GHOST

Ground-based Hardware for Optical Space Tracking

Project Manager: Jack Toland

Hardware: Kira Altman, Lucas Calvert, Seth Hill, Duncan McGough, Jacob Vendl

Software: Ginger Beerman, Connie Childs, Blaine Covington, Rachel Mamich, Connor Ott

Sponsor: The Aerospace Corporation

Advisor: Marcus Holzinger
Project Overview

Motivation

• Increasing number of space objects
  • CubeSats
  • Mega Constellations
  • Debris

• International dependence on space
  • Communication
  • Weather
  • National Security

Solution

Design a low-cost, ground-based, optical tracking system for space situational awareness (SSA) and space traffic management (STM).

Estimated satellite distribution by 2040

*Courtesy of Daily Mail*
Concept of Operations

Captured Image

GHOST

(α₁, δ₁, t₁), (α₂, δ₂, t₂)
(α₃, δ₃, t₃), (α₄, δ₄, t₄)
(α₅, δ₅, t₅), (α₆, δ₆, t₆)

Recorded Measurements
Observation Constraints

- Sun must be $18^\circ$ below horizon
- Object must be $0^\circ$-$30^\circ$ away from Moon
  - Depends on Moon’s phase
- Object must be $20^\circ$ above horizon
- Object must be out of Earth’s shadow
Limiting Stellar Magnitude (LSM)

- Sun: Very bright
- Moon: -25
- Venus: -10
- Hubble Telescope Limit: 5
- Faintest naked eye star: 10

Target value: 10

Very bright: -25
Very dim: 25
Design Solution
Hardware Design

Total Mass: ~15kg

Chassis
- 30-Series 8020 frame and corners
- Fits within 60 x 60 x 60 cm box
- Provides rigid platform and grab points
Hardware Design

**Chassis**

**Three Leveling Feet**
- 3 points of contact for stability
- 4” screws allow for leveling to 10°
Hardware Design

Chassis
Three Leveling Feet
Dual-Output Power Supply
- MEAN WELL 323741
- Powered by 120VAC (3-prong)
- Outputs 5V and 12V at up to 7A
Hardware Design

Chassis
Three Leveling Feet
Dual-Output Power Supply

Computer and GPS
- UDOO x86
  - 2.24GHz processor
  - 4Gb RAM
  - 256Gb storage
- Adafruit Ultimate Module
  - PPS
Hardware Design

Chassis
Three Leveling Feet
Dual-Output Power Supply
Computer and GPS

Actuation Mount
- iOptron A2 Pro
  - Azimuth/Elevation
  - 10 deg/sec slewing
  - Sidereal tracking
  - 0.1 arcsecond resolution
Hardware Design

Chassis
Three Leveling Feet
Dual-Output Power Supply
Computer and GPS
Actuation Mount

Camera and Lens
- Two ASI1600MM
  - 16.4MP - monochrome
- Canon EF 200mm f/2.8L
  - 4.5° effective circular FOV
Hardware Design

Chassis
Three Leveling Feet
Dual-Output Power Supply
Computer and GPS
Actuation Mount
Camera and Lens

Pedestal
  - 5" tall, 3" square steel tube
  - Prevents mechanical interference
Hardware Design

Chassis
Three Leveling Feet
Dual-Output Power Supply
Computer and GPS
Actuation Mount
Camera and Lens
Pedestal

Monitor
- GeekPi 7” 1024x600 LCD display
- HDMI input
- Used for calibration and output
Hardware Design

Chassis
Three Leveling Feet
Dual-Output Power Supply
Computer and GPS
Actuation Mount
Camera and Lens
Pedestal
Monitor

Emergency Stop
- Locking momentary switch
- Cuts power to all subsystems
Data Wiring

**NORAD IDs & TLE’s**
- USB 3.0 (M)

**Imaging Hardware**
- USB 3.0 (F)

**UDOoO Processor**
- USB 3.0 (F)
- USB 3.0 (M)
- HDMI (F)

**Data Protocol: INDI Driver**
- USB 3.0 (F)

**Data Driver: CircuitPython**
- Digital 2
- Digital 3
- Tx
- PPS
- GPS Receiver

**Arduino**
- USB 3.0 (M)
- RS-232 (F)

**LCD Monitor**
- HDMI (F)

**Actuation Hardware**
- USB -> RS232
- RS-232 (M)

**Legend**
- Digital I/O
- USB
- RS-232
- HDMI
## Power Budget

### Component | Voltage Req. | Max Current Draw | Max Power Consumption
---|---|---|---
Zwo Camera | 5V | 0.3A | 1.5W
iOptron Mount | 12V | 2.0A | 24W
Adafruit GPS | 5V | 0.02A | 0.1W
UDOO Computer | 12V | 3A | 36W* 
GeekPi Monitor | 5V | 1A | 5W
**Total** | - | - | **66.6W**

### Anticipated Power On Time: 3+ hours

#### Power Consumption

- **Total Power Consumption**: 66.6W
- **200Wh Portable Battery**
  - Outputs 120VAC
- **Anticipated Power On Time**: 3+ hours

*11W average
Critical Project Elements
Design

Requirements
CPE Camera & Lens

Relevant Requirements:
1. The optical system shall be capable of imaging space objects of LSM 10 or brighter
1.1 The optical system shall have an effective field of view (FOV) of at least 4 degrees
5. The system shall use COTS imaging hardware

Why is this a Critical Project Element?
The selected optical system must have these capabilities, which cannot be fully verified without actual testing. Therefore, reliance on mathematical predictions is necessary.
Camera & Lens Selection Capabilities

- Zwo ASI 1600MM
- Canon EF 200mm f/2.8L

Angular Resolution: 3.92 \(\text{arcsec/pixel}\)

Assembled FOV: 4.47° x 6.75°

Max LSM: 11.1

\(\text{FOV}_{\text{effective}} \geq 4.5°\)

FR 1.2 Verified

FR 1 Verified

LSM_{\text{Max}} \geq 10
<table>
<thead>
<tr>
<th>FR 1</th>
<th>Selected camera and lens modeled to show LSM capabilities of 11.1 or dimmer in ideal conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 1.1</td>
<td>Effective field of view is a 4.5° circle, allowing for flexibility in imaging</td>
</tr>
<tr>
<td>FR 5</td>
<td>Optical system is COTS and available to ship within two days</td>
</tr>
</tbody>
</table>
Relevant Requirements:

4.1 The system scheduling software shall be able to schedule imaging tasks given a list of NORAD IDs.

4.2 The GHOST module shall autonomously slew between scheduled pointing angles without operator input.

Why is this a Critical Project Element?
Once the observation opportunities have been identified and space objects are weighted, the process of tasking and interweaving observations is very complex.
Pipeline

NORAD ID’s → .obs file → Retrieve TLE → TLE file → SGP4 Propagator

Constraining & Weighting → Viable Passes → Scheduling → Schedule → Command Actuators & Imager

Coded up to here

Time continuous position vectors

FR 4.1 Verified Schedule observations

FR 4.1 Verified Schedule observations
Scheduling Imaging Sequences

Goal:
Ensure module can advance ahead to image at next scheduled observation.

Assumptions:
• Constant angular rates
• Constant delay and settling times
## Commanding Actuators and Imager

<table>
<thead>
<tr>
<th>Command</th>
<th>Time (Julian Days)</th>
<th>Az (deg)</th>
<th>El (deg)</th>
<th>NORAD ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>2458432.500000</td>
<td>45</td>
<td>34</td>
<td>32711</td>
</tr>
<tr>
<td>B</td>
<td>2458432.500058</td>
<td>45</td>
<td>34</td>
<td>32711</td>
</tr>
<tr>
<td>E</td>
<td>2458432.500148</td>
<td>45</td>
<td>34</td>
<td>32711</td>
</tr>
<tr>
<td>M</td>
<td>2458432.500954</td>
<td>151</td>
<td>78</td>
<td>32711</td>
</tr>
<tr>
<td>B</td>
<td>2458432.501003</td>
<td>151</td>
<td>78</td>
<td>32711</td>
</tr>
<tr>
<td>E</td>
<td>2458432.501068</td>
<td>151</td>
<td>78</td>
<td>32711</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Command</th>
<th>Time</th>
<th>Az &amp; El</th>
<th>NORAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>M - At time, t, <strong>MOVE</strong> to Az/El</td>
<td>Time at which the command is given</td>
<td>Pointing direction of actuation and imaging system</td>
<td>Current space object</td>
</tr>
<tr>
<td>B - At time, t, <strong>BEGIN</strong> imaging</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E - At time, t, <strong>END</strong> imaging</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Scheduler Requirements Met

<table>
<thead>
<tr>
<th>DR 4.1</th>
<th>Method identified to prioritize and shift observations when conflicted across multiple satellites</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 4.2</td>
<td>Method identified for communicating between scheduling software and actuation hardware</td>
</tr>
</tbody>
</table>

**Next Steps:** Coding the actuation and imaging commands
CPE Image Processing

Specific Requirements:
3.3 The system shall be capable of processing an image containing a space object brighter than or equal to an apparent magnitude of 10
4.3 The GHOST module will perform image processing on-board and without operator input.

Why is this a Critical Project Element?
Image processing is a complex task. Measurements must be returned from the raw images for orbit determination to provide an updated orbit estimate.
Image Processing Pipeline

Pre-Processing

- Image
- Star Removal
- Background Subtraction
- Pre-Processed Image

A priori Information

- Filter Template Creation
- Filter Template

Pre-Processed Image & Filter Template

- Matched Filter
- Streak (x,y)
- Right Ascension and Declination
Project
Purpose
Design
Solution
Critical
Project Elements
Design
Requirements
Project
Risks
Verification & Validation
Project Planning

Image Processing Example

Initial raw image

Ends of streak identified
Image Processing

**Matched Filter**

**Filter Template**
- Use astrometry.net to obtain orientation of image
- Retrieve expected length and slope of streak in pixel space
- Generate line and convolve with Gaussian PSF

**Matched Filter**
- Convolve template with image

---

FR 3.3 Verified

Process objects < LSM 10
• Laptop limited to 2.24 GHz, 4 GB RAM
• Processing 16 MP image on 1 core

Matched filter convolution: ~3 sec
Astrometry.net calibration: ~10 sec
### Image Processing Requirements

**Met**

<table>
<thead>
<tr>
<th>DR 3.3</th>
<th>Prototyped a matched filter, the optimal SNR filter, and tested on a representative image</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 4.3</td>
<td>Computation time has an order of magnitude FOS against computation time limit</td>
</tr>
</tbody>
</table>

**Next Steps:**
- Refine transformation for template creation
- Integrate with software pipeline
Relevant Requirements:

3 The system shall provide an orbit estimate if there are sufficient observations available.

Why is this a Critical Project Element?

Orbit determination requires the implementation of complex theory and fine tuning. Orbit determination is required to provide an orbit estimate for tasked objects.
Goal: Reduce residuals between the measured and estimated values

\[ \tilde{X} = [r_x, r_y, r_z, v_x, v_y, v_z]^T \]
## Textbook Example: Orbital Elements

### Position, km

<table>
<thead>
<tr>
<th>Textbook Data*</th>
<th>Prototype Estimate</th>
</tr>
</thead>
</table>

### Velocity, km/s

<table>
<thead>
<tr>
<th>Textbook Data*</th>
<th>Prototype Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>[−2.924, 5.493, 2.764]T</td>
<td>[−2.846 ± 0.3110, 5.611 ± 0.3980, 2.878 ± 0.3604]T</td>
</tr>
</tbody>
</table>

Percent Error in Position: 0.1008%  
Percent Error in Velocity: 2.671%

*Vallado, Fundamentals of Astrodynamics and Applications, 4th Ed
DR 3.3

Prototype software package is capable of running non-linear batch filter to return an estimated orbital state

Next Steps:
• Include drag and solar radiation pressure models
• Convert prototype code from MATLAB to Python
Project Risks
<table>
<thead>
<tr>
<th>Risk</th>
<th>Description</th>
<th>Likelihood of Related Problem</th>
<th>Severity</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOFT-1</td>
<td>Accuracy of image processing has not yet been determined and may effect system output</td>
<td>5</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>TEST-1</td>
<td>Outdoor testing ability subject to weather, location, timing and ambient lighting conditions</td>
<td>5</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>CAM-1</td>
<td>LSM modeling not matching up with real-world performance</td>
<td>3</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>SOFT-2</td>
<td>Limited testing data available for software development before hardware available for testing</td>
<td>5</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>CHAS-1</td>
<td>Cables are required to connect moving camera assembly with chassis and could be damaged during rotation</td>
<td>2</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>TEST-2</td>
<td>Equipment must be transported regularly for testing and could be damaged while doing so</td>
<td>3</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>CAM-2</td>
<td>Camera timing latency between reported lens open/close and actual open/close unknown</td>
<td>3</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>CAM-3</td>
<td>Camera and actuation mount calibration to accuracy desired may be difficult to achieve</td>
<td>1</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>
## Highest Risks

### 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>SOFT-2</td>
<td>SOFT-1, TEST-1</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td>TEST-2, CAM-2</td>
<td>CAM-1</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>TEST-2, CAM-2</td>
<td>CAM-1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>CHAS-1</td>
<td>CAM-3</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Green**: Low (1-4)
- **Yellow**: Moderate (4-9)
- **Orange**: High (10-14)
- **Red**: Extreme (15-25)
<table>
<thead>
<tr>
<th>Risk</th>
<th>Summary</th>
<th>Mitigation</th>
<th>Risk Before (Likelihood-Severity)</th>
<th>Risk After</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOFT-1</td>
<td>Software interfacing</td>
<td>Consult field experts and determine lowest risk image processing method for final implementation</td>
<td>20</td>
<td>12</td>
</tr>
<tr>
<td>TEST-1</td>
<td>Outdoor testing</td>
<td>Schedule frequent testing, setup testing to require only 2 team members</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td>CAM-1</td>
<td>LSM modelling</td>
<td>Use images from similar lens + camera in prototype software to validate model</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>SOFT-2</td>
<td>Limited test data</td>
<td>Work with graduate students working on similar projects to acquire test data for prototypes</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>CHAS-1</td>
<td>Cable management</td>
<td>Cylindrical cable carrier has been designed to prevent wires from tangling</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>TEST-2</td>
<td>Equipment transport</td>
<td>Create a protocol for transport and provide safety covers and lock-outs</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>CAM-2</td>
<td>Camera latency</td>
<td>Understand effects on orbit determination accuracy, research latency tests</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>CAM-3</td>
<td>Calibration</td>
<td>Understand sources of error and work to mitigate in design</td>
<td>5</td>
<td>-</td>
</tr>
</tbody>
</table>
Testing and Verification
Testing Levels

- Scheduler Prototype Testing
- Image Processing Prototype Testing
- Orbit Determination Prototype Testing

Preliminary System Test (Pointing)
- Scheduler Unit Test
- Actuation Hardware Unit Test
- Imaging Hardware Unit Test

Preliminary System Test (Processing)
- Image Processing Unit Test
- Orbit Determination Unit Test

Complete System Field Test

- Imaging Hardware Test
- Actuation Hardware Test
- Scheduling

- Prototype Testing
- Image Processing
- Orbit Determination

Fall 2018
- Jan
- Feb
- Mar

Schedule
- Fall 2018
- Jan
- Feb
- Mar

Testing Levels

- Complete System Field Test
- Preliminary System Test (Pointing)
- Preliminary System Test (Processing)

- Scheduler Prototype Testing
- Image Processing Prototype Testing
- Orbit Determination Prototype Testing

- Imaging Hardware Test
- Actuation Hardware Test
- Scheduling

- Prototype Testing
- Image Processing
- Orbit Determination

Fall 2018
- Jan
- Feb
- Mar

Schedule
- Fall 2018
- Jan
- Feb
- Mar
Preliminary System Testing

Pointing
Test Objectives:
1. Actuate hardware based on simulated observations
2. Quantify actuation rates and settling time for schedule

Processing
Test Objectives:
1. Complete image processing on sample images
2. Perform OD using data from image processing on sample images

Test Setup:
• GPS Disabled
• 120V Wall Power
Field System Testing

Test Setup:
- Boulder, CO – Walden Ponds
- GPS Enabled
- Powered by Portable Battery

Used to Test Satisfaction of:
- FR 1 – LSM
- FR 2 – Actuate
- FR 3 – Orbit Estimate
- FR 4 – Operate Autonomously
**Requirement Specific Testing**

**Field System Testing**

System will capture images of a variety of regions of the sky.

If the identified stars have cataloged visual magnitudes of 10 or dimmer, the system will satisfy FR 1.

---

**FR 1**

The system shall be capable of imaging space objects in Earth orbits with apparent magnitudes equal to or brighter than 10 under ideal conditions.
FR 2
The actuation system shall be capable of detecting in images space objects with motions corresponding to GEO, MEO, and LEO orbits.

Field System Testing
System will be tasked with variety of space objects are varying altitudes:
• Satellites, Rocket Bodies, and Debris
• LEO, MEO, and GEO Altitudes

If image processing resulting in angular measurements that can be used for orbit determination is completed, the system will satisfy FR 2.
Field System Testing

System will be tasked with space objects on well known orbits:

- GPS
- ISS
- Geostationary

If orbit determination using the generated angular observations can be completed and matches the known orbits, the system will satisfy FR 3.
Requirement Specific Testing

**FR 4**
The system, when given an operator specified list of NORAD IDs, shall without operator input propagate the space objects, schedule and task observations, process captured images, and provide an orbit estimate for each specified object.

Field System Testing

System will be provided with a NORAD ID list containing:

- LEO, MEO, and GEO space objects
- Satellites and debris
- Objects that should and should not be visible based on location

If the system schedules, observes and returns an orbit estimate for the objects given by FR 1 and FR 2, the system will satisfy FR 4.
Project Planning
## Work Breakdown Structure

<table>
<thead>
<tr>
<th>Hardware</th>
<th>Software</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chassis Fabrication</strong></td>
<td><strong>System Integration</strong></td>
</tr>
<tr>
<td><strong>Lead:</strong> Lucas, Duncan</td>
<td><strong>Lead:</strong> Kira, Seth</td>
</tr>
<tr>
<td><strong>Tasks:</strong></td>
<td><strong>Tasks:</strong> Manufacture frame components</td>
</tr>
<tr>
<td>- Manufacture frame components</td>
<td>- Complete chassis wiring</td>
</tr>
</tbody>
</table>

**MSR** | Manufacturing Status Review | **TRR** | Test Readiness Review | **SFR** | Spring Final Review
Work Plan

GHOST - Spring

Manufacturing
- Component Purchase
- Component Receiving
- Chassis Manufacturing
- Manufacturing Status Review

Integration
- Chassis Assembly
- Imaging and Actuation Assembly
- Processing Assembly
- Software Development
- Software Installation
- Test Readiness Review

Test
- Scheduler Prototype + Unit Testing
- Actuation and Imaging Prototype + U...
- Image Processing Prototype + Unit Te...
- Orbit Determination Prototype + Unit...
- Indoor System Testing (Pointing)
- Indoor System Testing (Processing)
- Field System Testing
- Spring Final Review

Critical Path
- MSR
- TRR
- SFR

Diagram elements:
- Critical Path
- Hardware
- Software
- Assembly
- Test
## Cost Plan

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
<th>Budget Allocation</th>
<th>Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chassis</td>
<td>$436.07</td>
<td>$600</td>
<td>27.3%</td>
</tr>
<tr>
<td>Actuation</td>
<td>$1078</td>
<td>$1500</td>
<td>28.1%</td>
</tr>
<tr>
<td>Imaging</td>
<td>$1943.59</td>
<td>$2000</td>
<td>2.8%</td>
</tr>
<tr>
<td>Processing</td>
<td>$285.55</td>
<td>$400</td>
<td>28.6%</td>
</tr>
<tr>
<td>GPS</td>
<td>$39.95</td>
<td>$100</td>
<td>60.1%</td>
</tr>
<tr>
<td>Power</td>
<td>$243.90</td>
<td>$400</td>
<td>39.0%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$4027.06</strong></td>
<td><strong>$5000</strong></td>
<td><strong>19.5%</strong></td>
</tr>
</tbody>
</table>
Test Plan

Unit Level Testing
Senior Projects Build Space

Preliminary System Testing
Senior Projects Build Space

Outdoor System Testing
Boulder, CO (Walden Ponds and other local location)
Requirements: Transport for 0.6x0.6x0.6 m system
Acknowledgements

• Project Advisory Board
• Dr. Marcus Holzinger
• Shez Virani
• Charles Labonde
• ARES Team
• Ian Cooke
• Christine Reilly
Questions
## General
- Miscellaneous
- Imaging Procedure
- Budget
- Testing

## Hardware
- Actuation Hardware
- Imaging Hardware
- Chassis
- GPS
- Computer

## Software
- Scheduler
- Image Processing
- Orbit Determination
Backup - Miscellaneous
Changes from PDR

- **SNR increased for Limiting Stellar Magnitude calculation**

<table>
<thead>
<tr>
<th></th>
<th>PDR</th>
<th>CDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR</td>
<td>6</td>
<td>30</td>
</tr>
</tbody>
</table>

- **Switched type of Actuation Mount**

<table>
<thead>
<tr>
<th></th>
<th>PDR</th>
<th>CDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA/Dec</td>
<td></td>
<td>Az/El</td>
</tr>
<tr>
<td>Critical Project Element</td>
<td>Justification</td>
<td></td>
</tr>
<tr>
<td>----------------------------------</td>
<td>-------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Camera &amp; Lens</td>
<td>Determines quality of the data. The optical system must be capable of capturing images of space objects.</td>
<td></td>
</tr>
<tr>
<td>Scheduler</td>
<td>Allows for system automation. The software must schedule observation periods.</td>
<td></td>
</tr>
<tr>
<td>Image Processing</td>
<td>Extraction of the data. The software must be able to change captured images into quantitative measurements.</td>
<td></td>
</tr>
<tr>
<td>Orbit Determination</td>
<td>Final output of the system. Filtering data to enhance the orbital update is paramount to system success.</td>
<td></td>
</tr>
</tbody>
</table>
### Requirements Satisfied - Hardware

<table>
<thead>
<tr>
<th>FR 1</th>
<th>The system shall be capable of imaging space objects in Earth orbits with apparent magnitudes equal to or brighter than 10 under ideal conditions.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Evidence</strong> – LSM Calculation showing capability of 11 or brighter</td>
</tr>
<tr>
<td>FR 2</td>
<td>The system shall be capable of tracking objects in GEO, MEO, and LEO orbits.</td>
</tr>
<tr>
<td>DR 2.1</td>
<td>The actuation system shall be capable of slewing at $\geq 4^\circ$/s</td>
</tr>
<tr>
<td></td>
<td><strong>Evidence</strong> – Manufacturer specifications</td>
</tr>
<tr>
<td>DR 2.2</td>
<td>The actuation mount hardware shall interface with the imaging hardware.</td>
</tr>
<tr>
<td></td>
<td><strong>Evidence</strong> – CAD model shows functional interfaces for camera mount</td>
</tr>
<tr>
<td>DR 3.2</td>
<td>The system shall provide timing with a precision of +/- 5 milliseconds</td>
</tr>
<tr>
<td></td>
<td><strong>Evidence</strong> – Manufacturer specifications</td>
</tr>
<tr>
<td>DR 4.5</td>
<td>The system shall know its own geodetic latitude, longitude, and altitude to an accuracy of 10 meters</td>
</tr>
<tr>
<td></td>
<td><strong>Evidence</strong> – Manufacturer specifications</td>
</tr>
<tr>
<td>FR 5</td>
<td>The system shall use commercial-off-the-shelf (COTS) imaging hardware</td>
</tr>
<tr>
<td></td>
<td><strong>Evidence</strong> – All components selected for imaging hardware are COTS</td>
</tr>
<tr>
<td>FR 6</td>
<td>The system shall be able to operate with a 120V, 60Hz power source, drawing under 20A</td>
</tr>
<tr>
<td></td>
<td><strong>Evidence</strong> – The system is estimated to use FILL THIS IN LATER</td>
</tr>
</tbody>
</table>
High-Level Data Flow Diagram

**Project Elements**
- **Scheduler Software**
  - NORAD ID’s [External USB]
  - TLE Database [Network]
- **Image Processing Software**
- **Orbit Determination Software**
- **STORAGE**
  - Image Archive
- **Images to Process & Capture Times**
  - Current Latitude, Longitude, & Altitude
  - 1PPS Timing Signal

**Data Type Legend**
- ASCII Text File
- Python Object
- .fits File
- Digital Pulse

**System Components**
- **PROCESSOR**
  - Azimuth/Elevation Targets and Pointing Times
  - Target Capture Times
  - TLEs to observe/ a priori orbit
  - Right Ascension, Declination & Capture Time Observations
- **OUTPUT**
  - Updated TLE [External USB]
  - Computed State Vectors

**Input/Output**
- NORAD ID’s [External USB]
- GPS
- Actuation Mount
- Imaging Hardware
- Output: Captured Images

**Project Planning**
- NORAD ID’s
- GPS
- 1PPS Timing Signal

---

**Project Purpose**
- Design Solution
- Critical Project Elements
- Design Requirements
- Project Risks
- Verification & Validation
- Project Planning

**GHOST CDR**

68
Backup - Imaging Procedure
Camera & Lens FOV

Simplification

Orientation of sensor unknown

Assume 4.47 deg circular FOV

4.47°

6.75°
Camera and Lens Selection Exposure Plan

1) take picture of background before satellite arrival into FOV

Predicted Object Path

(RA, Dec) Calculated from orbit propagation

4.47°
Camera and Lens Selection Exposure Plan

2) Begin imaging sequence, taking short exposures continuously.

Predicted Object Path

\[ t_1 \quad t_2 \]

4.47°
Camera and Lens Selection Exposure Plan

3) Continue short exposures as space object passes through the field of view

Predicted Object Path

\[
\begin{align*}
& t_3 \\
& t_4 \\
& 4.47°
\end{align*}
\]
4) Continue short exposures as space object passes through the field of view
Camera and Lens Selection Exposure Plan

Predicted Object Path

5) End imaging sequence when space object is predicted to have left the FOV

4.47° $t_f$
### Camera and Lens Selection Exposure Plan

<table>
<thead>
<tr>
<th>Image Taken</th>
<th>Info Gathered</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Empty celestial background for image processing</td>
</tr>
<tr>
<td>2</td>
<td>None. Partial streaks will be discarded</td>
</tr>
<tr>
<td>3</td>
<td>$(\alpha_1, \delta_1, t_1)$ and $(\alpha_2, \delta_2, t_2)$</td>
</tr>
<tr>
<td>4</td>
<td>$(\alpha_3, \delta_3, t_3)$ and $(\alpha_4, \delta_4, t_4)$</td>
</tr>
</tbody>
</table>
Backup - Budget
## Hardware Budget

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
<th>PDR Budget</th>
<th>Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chassis</td>
<td>$395.48</td>
<td>$500</td>
<td>20.9%</td>
</tr>
<tr>
<td>Actuation</td>
<td>$1078</td>
<td>$1500</td>
<td>28.1%</td>
</tr>
<tr>
<td>Imaging</td>
<td>$1943.59</td>
<td>$2000</td>
<td>2.8%</td>
</tr>
<tr>
<td>GPS</td>
<td>$39.95</td>
<td>$100</td>
<td>60.1%</td>
</tr>
<tr>
<td>Power</td>
<td>$250.36</td>
<td>$400</td>
<td>39.0%</td>
</tr>
</tbody>
</table>
# Chassis BOM

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/8&quot; Acrylic plates (12&quot;x48&quot;)</td>
<td>$55.94</td>
<td>McMaster</td>
</tr>
<tr>
<td>3&quot; x 3&quot; Steel Square Tube</td>
<td>$20.13</td>
<td>McMaster</td>
</tr>
<tr>
<td>Leveling Feet</td>
<td>$54.48</td>
<td>McMaster</td>
</tr>
<tr>
<td>1/2&quot; Aluminum Plate (8&quot;x8&quot;)</td>
<td>$33.07</td>
<td>McMaster</td>
</tr>
<tr>
<td>1/4&quot; Steel Plate (8&quot;x8&quot;)</td>
<td>$30.63</td>
<td>McMaster</td>
</tr>
<tr>
<td>80/20 x 210mm</td>
<td>$15.74</td>
<td>80/20 Inc</td>
</tr>
<tr>
<td>80/20 x 540mm</td>
<td>$7.05</td>
<td>80/20 Inc</td>
</tr>
<tr>
<td>80/20 x 250mm</td>
<td>$8.62</td>
<td>80/20 Inc</td>
</tr>
<tr>
<td>80/20 x 570mm</td>
<td>$7.34</td>
<td>80/20 Inc</td>
</tr>
<tr>
<td>80/20 30-4480</td>
<td>$53.64</td>
<td>80/20 Inc</td>
</tr>
<tr>
<td>80/20 30-4351</td>
<td>$15.16</td>
<td>80/20 Inc</td>
</tr>
<tr>
<td>80/20 14062</td>
<td>$13.60</td>
<td>80/20 Inc</td>
</tr>
<tr>
<td>80/20 M6 T-nut</td>
<td>$17.28</td>
<td>80/20 Inc</td>
</tr>
<tr>
<td>[M6x1] x 12mm</td>
<td>$11.09</td>
<td>McMaster</td>
</tr>
<tr>
<td>[M6x1] x 20mm</td>
<td>$14.12</td>
<td>McMaster</td>
</tr>
<tr>
<td>Display</td>
<td>$37.59</td>
<td>Amazon (GeeekPi)</td>
</tr>
</tbody>
</table>
## Component Hardware BOM

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>iOptron AZ Mount Pro</td>
<td>$999</td>
<td>iOptron</td>
</tr>
<tr>
<td>iOptron SkyTracker Pro CW Package</td>
<td>$79</td>
<td>iOptron</td>
</tr>
</tbody>
</table>
# Imaging Hardware BOM

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZWO ASI1600MM</td>
<td>$999</td>
<td>Zwo</td>
</tr>
<tr>
<td>Canon EF 200mm f/2.8L</td>
<td>$749</td>
<td>Amazon (Canon)</td>
</tr>
<tr>
<td>RS232 to USB cable</td>
<td>$18.60</td>
<td>Amazon (Letotech)</td>
</tr>
<tr>
<td>Lens Hood</td>
<td>$35</td>
<td>Amazon (Canon)</td>
</tr>
<tr>
<td>EOS-T2 Adapter</td>
<td>$48</td>
<td>Zwo</td>
</tr>
<tr>
<td>Scope Rings</td>
<td>$72.99</td>
<td>Amazon (Astomania)</td>
</tr>
<tr>
<td>8&quot; Dovetail Rail Plate</td>
<td>$21</td>
<td>Amazon (ORION)</td>
</tr>
</tbody>
</table>
## Processing BOM

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>UDOO x86 2.24GHz</td>
<td>$190.64</td>
<td>Mouser</td>
</tr>
<tr>
<td>UDOO memory SD card</td>
<td>$57.94</td>
<td>Amazon (Samsung)</td>
</tr>
<tr>
<td>UDOO Power Adapter</td>
<td>$8.90</td>
<td>UDOO</td>
</tr>
<tr>
<td>Fan</td>
<td>$7.50</td>
<td>UDOO</td>
</tr>
<tr>
<td>USB Drive (64 gb)</td>
<td>$13.34</td>
<td>Amazon (SanDisk)</td>
</tr>
<tr>
<td>USB Bulkhead Port</td>
<td>$7.23</td>
<td>Amazon (StarTech)</td>
</tr>
</tbody>
</table>
## GPS BOM

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adafruit Ultimate GPS Module</td>
<td>$39.95</td>
<td>Adafruit</td>
</tr>
<tr>
<td>Component</td>
<td>Cost</td>
<td>Supplier</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>--------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>Portable Power Source</td>
<td>$165.99</td>
<td>CHAFON</td>
</tr>
<tr>
<td>12V/5V Switching Power Supply</td>
<td>$25.49</td>
<td>Jameco</td>
</tr>
<tr>
<td>12 gauge wire (black)</td>
<td>$8.48</td>
<td>Amazon (BestConnections)</td>
</tr>
<tr>
<td>12 gauge wire (red)</td>
<td>$8.48</td>
<td>Amazon (BestConnections)</td>
</tr>
<tr>
<td>Kill Button</td>
<td>$7.01</td>
<td>Amazon (uxcell)</td>
</tr>
<tr>
<td>120V Plug and Lead (6ft)</td>
<td>$11.99</td>
<td>Amazon (Hanvex)</td>
</tr>
</tbody>
</table>
Backup - Actuation Hardware
Specifications iOptron AZ Pro

Power Consumption: 48W max (11.1V, 4.4A)
Weight: 15 lbs
Operating Temperature: -4°F to 104°F
Cost: $999
Purchasing: Available within a week
Tracking: Az/El Sidereal
Slewing: 10°/s
Angular Resolution: 0.1 arcseconds

iOptron AZ Mount Pro
Mount Selection Capabilities

- **Slew Rate**: 10°/sec
- **Angular Pointing Resolution**: 0.1 arcseconds
- **Tracking Type**: Sidereal

**iOptron AZ Mount Pro**
1) Onboard GPS and angle sensors will predict alignment

2) System LCD screen is used to locate a known star in the boresight

3) Onboard geometric algorithm completes the calibration process
Max Motor Deviation
Angular Pixel Resolution

\[
\frac{0.071 \text{ arcseconds}}{3.92 \text{ arcseconds/px}} = 1.8\% \text{ px}
\]

Maximum Deviation:
0.071 arcseconds

Mount Movement Resolution:
0.1 arcseconds
Backup – Imaging Hardware
Camera and Lens Terminology

- **Apparent Magnitude**
  - Relative measure of an object’s brightness
  - Sun has an apparent magnitude of -27
  - Human’s can typically see objects as dim as 6

- **Limiting Stellar Magnitude**
  - Dimmest object an optical system can image
  - Function of design parameters
    - Aperture diameter of lens
    - Pixel size of sensor
    - F-number of lens
Specifications 2wo ASI1600MM

- CCD Sensor: MN34230 – 4/3” 23.6x15.6mm
- Resolution: 4656x3520 (16.4MP)
- ADC: 12bit
- Quantum Efficiency: 60%
- Read Noise: 1.2e
- FPS: 23
- Full Well Capacity: 20000e
- Pixel Size: 3.8\(\mu\)m
- Where to Buy: 2wo website
- Cost: $999
- Availability: shipping within two days
Specifications Canon EF200mm f/2.8L

- Focal length: 200mm
- f-number: 2.8
- Lens construction: 9 elements in 7 groups
- Filter size: 72mm
- Diameter x Length: 83.2mm x 136.2mm
- Weight: 765g
- Where to buy: Amazon
- Cost: $749
- Availability: shipping within two days
Camera and Lens Selection

Interfacing

1.5W Power

INDI Protocol

EOS-T2 Adapter ($48)

To UDOO

To Actuation Mount

Vello Collar for Mounting ($50)
Camera and Lens Selection Field of View

Full FOV – 12°

Expected Errors and FOS (~2°)

Zwo Asi 1600MM CCD

15.6mm

23.6mm

4.47°

6.75°

Effective FOV
Limiting Stellar Magnitude (LSM)

Physics-based model says system can be designed based on 3 parameters:

- \( D \) – aperture diameter
  - 10mm - 100mm
- \( p \) – pixel size
  - 2.4\( \mu \)m - 8.3\( \mu \)m square
- \( N \) – f-number
  - 1.4 - 5.6

from *Multi-objective design of optical systems for space situational awareness* (Coder, Holzinger, 2015)

\[
m_v(N, D, p) = -2.5 \log_{10} \left[ \frac{\text{SNR}_{\text{alg}} \left[ \sqrt{m_i \omega N D (q_{p, \text{sky}} + q_{p, \text{dark}})} \right]^{1/2}}{\Phi_0 \tau_{\text{atm}} \tau_{\text{opt}} \left( \frac{\pi D^2}{4} \right) Q E \sqrt{p}} \right]
\]
Backup – Chassis
Drawings Frame Overview

600mm

250mm

210mm

90mm

570mm
Drawings 8020 Profile

6105-T5

8.13 TYP

2.21 TYP

2.54 TYP

30.00 TYP

11.64 TYP

16.51 TYP

6.80 TYP

6.65 THRU

15.00 TYP

9.18 TYP
Drawings Corner Leveling Plate

2.95

2.36

1.38

0.39

5.59

1.97

2.56

Ø.375 - 16UNC

4 x Ø.236 THRU

1/2" Aluminum stock
Drawings Base Flange

4.72

4 x 24 THRU

0.38 THRU

0.59

2.36

4.13

0.59

Base Flange

\( \frac{1}{4} \) steel
Drawings

Riser Tube

\[ \frac{3}{8} \text{ thick, 3" square tube} \]
Chassis Center Of Mass Analysis

- COM adjustable to achieve optimal stability
- Minimum Tipping Force: 13.3lbf
Chassis Future Weatherproofing

Out of scope for current project, but Chassis designed for future implementation.
Given:
\[ h = 450\text{mm} \]
\[ d = 184\text{mm} \]
\[ m = 15.8\text{kg} \]

\[ \sum M_P = 0 \]
\[ = Fh - mgd \]
\[ \Rightarrow F = \frac{mgd}{h} \]
\[ \Rightarrow \text{Tipping Force, } F = 63.4N = 14.2\text{ lbf} \]
Chassis Motion Study

- No interference between optics and chassis
- Full range of motion accessible
Chassis Wire Management

- Wires routed inside 8020 extrusions along base
- Circular Disk (mounted to pedestal) used for prevention of wire tangling during motion
Software Emergency Stop

"Unwrapping" procedure
- Performed **before** tracking action if angle is >360 degrees
- Performed **during** tracking action if angle becomes >540 degrees

Hardware Emergency Stop

Emergency Stop Button
- **Physical** button in case of software failure
  - Locking momentary switch
  - Immediately **cuts power** to all hardware
• Using equilibrium, power in = power out (Qdot used in analysis)

• Using the fan's "CFM" information we can determine how much energy the fan is removing from the box assuming ideal conditions

• The largest consumer in dissipator between the PSU and the UDOO can be selected as the UDOO if complete dissipation is assumed

• If an initial internal temperature of 293K is used, the equilibrium temperature inside the box will be around 300K. This is the temperature of the air flowing right past the electronics, and dictates the temperature inside the box.
Specifications Power Supply

- Size: 198mm x 99mm x 38mm
- Ripple and Noise: 80 mV p-p
- Load Regulation: 3.0%
- Line Regulation: 1.0%
- Input: 88-264VAC
- Output: 5V @ 7A or 12V @ 7A
- Short circuit / overload protection
Operational Requirements

- Power source: 12V 3A AC to DC barrel plug adapter
- Mount style: 4x included mount screws with standoffs
- Input/Output:
  - Input USB 3.0 Type A 64GB flash drive with TLE information
  - Input GPS through Arduino 101 header
  - Output mount control through USB 3.0 Type A
  - Output and input camera data through USB 3.0 Type A
  - Output and input OS data through microSD card slot
Specifications 7" LCD Screen

- Size: 165mm x 100mm x 5mm
- Resolution: 1024x600
- Connectivity: HDMI
- Where to Buy: Amazon
- Cost: $39.99
- Availability: Shipping within two days
Backup - GPS
Specifications
Adafruit Ultimate GPS

Size: 15 mm x 15 mm x 4 mm
Position Accuracy: < 1 meter
Timing Capabilities:
• NMEA text file output
  • Accuracy 1 millisecond
• 1 PPS output – Digital Pulse
  • Accuracy < 1 microsecond
Where to Buy: Adafruit
Cost: $39.95
Availability: Shipping within two days
GPS Receiver Specifications

15 mm x 15 mm x 4 mm
Position Accuracy: < 1 meter
Timing Capabilities
• NMEA text file output
  • Accuracy 1 millisecond
• 1 PPS output – Digital Pulse
  • Accuracy < 1 microsecond

AdaFruit Ultimate GPS Breakout
**NMEA text file**
- Sent through I/O output to Arduino every second
- Contains current position ~1 meter accuracy
  - Processor pulls longitude/latitude data
- Contains current time ~1 ms accuracy

**1PPS (pulse-per-signal)**
- Sent through I/O output to Arduino
- Digital pulse to which processor continuously aligns
- Negligible latency through Arduino connection
- Steers time to an accuracy of ~1 μs
GPS Receiver Logistics

• Slewing and Image Capture Timing

LEO satellites move 7km/s (7 meters per millisecond)

Timing error of one millisecond:
- Pixel will still capture satellite at its proper location

Conclusion: Can use NMEA text files for timing synchronization across actuation and image capture
GPS Receiver Logistics

• Orbit Determination
  • Need highly accurate image capture times for an orbit solution
  • Higher capability needed than NMEA text files can provide

• Camera Latency
  • All cameras have latency: must solve for upper bound on image timestamp

LATENCY TEST:
Image array of LEDs flashing at 1 μs intervals

Flash down the line with time

IMAGE TIMESTAMP:

--> Compare timestamp record to which LED is lit to extract latency
Backup – Computer
Specifications UDOO x86

**CPU:** 4-core 2.24GHz Intel Celeron N3160

**Microcontroller:** Intel Curie

**RAM:** 4GB DDR3L

**I/O:** Gigabit Ethernet

3 x USB type-A

Arduino Pinout (from onboard M/C)

**Where to Buy:** Mouser

**Cost:** $190.64

**Availability:** Shipping within two days
Onboard Computer Port Usage

- Barrel Jack to Power Adapter
- USB3 Type A to USB Drive (Input)
- HDMI to LCD display
- MicroSD card slot to 256GB MicroSD Card (on back)
- Arduino pinout to Arduino shield
- Arduino shield to GPS header
- USB3 Type A to ZWO Camera
- USB3 Type A to iOptron Mount
Backup – Scheduler
TLE Retrieval

• .obs file
  • Ignores NORAD IDs not under module of interest

• Space-track.org
  • Read by Spacetrack’s API

• TLE file
  • Designed for the SGP4 propagator

Latest TLE file

1 25544U 98067A 18304.82506281 .00001186 00000-0 25372-4 0 9997
2 25544 51.6422 57.8134 0004309 357.1841 147.3410 15.53881922139765

TLE catalog downloaded from Space-track.org

Module Name
NORAD ID 1, override #
NORAD ID 2
NORAD ID 3

Module Name 2
NORAD ID 4
NORAD ID 5, override #
SGP4 Propagation

- SGP4 Propagator: DR 4.1.3
  - TLEs are designed for this model
  - Used by the “Skyfield” python package
  - Outputs \( \vec{r} \) and \( \vec{v} \)

- Convert to Right Ascension & Declination

- Convert to Azimuth & Elevation
  - Required for actuation system
  - “Human readable” intuitive format
  - Required for ruling out and weighting passes
Weighting Priority to Observations

LEOs

Time

LEO 1

0.8

NO CONFLICT

LEO 2

Option for user to override

LEO 3

1.7

NO CONFLICT

LEOs
Weighting Priority to Observations

(1) LEO’s get priority near sunset/rise for ~30 minutes.
(2) Passes with a high max elevation get high weight.
(3) Space objects with an older TLE epoch get a high weight.

Option to apply biases to each weight

(1) \( f(x) = \text{step}(x + 25) - u(x + 18) \)

(2) \( f(x) = \left( 0.5 - 0.5 \cos \left( 1.4 \pi \frac{20 - x}{90 - 20} \right) \right) u(x - 20) \)

(3) \( f(x) = \exp((-2.78(x - 0.5))^2) \)
Creating Actuation/Imaging Commands

Key to image near horizon and near max elevation

- Do not continuously track
- Add in more imaging sequences where possible

Time

<table>
<thead>
<tr>
<th>Sat 1</th>
<th>Sat 2</th>
<th>Sat 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.3</td>
<td>0.9</td>
</tr>
</tbody>
</table>

- Do not continuously track
- Add in more imaging sequences where possible
Backup – Image Processing
Image Processing

Object Tracking
Backup – Orbit Determination
Batch Process Algorithm Breakdown

Format Data

Set initial conditions for filter

Iterative Non-Linear Batch

Propagate State Forward

If Not Converged

Calculate Difference Between Estimated and Measured

While Not Converged

Update Estimate and Covariance

If Converged

Return Position and Velocity Estimation and Covariance
Goal: Reduce residuals between the estimation and the measured values

\[ \tilde{X} = [r_x, r_y, r_z, v_x, v_y, v_z]^T \]

\[ \tilde{Y} = [\alpha, \delta]^T \]
Coordinate Transformations

\( \hat{X}\hat{Y}\hat{Z}, \text{Earth's Center: Earth Centered Inertial Frame} \)

\( \hat{N}\hat{E}\hat{U}, \text{Observation Site: Topocentric Frame} \)

\( \hat{o}: \text{Position vector in the ECI frame} \)

\( \hat{L}: \text{Line of sight vector in the topocentric frame} \)

\( \hat{r}: \text{Position vector of the space object in the ECI frame} \)
Equations of Motion

- Two body Problem with J2 Perturbations

\[ a_x = -\frac{\mu}{r^3} r_x - \frac{3}{2} J_2 \left( \frac{\mu}{r^2} \right) \left( \frac{r_{eq}}{r} \right)^2 \left( 1 - 5 \left( \frac{r_z}{r} \right)^2 \right) \frac{r_x}{r} \]

\[ a_y = -\frac{\mu}{r^3} r_y - \frac{3}{2} J_2 \left( \frac{\mu}{r^2} \right) \left( \frac{r_{eq}}{r} \right)^2 \left( 1 - 5 \left( \frac{r_z}{r} \right)^2 \right) \frac{r_y}{r} \]

\[ a_z = -\frac{\mu}{r^3} r_z - \frac{3}{2} J_2 \left( \frac{\mu}{r^2} \right) \left( \frac{r_{eq}}{r} \right)^2 \left( 3 - 5 \left( \frac{r_z}{r} \right)^2 \right) \frac{r_z}{r} \]
Textbook Example Residuals

Residual in Position v Iteration

Residual in Velocity v Iteration
The filter is initialized with $X = X_0$, $\Phi = I_{6 \times 6}$, $\Lambda = 0$, and $N = 0$

A measurement is read in at $t_i, Y_i, R_i$

ODE 45 is used to propagate $\bar{X}$ and $\Phi$ from $t_{i-1}$ to $t_i$

The current observation equations are calculated (see Equations section)

If $t_i < t_{final}$, the next observation is read and the process is repeated from step 2.

If $t_i > t_{final}$, the normal equations are solved

If the process has not converged, the nominal trajectory is updated and the process re-starts at step 1.

If the process has converged, congratulations!
Backup – Testing
Field System Testing

Environment

- Temperature
  - Lens Condensation
  - Battery Capacity

- Precipitation
  - Electronics Housing
  - Lens Obstruction
  - Camera, Lens, Actuation Rating

- Transportation
  - Weight
  - Mobility (handles)
End-to-End Observation Session

• Start
  • USB Drive w/.obs text file and latest TLE catalog connected via internet
  • Start button on enclosure pushed

• Operation Status
  • LED Lights indicating status (Scheduling, Error, Shutter, Actuation, Complete)

• Test End
  • Orbit Estimates written to USB Drive

• Troubleshooting
  • Active ODROID connection (Ethernet)