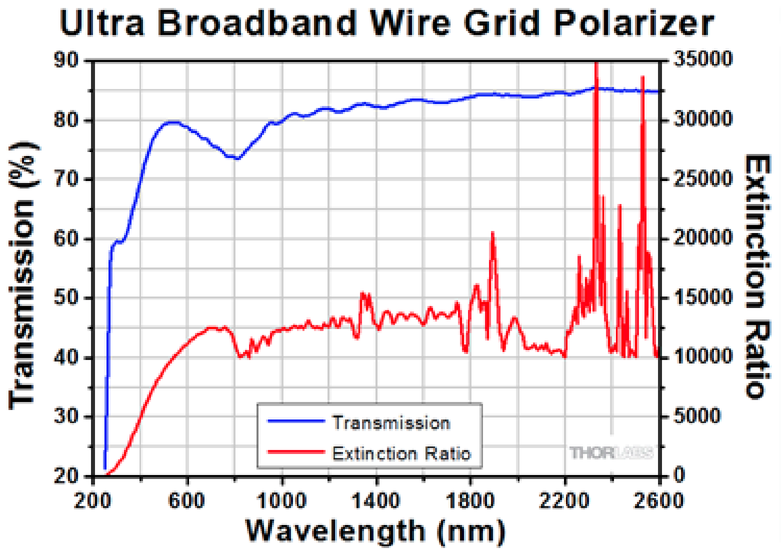


Price	$969
Focal Length	150mm
Clear Aperture	18mm

Polarizer Baseline Design

Thorlabs 25 mm Diameter Mounted Wire Grid Polarizer

- ➢ Provided by Customer



Spectrometer Baseline Design

Avantes Mini 2048

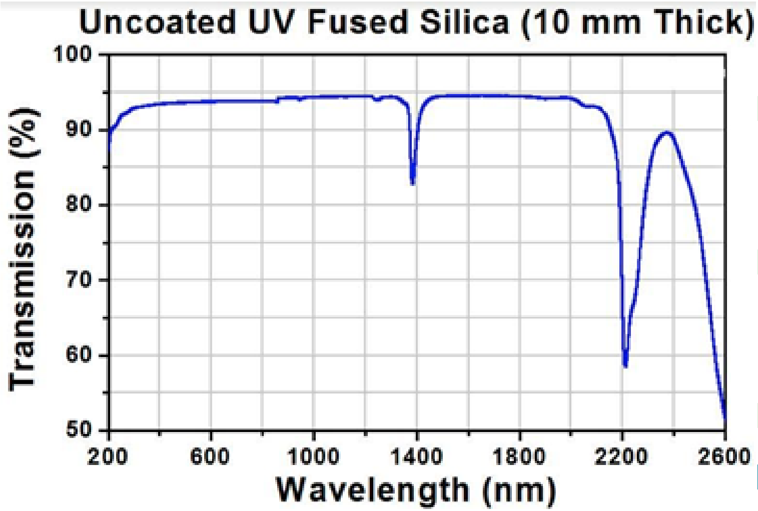
- ➢ Inherited From RADIANCE

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

Spectrometer Coupling Design

Avantes COL-UV/VIS-25

➢ Collimating lens attached to spectrometer delivers light from image plane to the spectrometer aperture



Price	$600
Diameter	25 mm
FOV	~25º

Polarizer Mount

Key Specifications	
Maximum Speed	10 deg/sec
Minimum Speed	0.005 deg/sec
Repeatable Incremental Movement	0.03 deg
Absolute Accuracy	+/- 0.14 deg

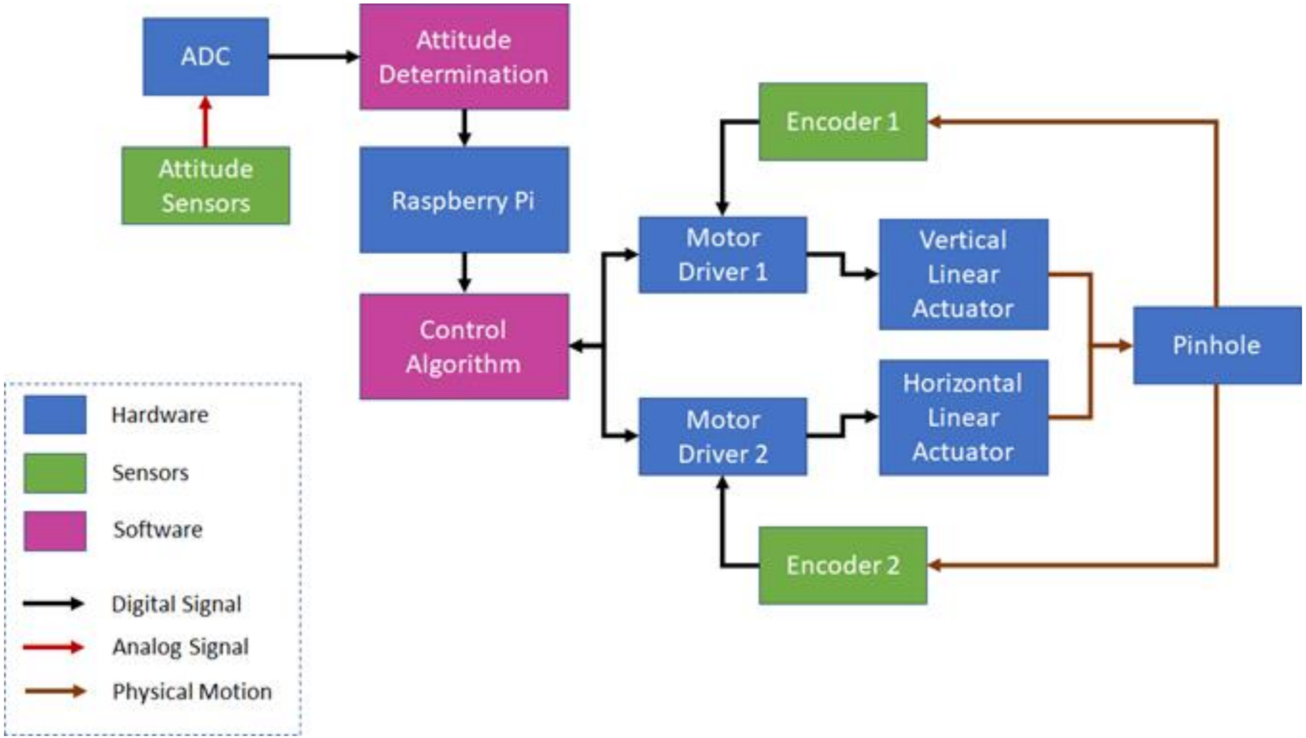
Instrument Actuators

Haydon Kerk Size 8 Type U Linear Actuators

- ➢ Non-captive for horizontal movement

Key Specifications	
Step Size	.0015 mm
Dimensions	28.8 mm x 20 mm
Max Displacement	101.6 mm

Functional Block Diagram – Controls



Battery Baseline Design

Table 3 Battery Types

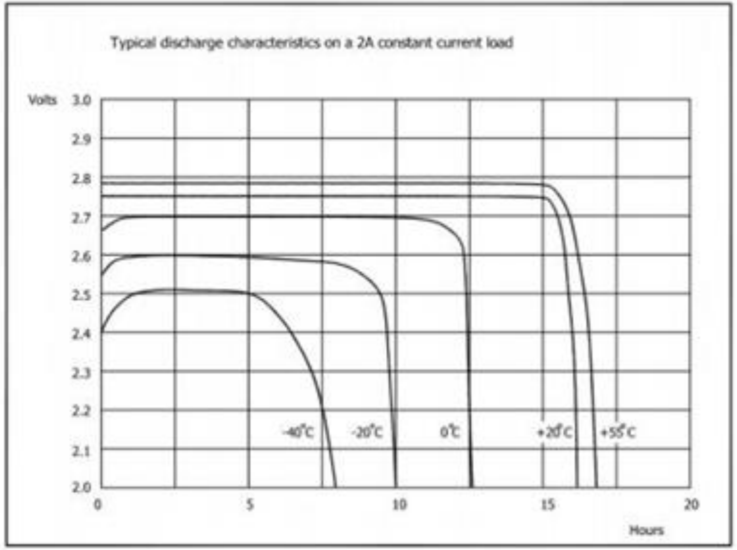
Battery	Cells per Pack	Loaded Voltage	Ampere Hour*
B7901-10	10	26	30
B7901-11	11	29	30
B7901-12	12	32	30
B9660	10	26	7
B9525	5	14	7
B9808	4	11.2	1
G20-12	1	2.6	7
G62-12	1	2.6	30

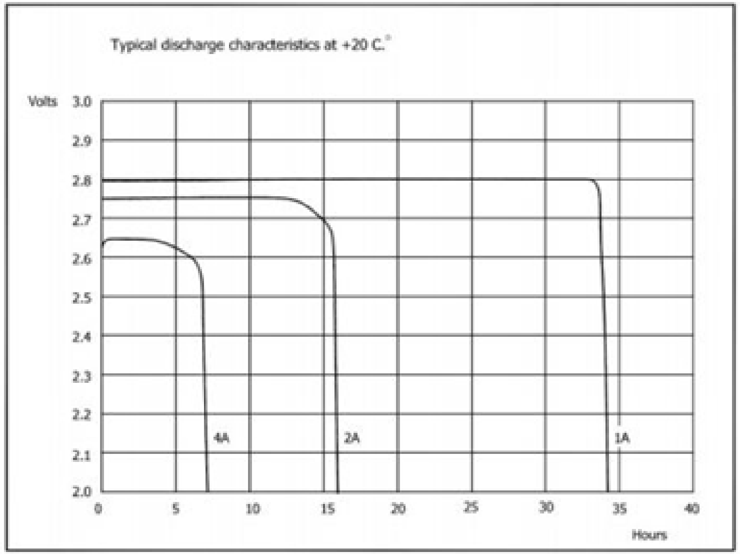
* De-rate ampere hour ratings for temperatures below -20°C.

Size (ASA Designation) ..	N/A
Length......................	141.0mm
Diameter	41.7mm
Weight	300g
Construction	Hermetically sealed, all welded steel casing, incorporating a safety vent and a glass to metal seal

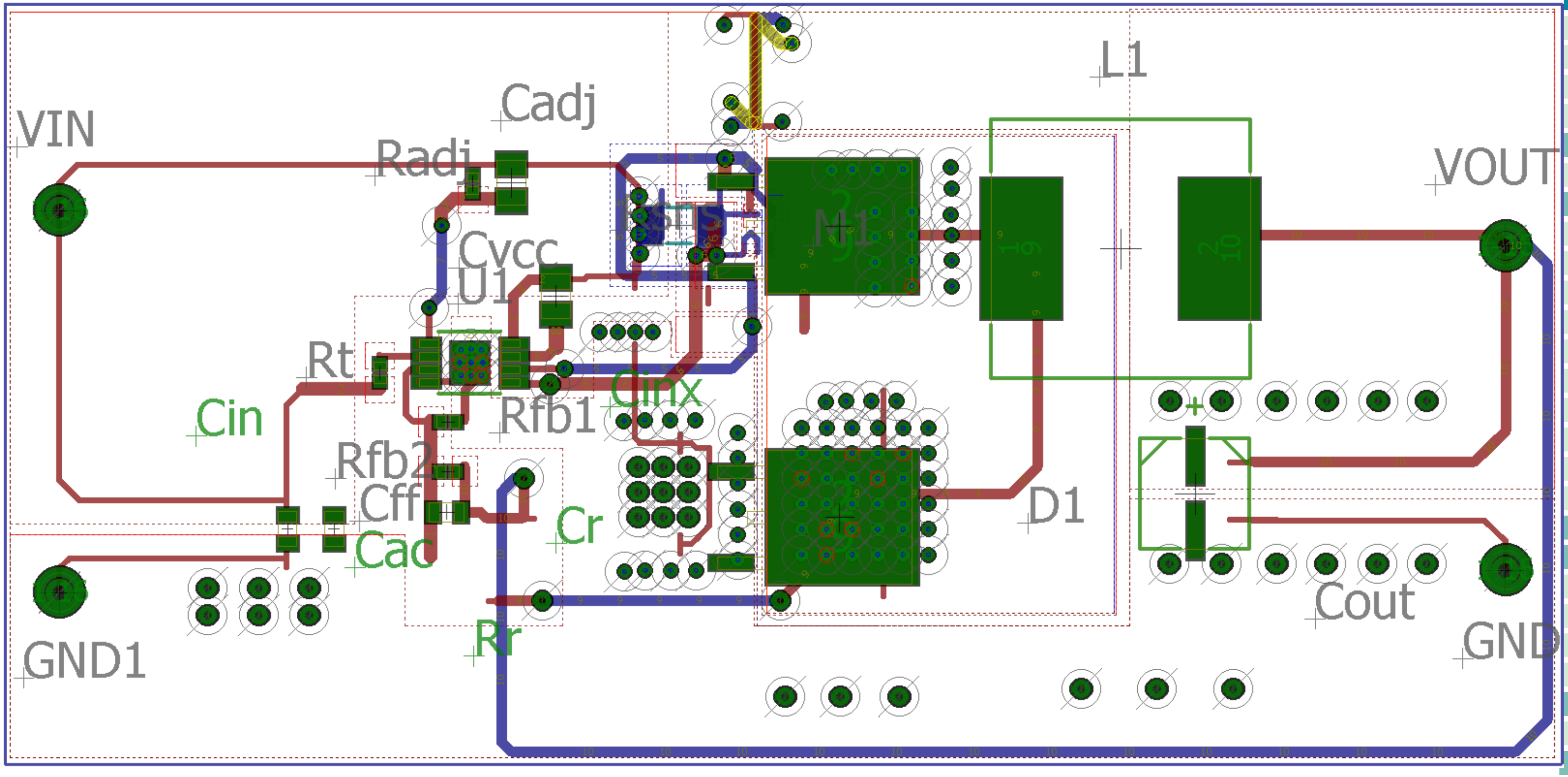
Voltage	Nominal 3.0 volts
Typical operating Voltage	2.65 - 2.80 volts
Capacity (1000mA - 2.0v)	34Ah
50% capacity achieved at	8000mA
Temperature range	-50°C + 70°C
Shelf life at ambient temperature ...	10 years
Self discharge	Typical 2% p.a.

Power Feasibility: Batteries

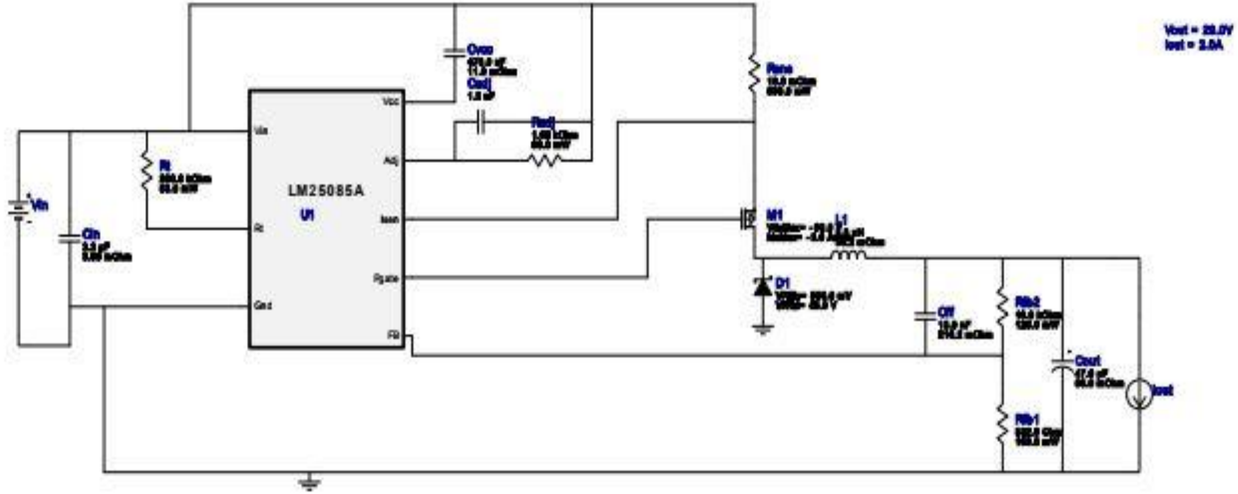




Power PCB Design



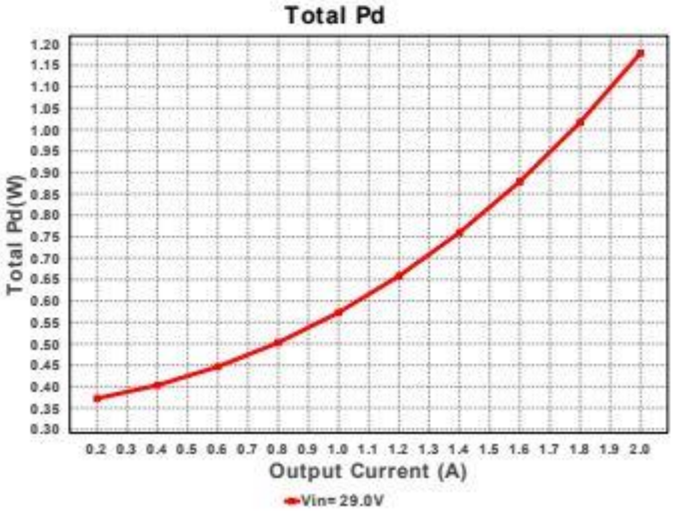
Converter Specifications: 29 V to 28 V

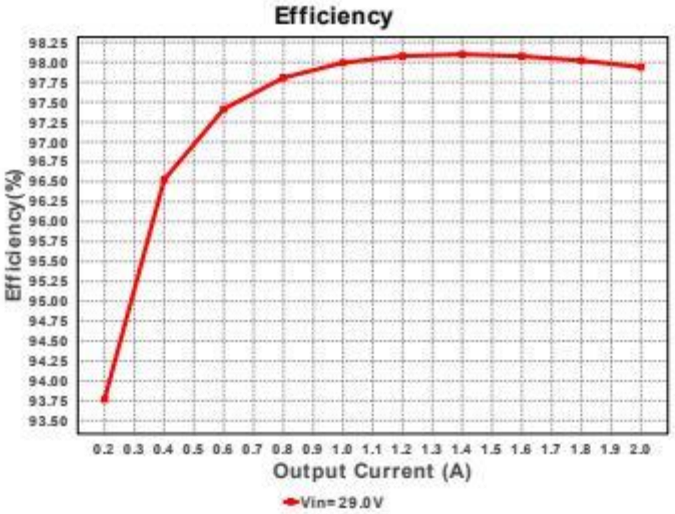


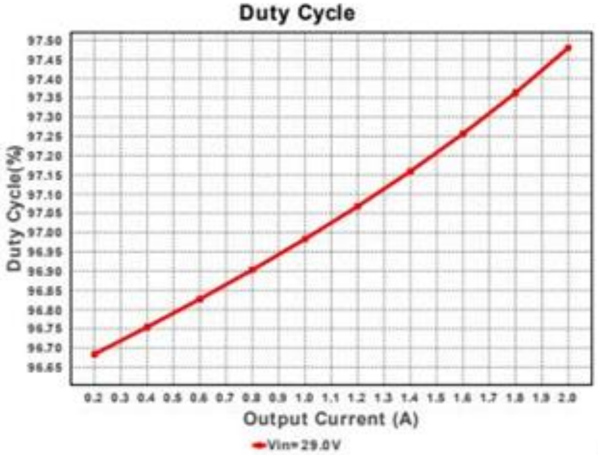
VinMin = 29.0V
VinMax = 29.0V
Vout = 28.0V
Iout = 2.0A

Device = LM25085AMY/NOPB
Topology = Buck
Created = 2017-11-29 16:04:52.713
BOM Cost = $2.18
BOM Count = 14
Total Pd = 1.17W

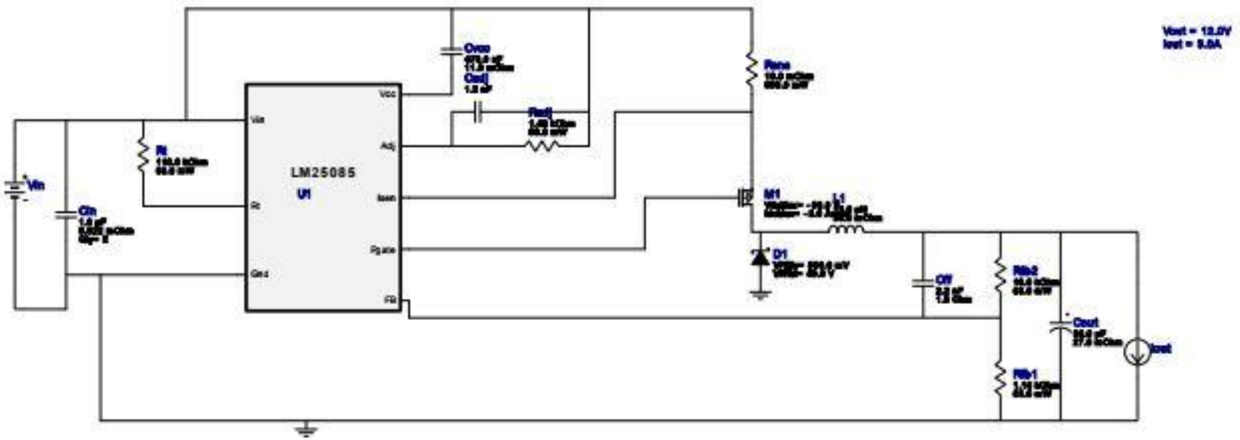
Converter Specifications: 29 V to 28 V







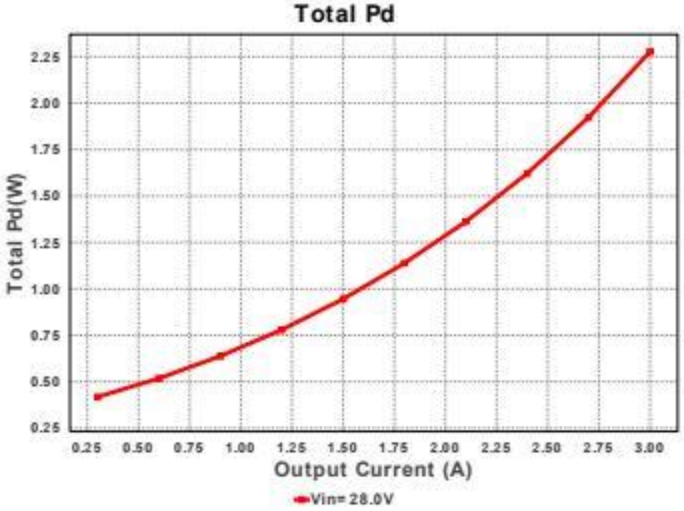
Converter Specifications: 28 V to 12 V

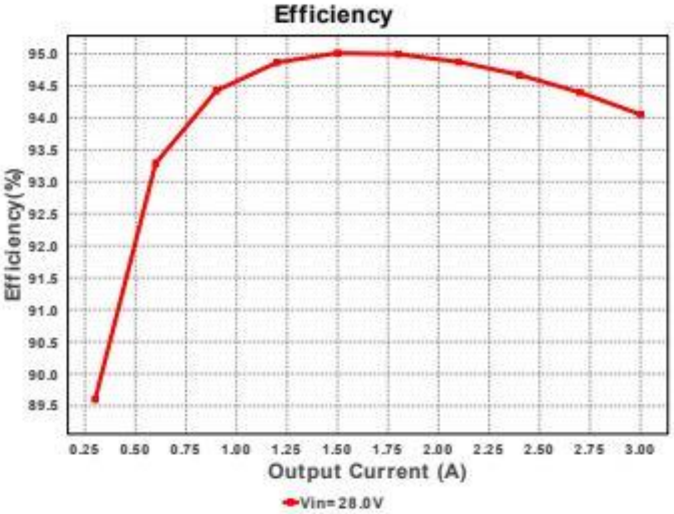


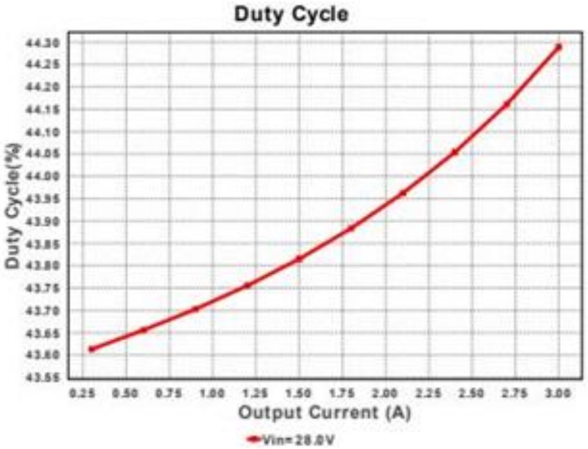
VinMin = 28.0V
VinMax = 28.0V
Vout = 12.0V
Iout = 3.0A

Device = LM25085MY/NOPB
Topology = Buck
Created = 2017-11-29 16:06:10.910
BOM Cost = $2.01
BOM Count = 15
Total Pd = 2.27W

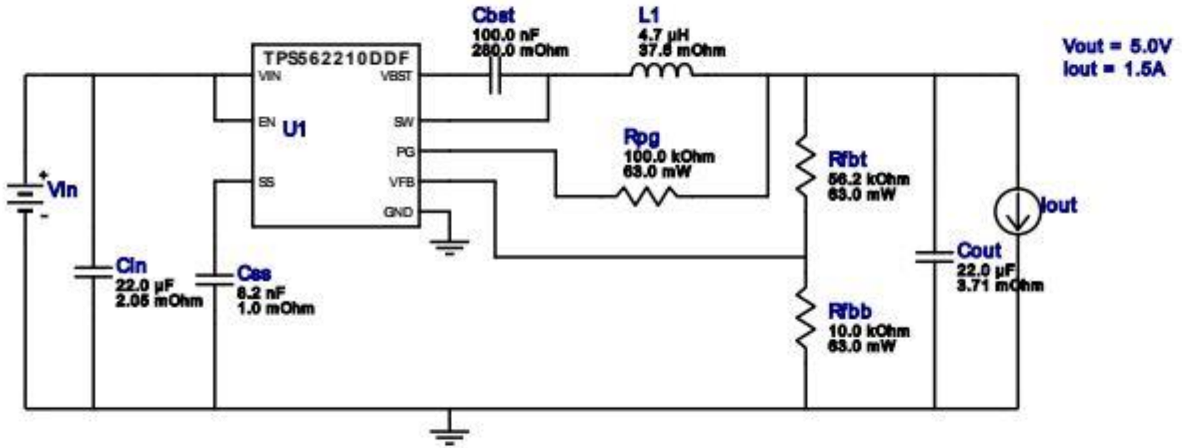
Converter Specifications: 28V to 12 V







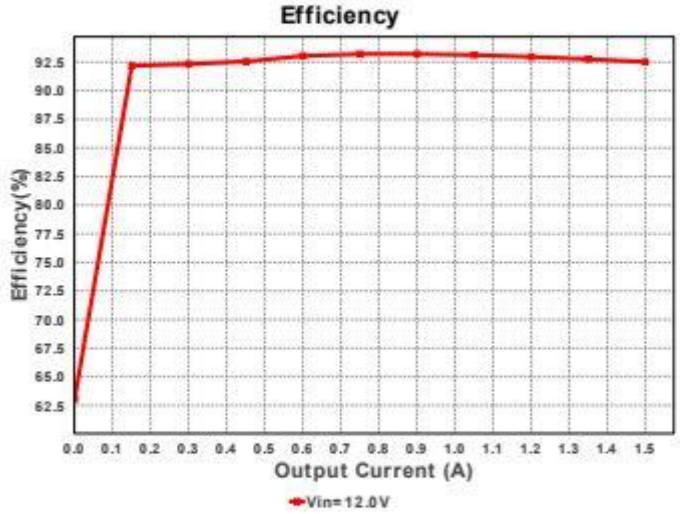
Converter Specifications: 12 V to 5 V

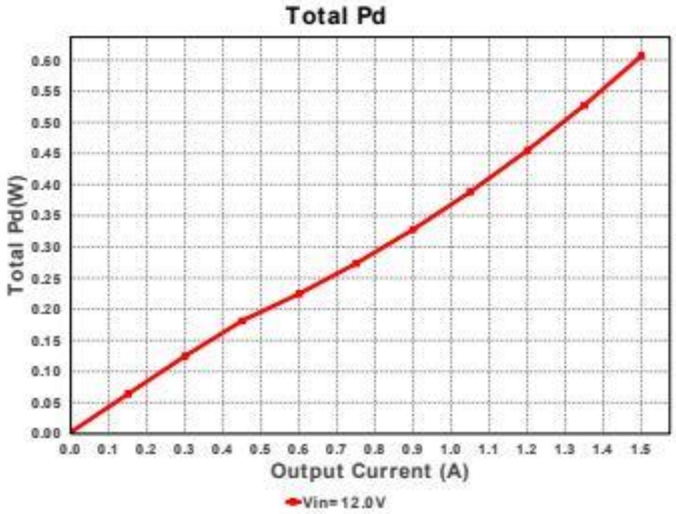


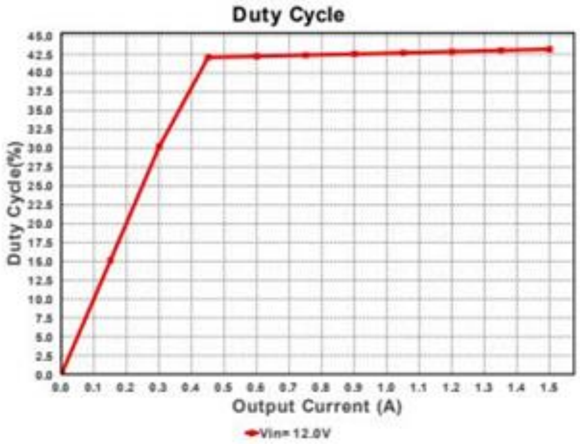
VinMin = 12.0V
VinMax = 12.0V
Vout = 5.0V
Iout = 1.5A

Device = TPS562210DDFR
Topology = Buck
Created = 2017-11-29 16:03:38.620
BOM Cost = $1.07
BOM Count = 9
Total Pd = 0.61W

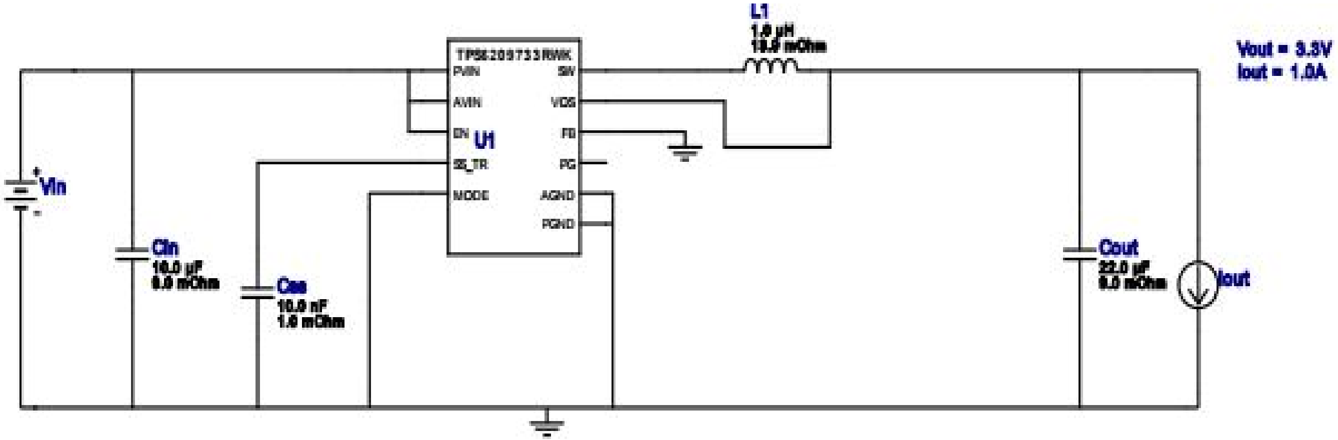
Converter Specifications: 12 V to 5 V







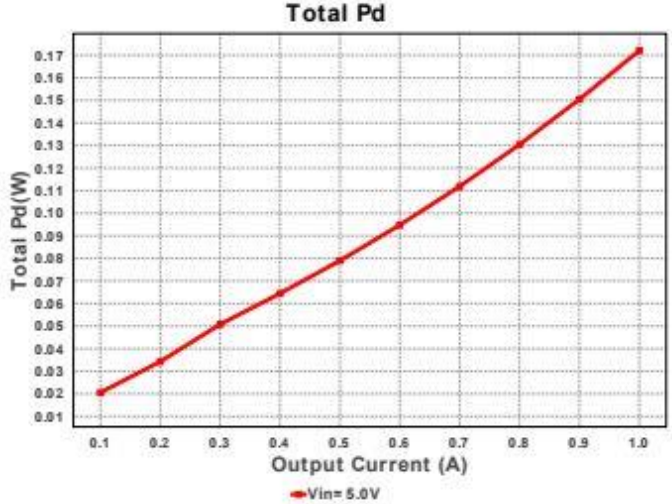
Converter Specifications: 5 V to 3.3 V

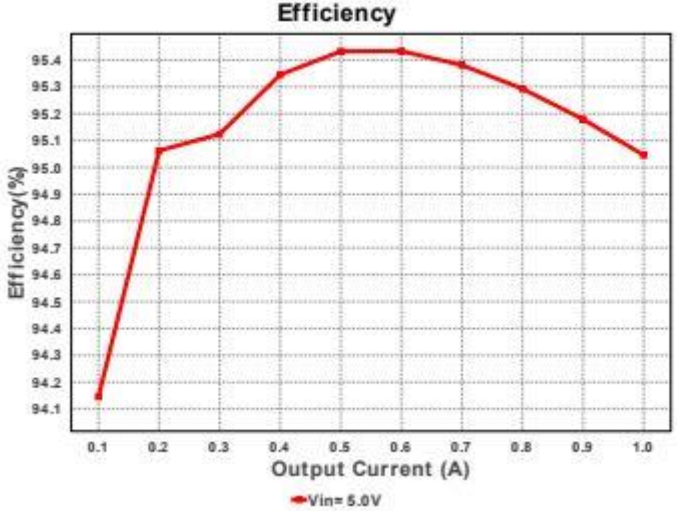


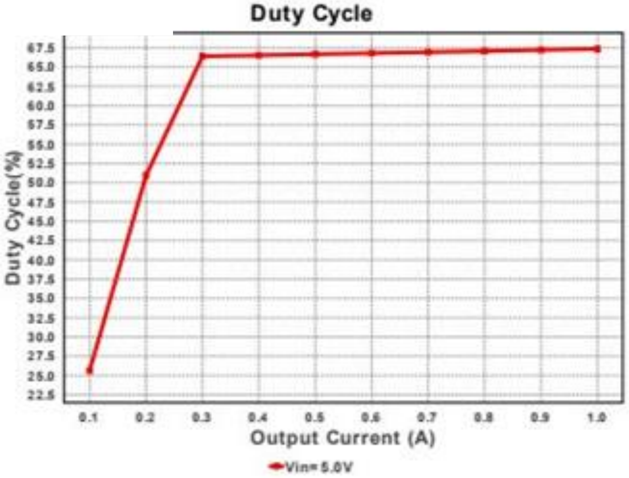
VinMin = 5.0V
VinMax = 5.0V
Vout = 3.3V
Iout = 1.0A

Device = TPS6209733RWKR
Topology = Buck
Created = 2017-11-29 16:07:26.646
BOM Cost = $0.99
BOM Count = 5
Total Pd = 0.17W

Converter Specifications: 5 V to 3.3 V







Storage Calculations for Storage Medium

Component	Number of Sensors	Size of Meas. [bits]	Times Recorded	Total Data Over Flight [GB]
External Temp	2	16	1209600	0.0387072
Internal Temp	7	64	1209600	0.5419008
GPS	1	520	10	0.0000052
Pressure	1	24	1209600	0.0290304
Camera	1	600000	60480	36.288
Humidity	1	8	1209600	0.0096768
Spectrometer	2	10000	248220	9.9288
ADS	2	17	6048000	0.205632
			Total:	47.0417524

Assumptions:

- ➢ Time of flight is two weeks=1,209,600s
- ➢ Pictures will only be taken during daytime
- ➢ Each single number measurement will be stored as a C++ double; 8 bytes

Read Rates Calculations

Component	Number of Sensors	Size of Meas. [bits]	Read Rate	Sub Total [s]
External Temp	2	16	100 kbit/s	.00016
Internal Temp	7	64	83 ns/port	.00000581
GPS	1	520	9600 bit/s	.0542
Pressure	1	24	100 kbits/s	.00024
Camera	1	600000	40 MB/s	0.15
Humidity	1	8	10 KB/s	0.0001
Spectrometer	2	10000	30 MB/s	0.00034
ADS	2	17	9600 bits/s	0.001770
			Total:	0.2069766433

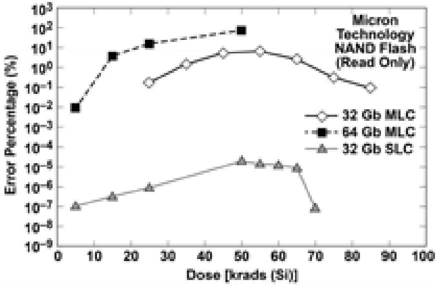
Data Storage Feasibility

Spectrometer Data Approximation:

- 788 scan points on sun * 8 polarization angles per scan
  - 6304 measurements
- 10 kB per measurement
- 63.4 MB required for full sun scan
- MX-ES 64GB SLC Flash Drive
  - Has radiative protection
- Assume 3 second integration time: 1.0945 days for full sun scan
- 12 full scans possible

Data Storage Radiation Effect Research

- Radiation events are common at altitude
  - Graph shows that number of detected radiation events grows with altitude
  - STOUT will fly at 40km
  - Hundreds of events detected at 35 km
- Radiation Events can affect flash memory
  - Single event upsets can cause bit flips in flash memory
  - Single layer cell flash memory has less chance of having a bit flip due to a Single event upset



Source: "Single Event Effect and Total Ionizing Dose Results of Highly Scaled Flash Memories" http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6658209

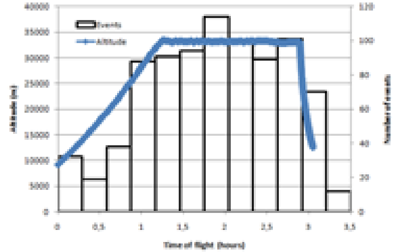


Figure 9 : Comparison between the evolution of the number of detected events as a function of time of flight and altitude profile.

Source: "Radiation Measurements in the Stratosphere" http://spaceflight.esa.int/pac-symposium_archives/files/papers/s7_10pantel.pdf

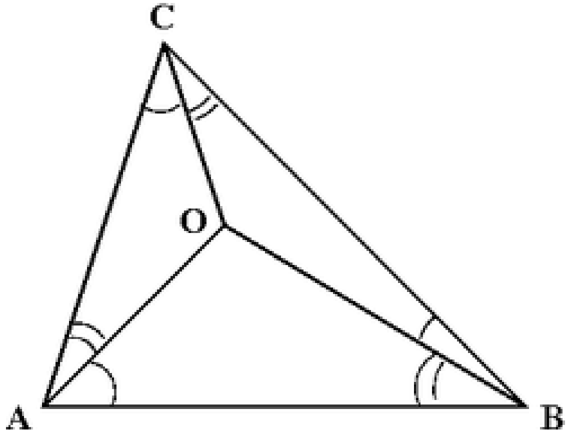
Photodiode for Testing

- **SG01S-18**
  - UV broadband spectrum
  - 0.06 mm^2 detector area
  - 10 mW/cm^2 irradiation at 280 nm (peak responsivity)

Pointing Angle Determination

1. Positions of A (vertical gimbal), B (front gimbal), C(horizontal gimbal) always known
2. Lengths of AB, BC, AC,BO always known
3. Knowing desired azimuth and altitude of pointing, can find vector of BO - [Sin(azimuth)*Cos(altitude), -Sin(altitude), Cos(azimuth)*Cos(altitude)] * |BO|
1. Position and direction of actuator connections to optical cage relative to O are constant in the frame of the optical cage
1. Once O coordinates are found, can find coordinates of ball joint centers, which connect linear actuators to the optical cage. This is accomplished by rotating their vectors relative to O by the azimuth and altitude.
1. The normal of the vector between the ball joint center, and motor gimbal center is taken. This is considered to be the extension length of the two actuators. To find the actual actuator extension the actuators need to measured inside their mounting cases on their gimbals, in order to find the extension of the center of the gimbal to the edge of the motor

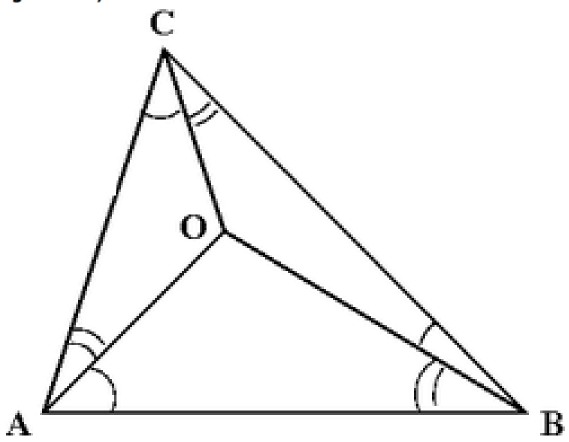
A: Vertical actuator center
B: Optics cage gimbal center
C: Horizontal actuator center
O: Center of actuator pushing plane



Pointing Angle Determination

```
(*Declare positions of gimbal and ball joint centers*)
(*Offset from CAD origin*)(**)
FrontGim1 = {33.7, 330.74, 381.61};
(*Center of optics cage gimbal*)
FrontGim = {0, 0, 0};
(*Center of vertical actuator gimbal*)
VertGim = {59.2, 232.47, 280.25} - FrontGim1;
(*Center of horizontal actuator gimbal*)
HorGim = {15.60, 287.47, 280.32} - FrontGim1;
(*Center of vertical actuator spherical rolling joint*)
VertBall = {66.85, 274.42, 281.73} - FrontGim1;
(*Center of horizontal actuator spherical rolling joint*)
HorBall = {54.34, 286.93, 281.75} - FrontGim1;

(*Determine lengths between nodes*)
(*Length between vertical actuator spherical rolling joint and optics gimbal*)
FVlength = √(FrontGim.VertGim) ;
(*Length between horizontal actuator spherical rolling joint and optics gimbal*)
FHlength = √(FrontGim.HorGim) ;
(*Length between vertical actuator spherical
 rolling joint horizontal actuator spherical rolling joint*)
VHlength = √(VertGim.HorGim) ;
(*Distance from pointing apex to front gimbal mount*)
FApexlength = 99.86;
```

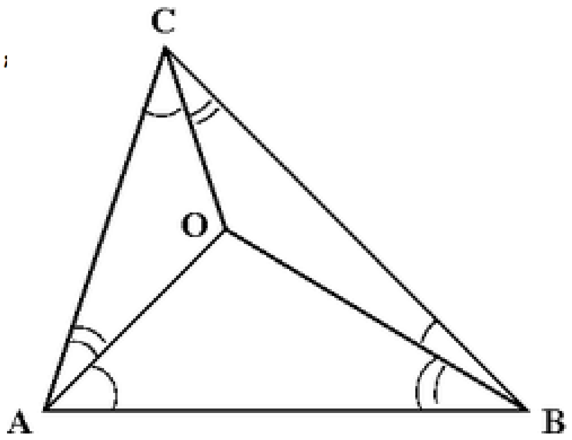
A: Vertical actuator center
B: Optics cage gimbal center
C: Horizontal actuator center
O: Center of actuator pushing plane



Pointing Angle Determination

```
(*Find apex cartesian coordinates for zero degree actuation*)
ApexZero = FrontGim - {0, 0, FApexlength};
(*Vector between apex center and spherical rolling joints*)
ApexHorVec = ApexZero - HorBall;
ApexVertVec = ApexZero - VertBall;

(*Input desired deflections*)
azimuth = -1 * π/180;
altitude = -1 * π/180;
(*Find optical axes vector at desired pointing angles*)
normalVecUnit = {Sin[azi ] * Cos[alt ], -Sin[alt ], Cos[azi ] * Cos[alt]};
normalVec = normalVecUnit * FApexlength;

(*Find cartesian coordinates of pointing apex at desired pointing angle*)
Apex = FrontGim - normalVec;
(*Rotation matrix for vectors between apex center and spherical rolling joints*)
ConvertMat = {{Cos[azimuth], Sin[azimuth] * Sin[altitude],
     Sin[azimuth] * Cos[altitude]}, {0, Cos[altitude], -Sin[altitude]},
    {-Sin[azimuth], Cos[azimuth] * Sin[altitude], Cos[altitude] * Cos[azimuth]}};
(*Find cartesian coordinates of spherical rolling joints*)
ApexHorVecNew = ConvertMat.ApexHorVec;
ApexVertVecNew = ConvertMat.ApexVertVec;
VertBallNew = Apex - ApexVertVecNew;
HorBallNew = Apex - ApexHorVecNew;
VertBallFinal = Transpose[ConvertMat].VertBallNew;
```

A: Vertical actuator center
B: Optics cage gimbal center
C: Horizontal actuator center
O: Center of actuator pushing plane

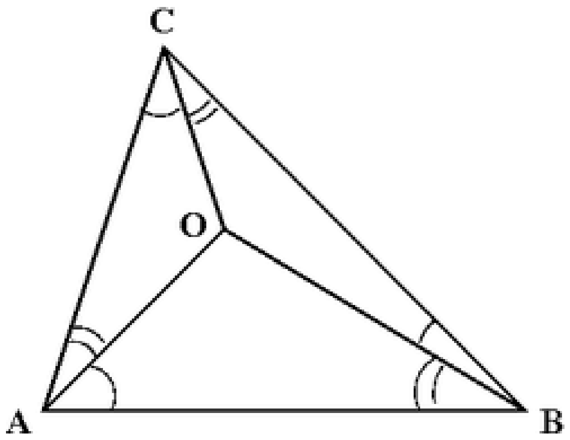


Pointing Angle Determination

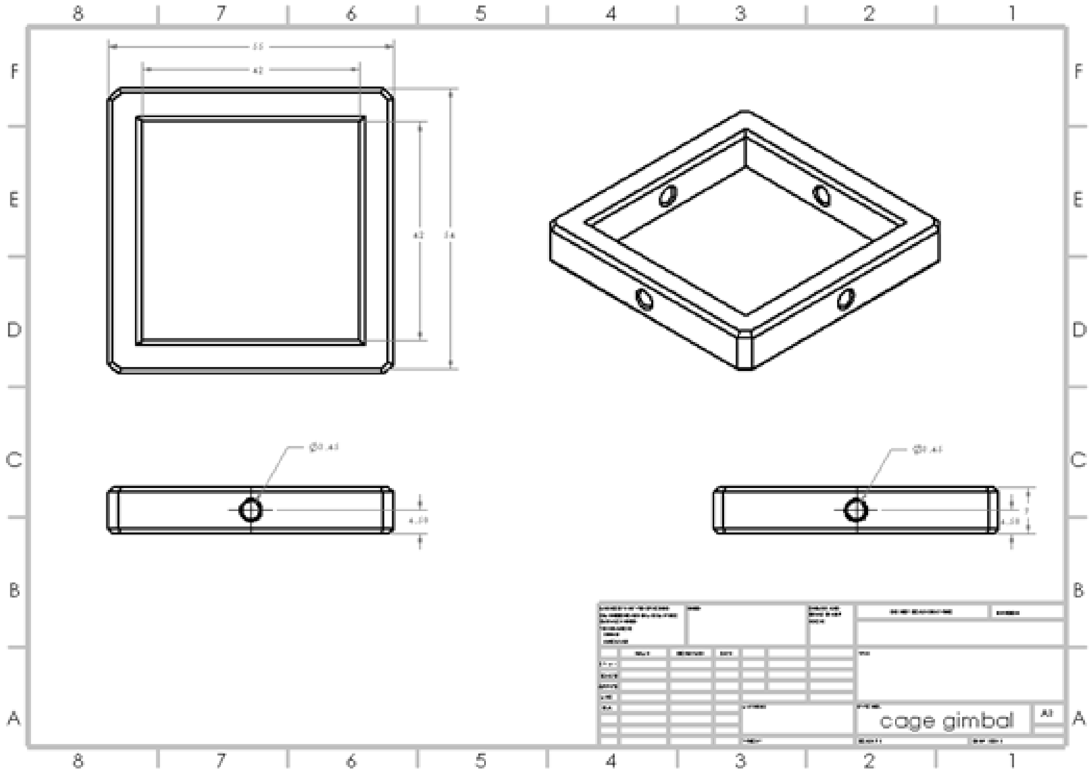
```
HorBallFinal = Transpose[ConvertMat].HorBallNew;
(*Find vectors between spherical rolling joints and motor gimbals*)
HorBallGimVec = HorBallFinal - HorGim;
VerBallGimVec = VertBallFinal - VertGim;
(*Determine length between spherical rollings joints and motor gimbals*)
"Vertical Length"
VertActLength = Norm[VerBallGimVec]
"Horizontal Length"
HorActLength = Norm[HorBallGimVec]
```

```
Out[156]= Vertical Length

Out[157]= 42.6675

Out[158]= Horizontal Length

Out[159]= 38.7701
```

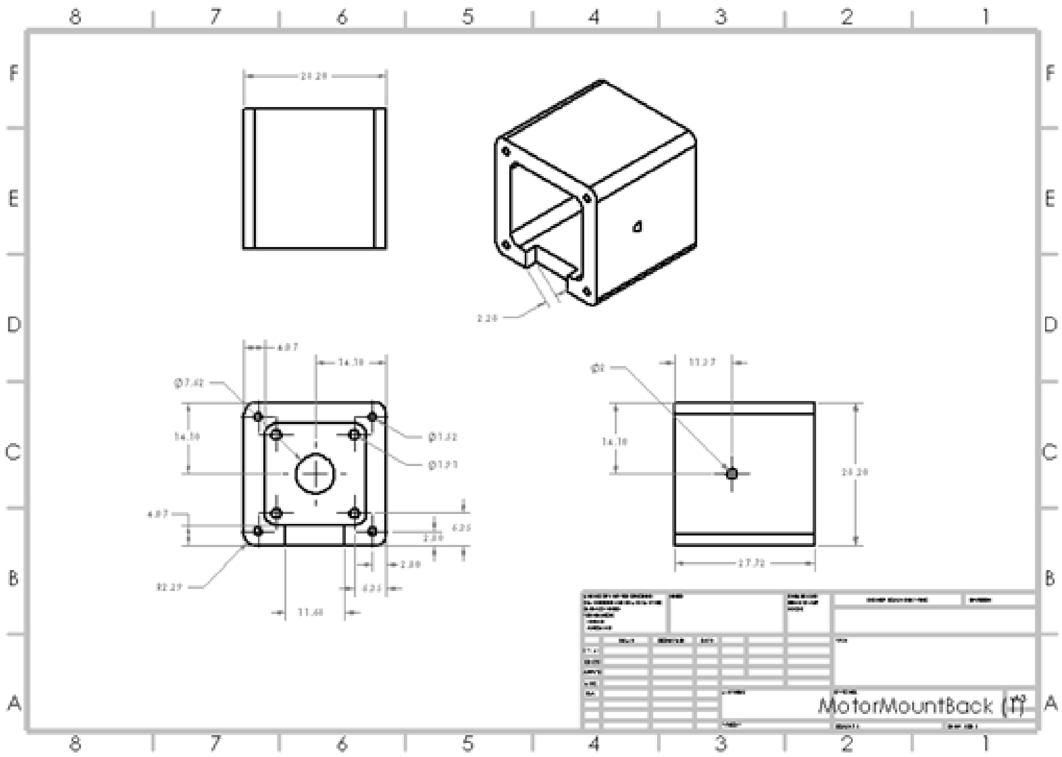
A: Vertical actuator center
B: Optics cage gimbal center
C: Horizontal actuator center
O: Center of actuator pushing plane



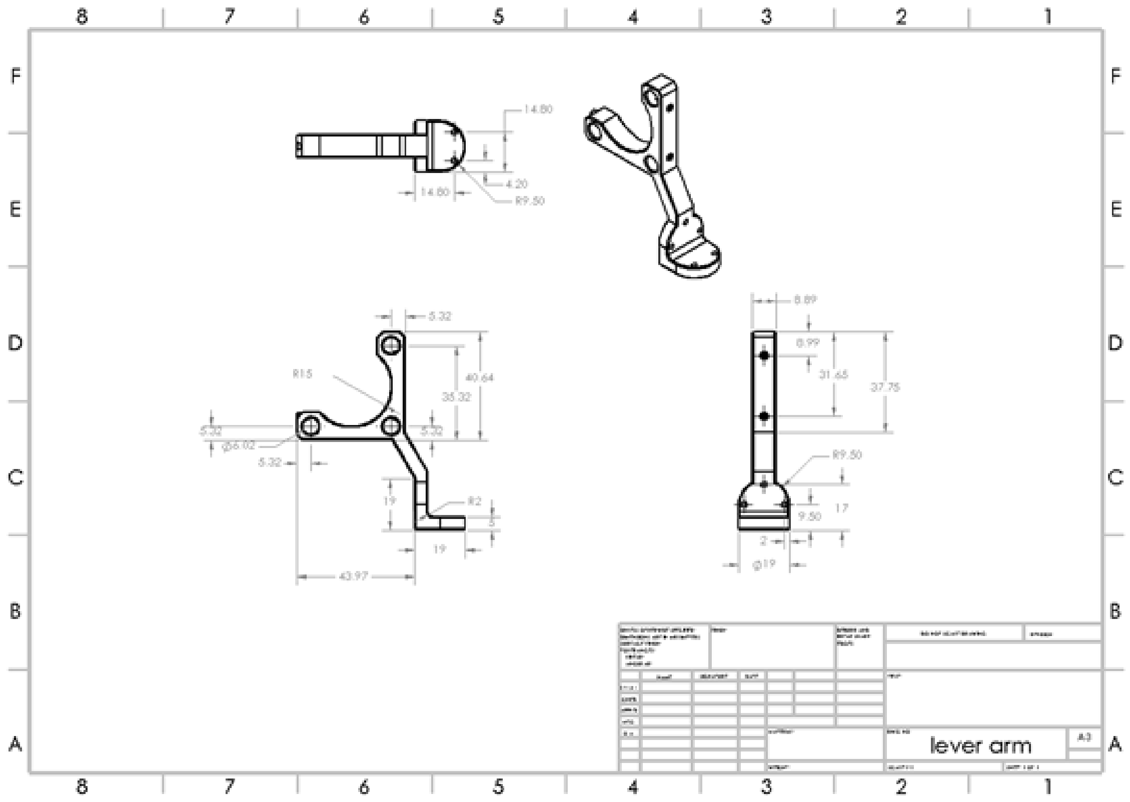
Cage Gimbal Drawing



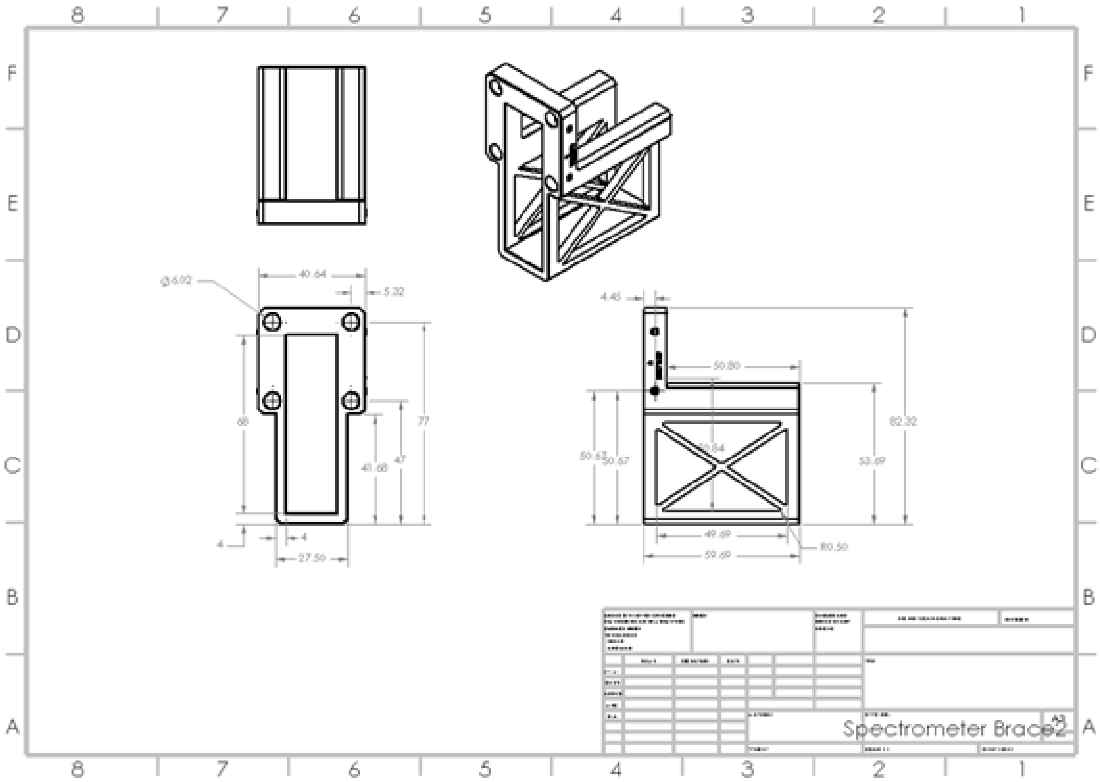
Motor Case Gimbal – Back Drawing



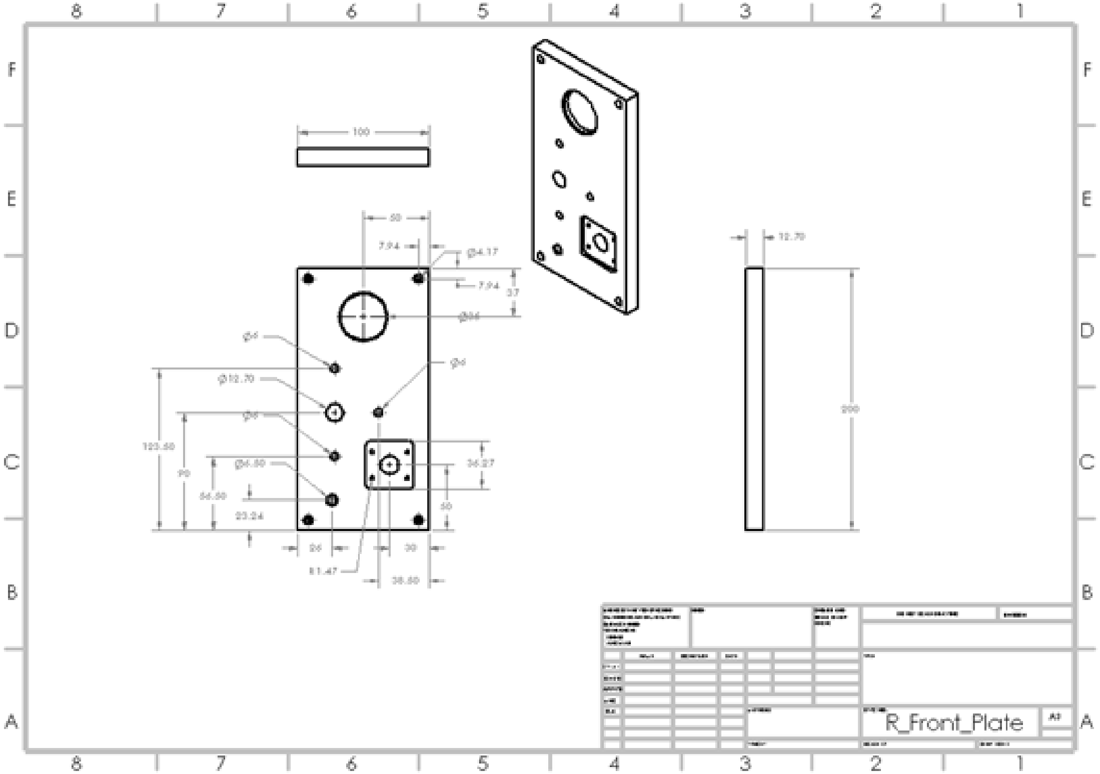
Actuation Arm Drawing



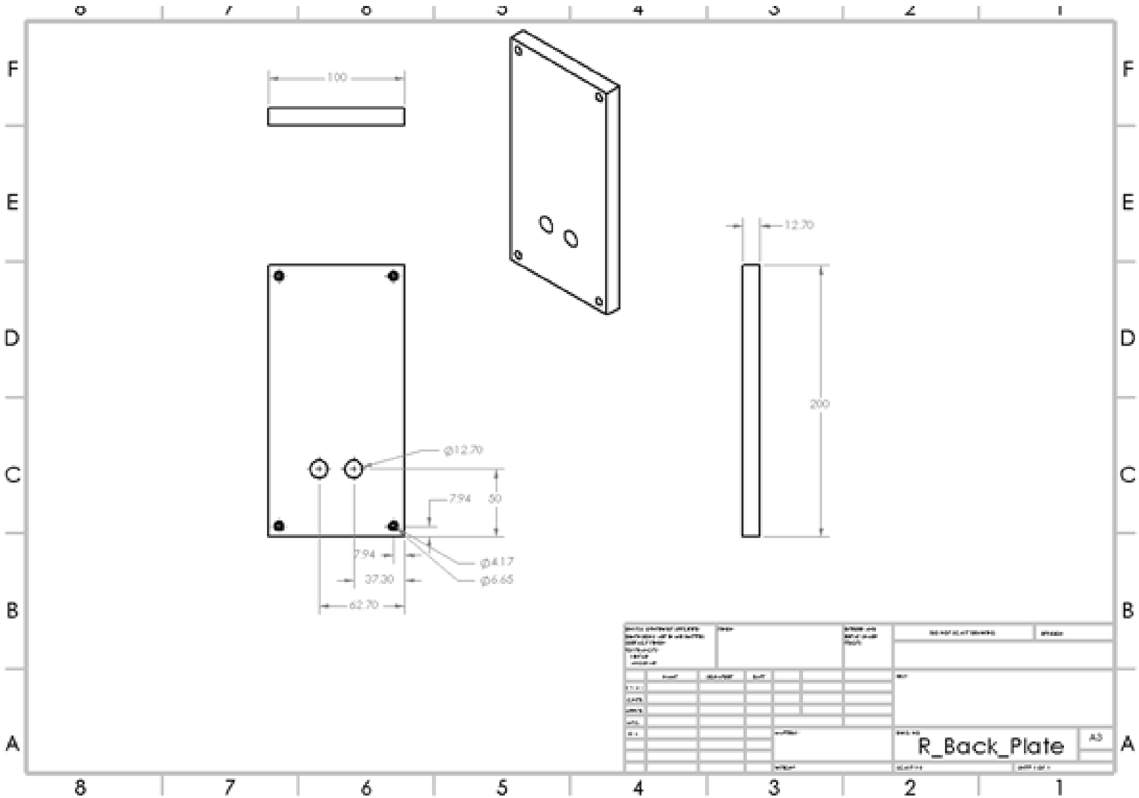
Spectrometer Brace Drawing



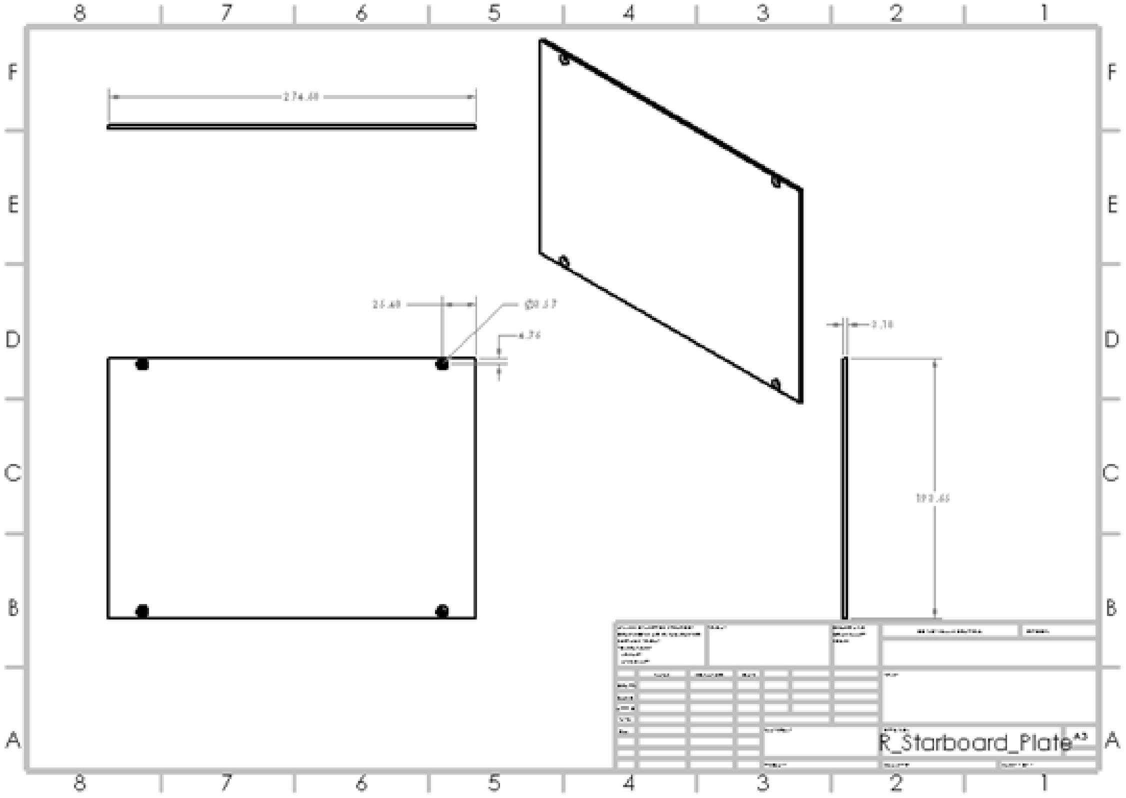
Front Plate Drawing



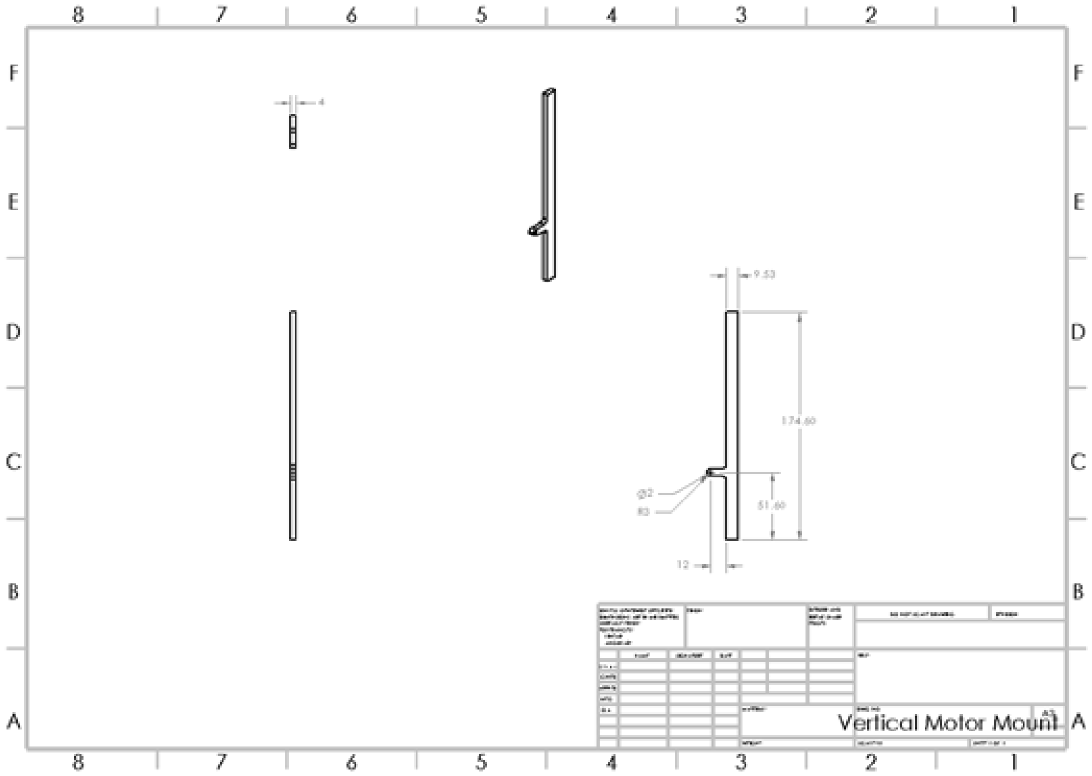
Back Plate Drawing



Side Panel Drawing



Vertical Motor Brace Drawing



Horizontal Motor Brace Drawing