STOUT

Spectropolarimeter Telescope Observatory for Ultraviolet Transmissions

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5. Ian Geraghty
6. Andrew Lux
7. Dawson Stokely

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

**Customer:**
NCAR High Altitude Observatory
1. Phil Oakley
2. Scott Sewell

**Advisor:**
Francisco López Jiménez
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 Balloon

Pointing extremes

NASA Gondola: Controlled FOV

Optics Cage
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 +/- 5º of the Sun
  - Solar irradiance data collected
  - Polarized UV spectra collected
- Descent: 1 hr
  - Customer retrieves data
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

Delimitate Light Spectrum Through Optics Train
Using STOUT optics train, obtain UV spectrum intensity data by passing whole spectrum light through optical axis

Data Collection
Scan entirety of Sun, collecting and saving UV spectrum intensity data
Design Solutions
System Overview

Summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>10x20x30 cm</td>
</tr>
<tr>
<td>Mass</td>
<td>4.4 kg</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>74.5 W</td>
</tr>
<tr>
<td>Flight Environment</td>
<td>-70°C - 20°C</td>
</tr>
<tr>
<td>Materials</td>
<td>Aluminum 6061 (Structure) Polyisocyanurate (Insulation)</td>
</tr>
</tbody>
</table>
Functional Block Diagram

- Camera
- External Environmental Sensors
- Internal Environmental Sensors
- Attitude Sensors
- UV Spectrometer
- UV-Visible Spectrometer
- Data Handling Unit (USB Drives)
- Command Unit (UDOOS X86)
- Power Control Unit
- Pointing/Polarizer Control System
- Attitude Determination System
- Thermal Control System
- Gondola Power

Legend:
- Instrumentation
- Hardware
- Control Software
- External Hardware
- Command Data
- Power Line
- Image Data
- Environmental Data
- Attitude Data
- RADIANCE Component

Environmental sensors include: humidity, pressure, and temperature
Hardware Architecture Diagram
**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
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

Design Solutions
Components

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

Components
  ○ Custom PCB to distribute power to subsystems
Critical Project Elements
Critical Project Elements

- Instrumentation & Control
  - Lenses
  - Polarizer Mount
  - Pointing Actuators
  - Optics Mount

- Environmental Monitoring & Control
  - Active Control

- Attitude Determination
  - Sun Sensor

- Data Acquisition
  - Software

Legend:
- Subsystem
- Sub-Subsystem
- Controlled Sub-Subsystem
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

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>During ascent and descent the system shall survive external temperatures ranging from -65°C to 20°C</td>
</tr>
<tr>
<td>5.2</td>
<td>During cruise the system shall operate under external temperatures ranging from -25°C to -15°C</td>
</tr>
<tr>
<td>5.3</td>
<td>The system shall operate at pressure values of 100 kPa to 10 Pa</td>
</tr>
</tbody>
</table>
EMCS Requirements

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

![Graph showing temperature changes during ascent]

- Survival temperature determined by spectrometer.
- Survivability temperature.
- Internal Temperature (20 W Heating).

Design Requirements and Satisfaction
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)

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>STOUT Internal Temp.</td>
<td>15°C (STD sea level)</td>
</tr>
<tr>
<td>Ambient Temperature</td>
<td>-65°C (Lower temperature limit of ascent)</td>
</tr>
<tr>
<td>Air Convective Heat Transfer Coefficient (External and Internal)</td>
<td>~5 W/m²K</td>
</tr>
</tbody>
</table>
Expected Spectrometer Temperatures at -65°C Environment

1”x2" Heat Pad 25 W Power Output

1”x2" Heat Pad 20 W Power Output

Spectrometer 1: 36°C

Spectrometer 2: 29°C

Power Board 5W Power Output
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**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>The off-light source angle attitude shall be determined to within 3′ (0.05°) of light source center</td>
</tr>
<tr>
<td>3.2</td>
<td>Attitude data shall be recorded synchronously with instrument data</td>
</tr>
<tr>
<td>3.3</td>
<td>Attitude data shall be interfaced with instrumentation pointing control</td>
</tr>
</tbody>
</table>
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

Sun Off-Angles ($\alpha$ & $\beta$)
- Communicates the sun's position relative to field of view to the system
- Data saved and used in optics controls

\[
\begin{align*}
 x_1 &= V_3 + V_4 \\
 x_2 &= V_1 + V_2 \\
 F_x &= \frac{x_2 - x_1}{x_2 + x_1} \\
 y_1 &= V_1 + V_4 \\
 y_2 &= V_2 + V_3 \\
 F_y &= \frac{y_2 - y_1}{y_2 + y_1} \\

\alpha &= \arctan(C \times F_x) \\
\beta &= \arctan(C \times F_y)
\end{align*}
\]

Parametric Value ($C$) *Dependent on Sensor*
# Optical System Requirements

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

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
<th>Level Met</th>
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</thead>
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<tr>
<td>2.1</td>
<td>Isolation of $\leq 1'$ (0.0167°) spot in the FOV</td>
<td>1</td>
</tr>
<tr>
<td>2.2</td>
<td>Take spectrum measurements over the 270 - 400 nm range</td>
<td>3</td>
</tr>
<tr>
<td>2.3</td>
<td>Rotate polarizer with $\leq 0.5$° accuracy</td>
<td>2</td>
</tr>
<tr>
<td>2.4</td>
<td>Pointing capabilities of $\pm 1$° in azimuth and $\pm 5$° in elevation</td>
<td>1</td>
</tr>
</tbody>
</table>
Optical System

**FR 2.1:** Isolation of $\leq 60''$ (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: $d = 40 +/\!/- 3 \mu m$
Lens Focal Length: $f = 150 +/\!/- 1.8 \text{ mm}$

**Isolated Spot Size**

$$\theta = 2\tan^{-1}\left(\frac{d}{2f}\right) = 55 +/\!/- 7''$$
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

### 200 - 400 nm Flux Budget

<table>
<thead>
<tr>
<th>Station</th>
<th>Total Power</th>
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<tbody>
<tr>
<td>1</td>
<td>41.8 mW</td>
</tr>
<tr>
<td>2</td>
<td>38.7 mW</td>
</tr>
<tr>
<td>3</td>
<td>23.7 mW</td>
</tr>
<tr>
<td>4</td>
<td>19.5 μW</td>
</tr>
<tr>
<td>5</td>
<td>18.1 μW</td>
</tr>
</tbody>
</table>

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

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

60” Spot Diagrams

60” Enclosed Energy

Perfectly in focal plane

40 µm Pinhole Diameter

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

Pinhole Diameter

-270 nm
-335 nm
-400 nm
**Optical System**

**FR 2.3:** Rotate polarizer with $\leq 0.5^\circ$ 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°
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

![Diagram](https://via.placeholder.com/150)

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
xₐ: Angles b/t Sun center & desired scan location
xₐc: Angles b/t Sun center & CubeSat normal axis
xₒ: Angles b/t optical axis & CubeSat normal axis
xₒc: Actual, measured value

1. Select 1st set of predetermined angles between Sun center and desired scan location (θᵣ & ψᵣ).
2. Measure angles between Sun center and CubeSat normal axis in elevation (θₑ) and azimuth (ψₑ) from ADS.
3. Transmit θₑ, θᵣ, ψₑ, & ψᵣ from Braswell processor to Curie processor.
4. Determine stepper motor linear actuations (d₁ & d₂) to achieve desired optical train angles (θₑ & ψₑ). Send step commands to both motor drivers.
5. Measure actual linear actuations with encoders.
6. Is d₁,act = d₁ & d₂,act = d₂?
   - Yes: Send new step commands for (d₁ - d₁,act) & (d₂ - d₂,act).
   - No: Measure angles between Sun center and desired scan location (θₑ & ψₑ).
7. Change polarization angle.
8. Have measurements been taken at all polarization angles?
   - Yes: Update predetermined angles between Sun center and desired scan location (θₑ & ψₑ).
   - No: Store & backup spectrometer data. Wait required spectrometer exposure time & take readings.

Design Requirements and Satisfaction
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

**Write Times**

<table>
<thead>
<tr>
<th>USB Type</th>
<th>Message Time</th>
<th>Write Rate</th>
<th>Write Sub Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>MX-ES Ultra</td>
<td>620.08 KB</td>
<td>26.7 MB/s</td>
<td>0.023 s</td>
</tr>
<tr>
<td>Samsung Fit</td>
<td>620.08 KB</td>
<td>42.12 MB/s</td>
<td>0.014 s</td>
</tr>
</tbody>
</table>

Total Time/Worst Case Write: **0.23 s**

Total Read Time: **0.2068 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

<table>
<thead>
<tr>
<th>Component</th>
<th>Wattage (W)</th>
<th>Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Udoo x86 ultra (DAQ)</td>
<td>36</td>
<td>12.0</td>
</tr>
<tr>
<td>Linear Actuators</td>
<td>2.45</td>
<td>5.0</td>
</tr>
<tr>
<td>Pad Heaters</td>
<td>40.0</td>
<td>28.0</td>
</tr>
<tr>
<td>Sun Sensor</td>
<td>0.045</td>
<td>5.0</td>
</tr>
<tr>
<td>Total</td>
<td>68.5</td>
<td>-</td>
</tr>
<tr>
<td>Converter Efficiency</td>
<td>0.8101</td>
<td>-</td>
</tr>
<tr>
<td>Needed Supply</td>
<td>74.5</td>
<td>28.0</td>
</tr>
<tr>
<td>Supply</td>
<td>87 W @ 3.0 A draw</td>
<td>29.0</td>
</tr>
<tr>
<td>Margin</td>
<td>16.7%</td>
<td>3.5%</td>
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</table>
Power Flow
Project Risks
### Risk Summary

<table>
<thead>
<tr>
<th>Risk</th>
<th>Risk Description</th>
<th>Pertaining Functional Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>Software Data Write Failure</td>
<td>FR 2, FR 3, FR 4, FR 5</td>
</tr>
<tr>
<td>R2</td>
<td>Software Bit Flip</td>
<td>FR 2, FR 3, FR 4, FR 5</td>
</tr>
<tr>
<td>R3</td>
<td>Under-heating of CubeSat Internal Components</td>
<td>FR 1, FR 2, FR 4, FR 5</td>
</tr>
<tr>
<td>R4</td>
<td>Over-heating of CubeSat Internal Components</td>
<td>FR 1, FR 2, FR 4, FR 5</td>
</tr>
</tbody>
</table>

#### Likelihood vs. Severity

<table>
<thead>
<tr>
<th>Likelihood</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>R8</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>R7</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>R3</td>
<td>R4</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>R2</td>
<td>R1/R6</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>R5</td>
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</table>
# Risk Summary

<table>
<thead>
<tr>
<th>Risk</th>
<th>Risk Description</th>
<th>Pertaining Functional Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>R5</td>
<td>Operation Failure &quot;Freeze&quot; of UDOO X86</td>
<td>FR 1, FR 2, FR 4, FR5</td>
</tr>
<tr>
<td>R6</td>
<td>Loss of Attitude Determination Calibration</td>
<td>FR 3, FR 4</td>
</tr>
<tr>
<td>R7</td>
<td>Manufacturing/Calibration/Test Delays</td>
<td>FR 1-5</td>
</tr>
<tr>
<td>R8</td>
<td>Manufacturing creates optical precision errors</td>
<td>FR2, FR4</td>
</tr>
</tbody>
</table>

**Severity Table**

<table>
<thead>
<tr>
<th>Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>1</td>
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</tbody>
</table>
# High Risk Mitigation

<table>
<thead>
<tr>
<th>Risk</th>
<th>Risk Description</th>
<th>Risk Mitigation</th>
</tr>
</thead>
</table>
| 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 Matrix

<table>
<thead>
<tr>
<th>Likelihood</th>
<th>Severity</th>
</tr>
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<tbody>
<tr>
<td>1</td>
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<tr>
<td>2</td>
<td>3</td>
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<tr>
<td>3</td>
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<tr>
<td>4</td>
<td>5</td>
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<td>5</td>
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</tr>
</tbody>
</table>

- R8
- R7
- R4

## Project Risks
## Medium Risk Mitigation

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

### Types of Risks

- **X** Budget
- **X** Technical
- □ Safety
- □ Schedule

### Risk Matrix

<table>
<thead>
<tr>
<th>Severity</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
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<tr>
<td>2</td>
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<td>R3</td>
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<tr>
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<td>R1/R6</td>
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**Likelihood**

- 1
- 2
- 3
- 4
- 5

**Project Risks**
Verification and Validation
Verification and Test Plan

<table>
<thead>
<tr>
<th>Component Selection</th>
<th>Component Testing</th>
<th>Subsystem Testing</th>
<th>Integration Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Operational &amp; Survival Conditions</td>
<td>- Motors - Polarizer Mount - DAQ/CPU - Powerboard circuit Breadboard</td>
<td>- Optics Train - Udoo Board &amp; Storage Devices</td>
<td>- ADS/Pointing Integration and Calibration</td>
</tr>
<tr>
<td>- Resolution</td>
<td>- Heaters &amp; Thermocouples - Spectrometers - Sun Sensor</td>
<td>- Power Board - EMCS - RADIANCE Systems</td>
<td>- FlatSat - TVAC</td>
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<tr>
<td>- Read/Write Speeds</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>- Control Requirements Size</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Completed - Jan 16 - Jan 26 - Jan 26 - Feb 27 - Feb 27 - Apr 16

Functional Requirements

- Take variable polarization angle UV spectrum measurements at various points on the sun
- Determine its attitude relative to the Sun
- Operate and collect data during the environmental conditions of a 40km high altitude balloon flight

Requirements Tests

- Sommers-Bausch Campaign, Integration Time Test, Focal Length Determination Test
- Sommers-Bausch Campaign
- 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 18.1 μW
- 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

\[
P_{\text{expected}} = 18.1 \, \mu\text{W} \\
d = 100 \, \text{mm} \\
d_s = 6 \, \text{mm} \\
A_{\text{light source}} = \pi \times (d_s/2)^2 = 785.4 \, \text{mm}^2 \\
A_{\text{spectrometer}} = \pi \times (d/2)^2 = 28.3 \, \text{mm}^2 \\
P_{\text{output, needed}} = P_{\text{expected}} \times (A_{\text{light source}}/A_{\text{spectrometer}}) = 0.5 \, \text{mW}
\]
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

*Simplified FlatSat Test Connections*

*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*
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
Verification and Validation

ADDS 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

Verification and Validation

\[ \theta_{x\text{-offset}} = \tan^{-1} \left( \frac{\delta_y - 5^\circ}{\delta_x - 5^\circ} \right) \]

\[ \theta_{y\text{-offset}} = \tan^{-1} \left( \frac{\delta_x - 5^\circ}{\delta_y - 5^\circ} \right) \]
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 ($d\psi$ & $d\theta$)

$$\delta\psi = \psi_{\text{edge}} - r_{\text{Sun}} = \psi_{\text{edge}} - 0.5333^\circ$$
**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
## Cost Plan

<table>
<thead>
<tr>
<th>System</th>
<th>Part</th>
<th>Price ($)</th>
<th>Shipping</th>
<th>Quantity</th>
<th>Total</th>
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---

**Engineering Excellence Fund**

Budget Increased to $73'
Thank you for listening! We appreciate your feedback.

Are there any questions?
References

➢ Pad Heaters - https://www.omega.com/pptst/KHR_KHLV_KH.html
➢ Reflectance and Albedo of Surfaces - http://curry.eas.gatech.edu/Courses/6140/ency/Chapter9/Ency_Atmos/Reflectance_Albedo_Surface.pdf
References Continued

- Structural Requirements and Recommendations for Balloon Gondola Design - Columbia Scientific Balloon Facility/NASA
- Actuator Supplier - http://www.haydonkerkpittman.com
<table>
<thead>
<tr>
<th>Sections</th>
<th>Backups</th>
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<tr>
<td>Project Purpose/Objectives</td>
<td>EMCS</td>
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<tr>
<td>Design Solutions</td>
<td>ADS</td>
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<tr>
<td>Critical Project Elements</td>
<td>Optical Components</td>
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<tr>
<td>EMCS Design</td>
<td>Instrument Control Components</td>
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<tr>
<td>ADS Design</td>
<td>EPS</td>
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<td>DAQ</td>
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<td>Photodiode for Testing</td>
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<td>Other Subsystem Design</td>
<td>Pointing Angle Algorithm</td>
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<td>Risk Analysis</td>
<td>Parts to Manufacture</td>
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<tr>
<td>Test</td>
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<tr>
<td>Project Planning</td>
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</table>
Backups
Customer

High Altitude Observatory
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
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**

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

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

**Absorbed Heat**

\[
\dot{Q}_{in} = \dot{Q}_{Source} A \alpha
\]

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

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

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

**Convection**

\[
Nu(Ra,Pr) = \frac{gC_p \rho(T_s - T_\infty)L_c^3}{k \nu}
\]

\[
h = \frac{k}{L_c} Nu
\]
Atmospheric Model

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

<table>
<thead>
<tr>
<th>Component</th>
<th>Minimum Pressure Rating (Pa)</th>
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<tr>
<td>Actuators</td>
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<tr>
<td>Polarizer Mount</td>
<td>0.133</td>
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<tr>
<td>ADS Sensor</td>
<td>5</td>
</tr>
<tr>
<td>Pressure Sensor</td>
<td>0</td>
</tr>
</tbody>
</table>
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
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
\[ \hat{\theta} = \hat{z}, \quad \hat{R}_{0\backslash S}, \hat{R}_{z\backslash S} \gg \hat{R}_{S\backslash 0} \]

Conclusion
Sun off-angles relative to Sun Sensor axis is equal to that of the optical axis
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)
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 $\Delta \psi = 0.00886°$.
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)

θ_{S+} = \tan^{-1}\left(\frac{D_S \times (1+\varepsilon)}{D}\right) = 0.532904°
θ_{S-} = \tan^{-1}\left(\frac{D_S \times (1-\varepsilon)}{D}\right) = 0.532851°

Δθ = |θ_{S+} - θ_{S-}| = 5.3e-05° = 0.00318 arc minutes

No, we can assume a perfect circle
Lens Baseline Design

Thorlabs ACA254-UV-150

➢ Air-Spaced Doublet to correct for chromatic aberrations

<table>
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<th>Feature</th>
<th>Value</th>
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<tr>
<td>Focal Length</td>
<td>150mm</td>
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<td>Clear Aperture</td>
<td>18mm</td>
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Polarizer Baseline Design

Thorlabs 25 mm Diameter Mounted Wire Grid Polarizer

➢ Provided by Customer
Spectrometer Baseline Design

Avantes Mini 2048
➢ Inherited From RADIANCE

<table>
<thead>
<tr>
<th>Avantes AvaSpec-Mini 2048L-UVI25</th>
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<tr>
<td><strong>Optics</strong></td>
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<tr>
<td><strong>Grating</strong></td>
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<tr>
<td><strong>Slit Size</strong></td>
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<tr>
<td><strong>Price</strong></td>
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Spectrometer Coupling Design

**Avantes COL-UV/VIS-25**

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

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<td>FOV</td>
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Uncoated UV Fused Silica (10 mm Thick)
# Polarizer Mount

## Key Specifications

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<tr>
<td><strong>Minimum Speed</strong></td>
<td>0.005 deg/sec</td>
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<tr>
<td><strong>Repeatable Incremental Movement</strong></td>
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<tr>
<td><strong>Absolute Accuracy</strong></td>
<td>+/- 0.14 deg</td>
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Haydon Kerk Size 8 Type U Linear Actuators

➢ Non-captive for horizontal movement

<table>
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<tr>
<td>Dimensions</td>
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<tr>
<td>Max Displacement</td>
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Functional Block Diagram - Controls
Battery Baseline Design

### Table 3 Battery Types

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<td>7</td>
</tr>
<tr>
<td>B9808</td>
<td>4</td>
<td>11.2</td>
<td>1</td>
</tr>
<tr>
<td>G20-12</td>
<td>1</td>
<td>2.6</td>
<td>7</td>
</tr>
<tr>
<td>G62-12</td>
<td>1</td>
<td>2.6</td>
<td>30</td>
</tr>
</tbody>
</table>

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

### Specifications

- **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

### Technical Details

- **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

Typical discharge characteristics on a 2A constant current load

Typical discharge characteristics at +20°C
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  
lout = 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

- **Total Pd**: Graph showing the total power dissipation as a function of output current (A).
- **Efficiency**: Graph showing the efficiency as a function of output current (A).
- **Duty Cycle**: Graph showing the duty cycle as a function of output current (A).
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

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

### 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

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

Total: 0.2069766433
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

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 mm² detector area
  - 10 mW/cm² 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:
   \[ \text{vector of BO} = [\sin(\text{azimuth}) \cdot \cos(\text{altitude}), -\sin(\text{altitude}), \cos(\text{azimuth}) \cdot \cos(\text{altitude})] \times |BO| \]

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 be 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

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

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

(*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*)
\[ \text{azimuth} = -1 \times \frac{\pi}{180}; \]
\[ \text{altitude} = -1 \times \frac{\pi}{180}; \]

(*Find optical axes vector at desired pointing angles*)
normalVecUnit = \{\sin[\text{azi}] \times \cos[\text{alt}], -\sin[\text{alt}], \cos[\text{azi}] \times \cos[\text{alt}]\};
normalVec = normalVecUnit \times 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[\text{azimuth}], \sin[\text{azimuth}] \times \sin[\text{altitude}], \sin[\text{azimuth}] \times \cos[\text{altitude}]), (0, \cos[\text{altitude}], -\sin[\text{altitude}]\), (-\sin[\text{azimuth}], \cos[\text{azimuth}] \times \sin[\text{altitude}], \cos[\text{altitude}] \times \cos[\text{azimuth}]\}\};

(*Find cartesian coordinates of spherical rolling joints*)
ApexHorVecNew = ConvertMat.ApexHorVec;
ApexVertVecNew = ConvertMat.ApexVertVec;
VertBallNew = Apex - ApexVertVecNew;
HorBallNew = Apex - ApexHorVecNew;
VertBallFinal = Transpose(ConvertMat).VertBallNew;
Pointing Angle Determination

HorBallFinal = Transpose(ConvertMat).HorBallNew;
(*Find vectors between spherical rolling joints and motor gimbals*)
HorBallGimVec = HorBallFinal - HorGim;
VertBallGimVec = VertBallFinal - VertGim;
(*Determine length between spherical rollings joints and motor gimbals*)
"Vertical Length"
VertActLength = Norm[VertBallGimVec]
"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
Spectrometer Brace Drawing
Front Plate Drawing
Back Plate Drawing
Side Panel Drawing
Vertical Motor Brace Drawing
Horizontal Motor Brace Drawing