GHOST

<u>G</u>round-based <u>H</u>ardware for <u>O</u>ptical <u>S</u>pace <u>T</u>rackin

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

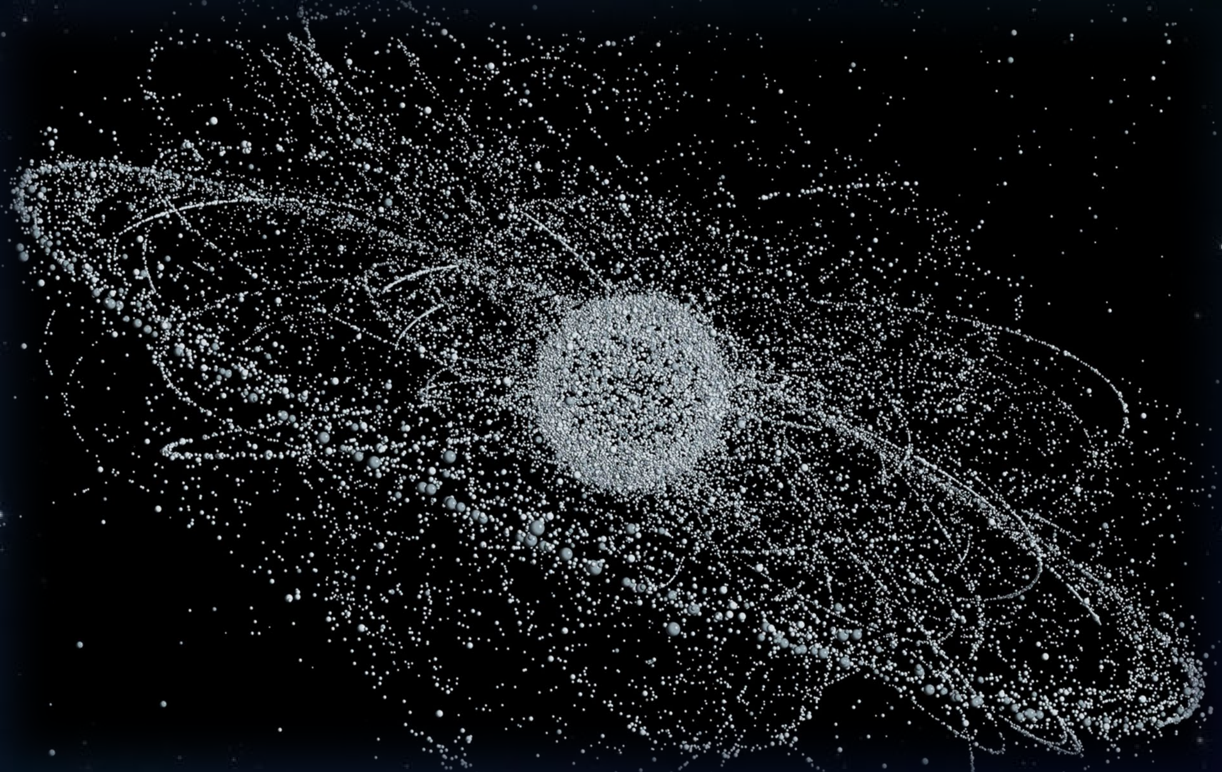
Project Overview

Motivation

- Increasing number of space objects
  - CubeSats
  - Mega Constellations
  - Debris
- International dependence on space
  - Communication
  - Weather
  - National Security

Solution

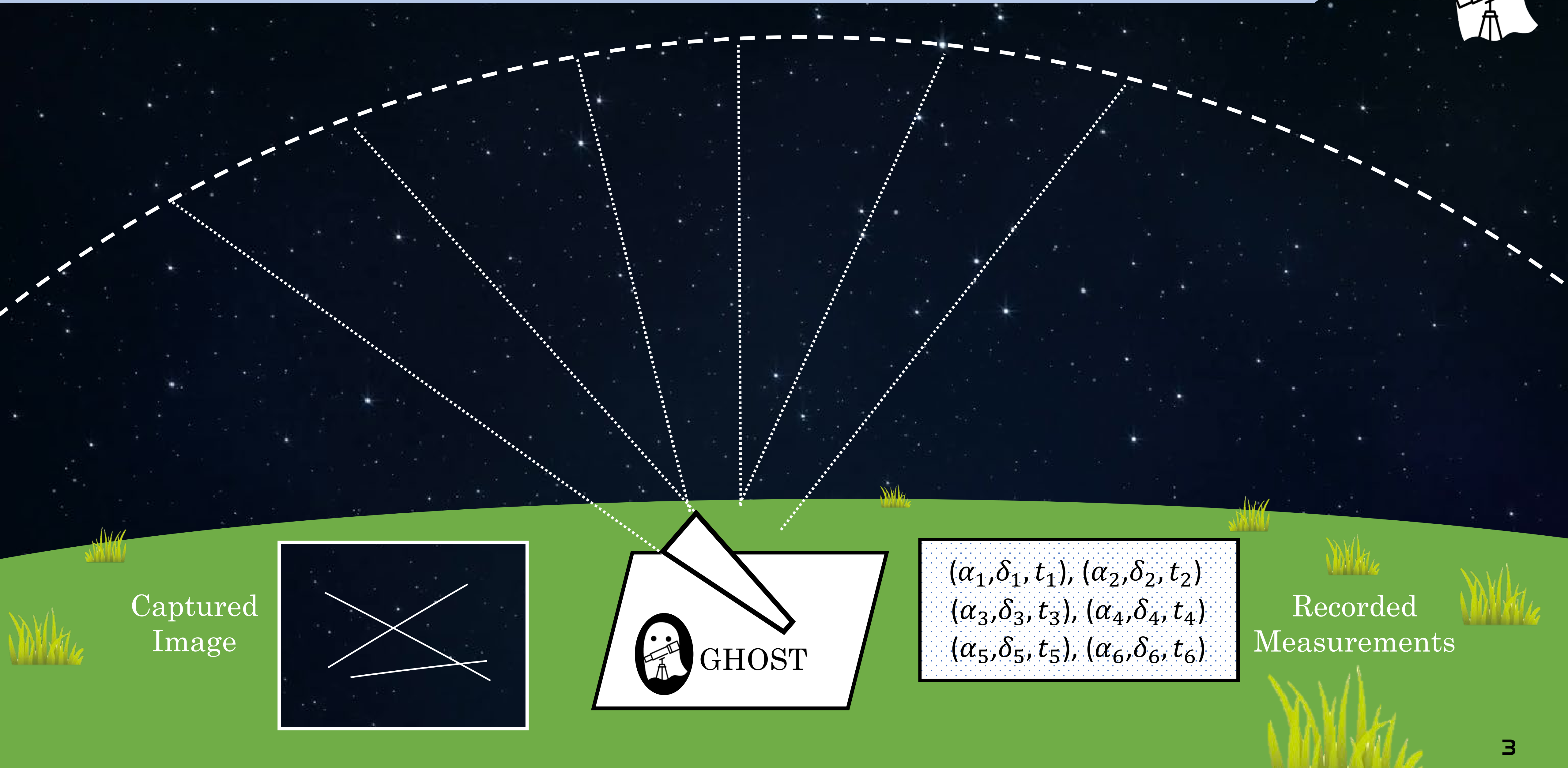
Design a low-cost, ground-based, optical tracking system for space situational awareness (SSA) and space traffic management (STM).



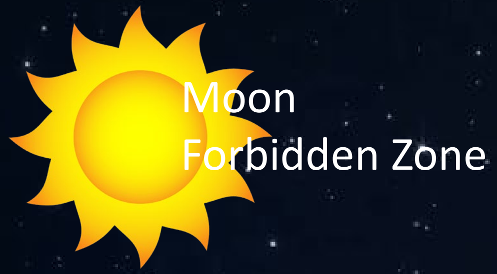
Estimated satellite distribution by 2040

*Courtesy of Daily Mail

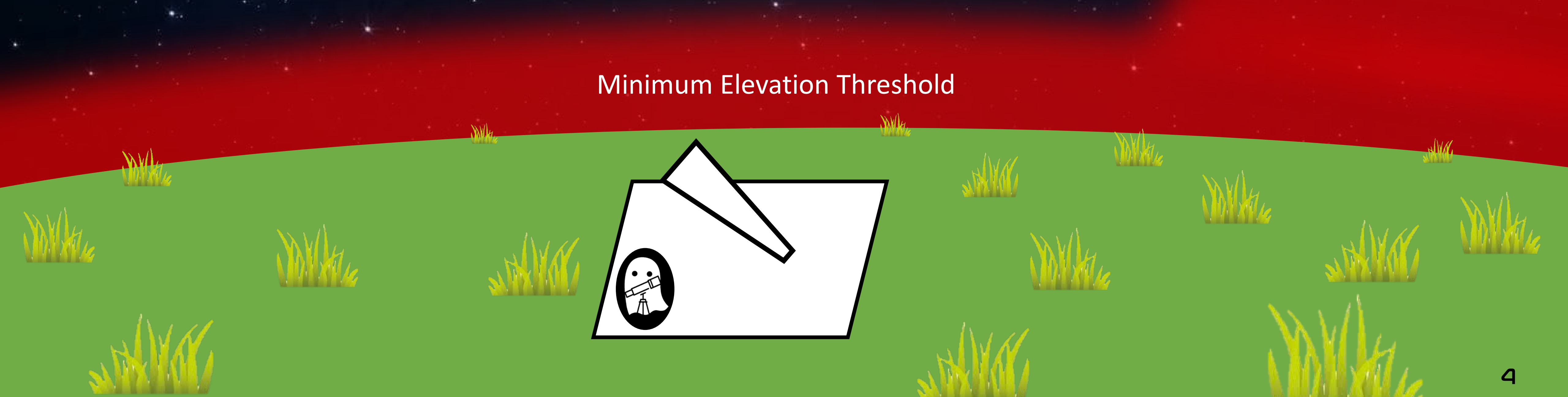
Concept of Operations



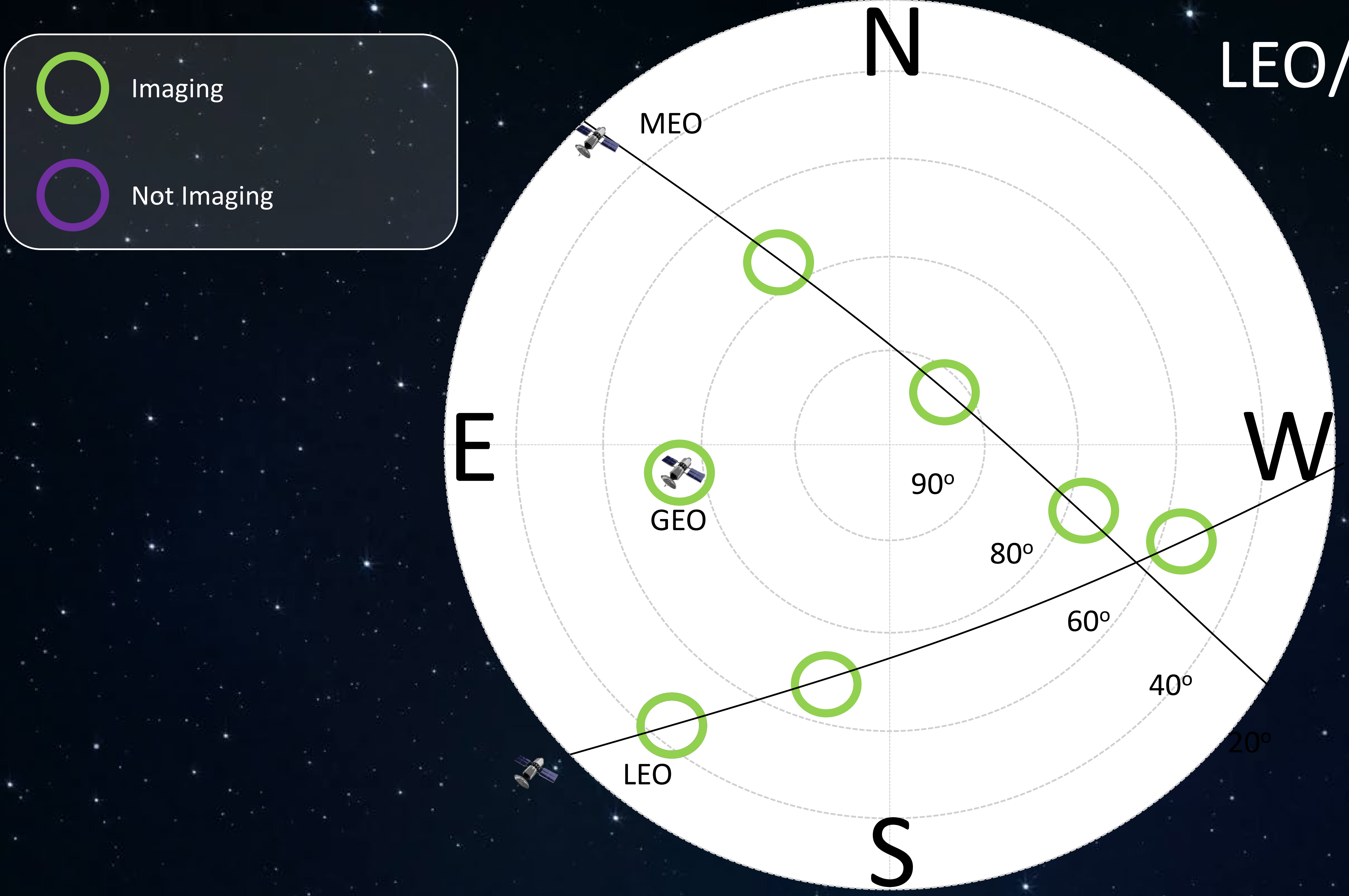
Observation Constraints



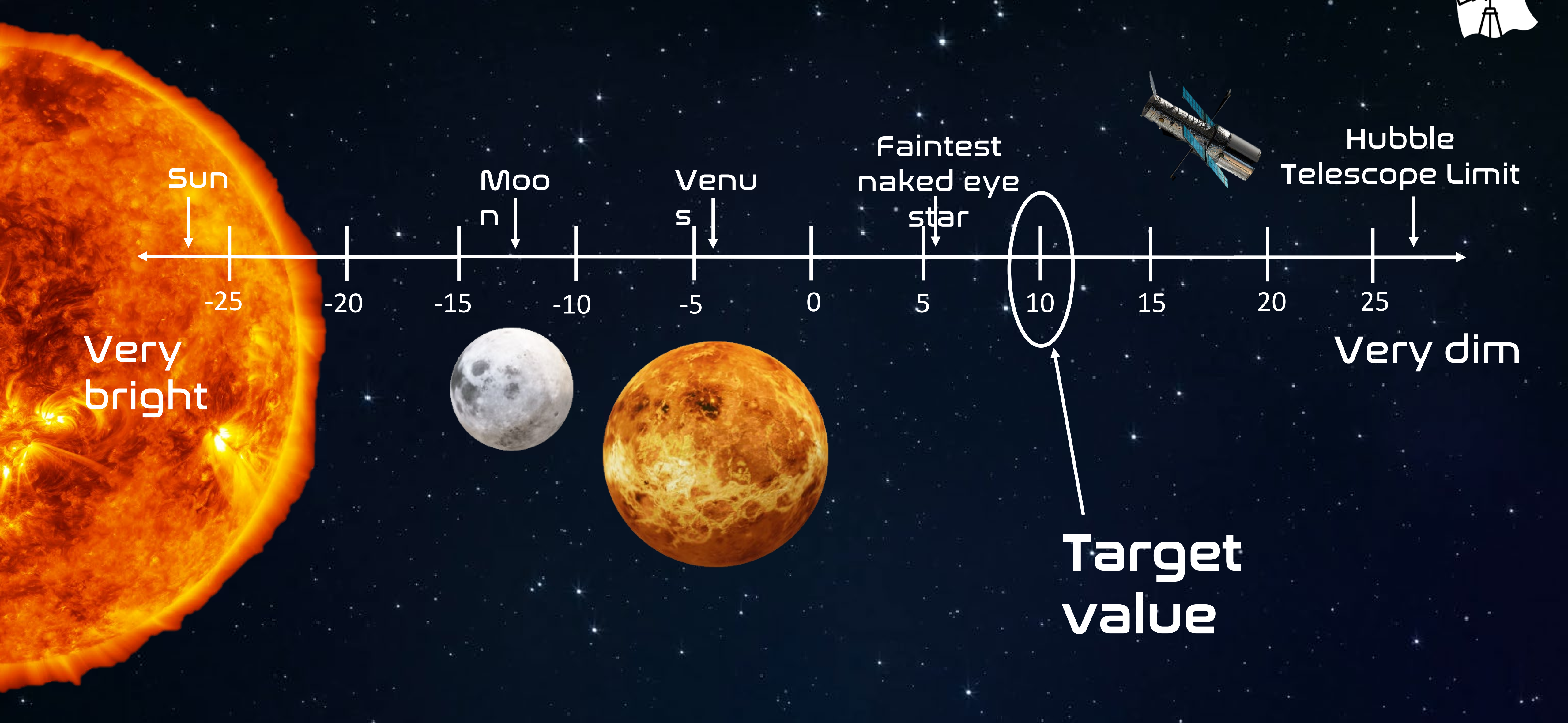
- Sun must be 18º below horizon
- Object must be 0º-30º away from Moon
  - Depends on Moon's phase
- Object must be 20º above horizon
- Object must be out of Earth's shadow



LEO/MEO/GEO Pass

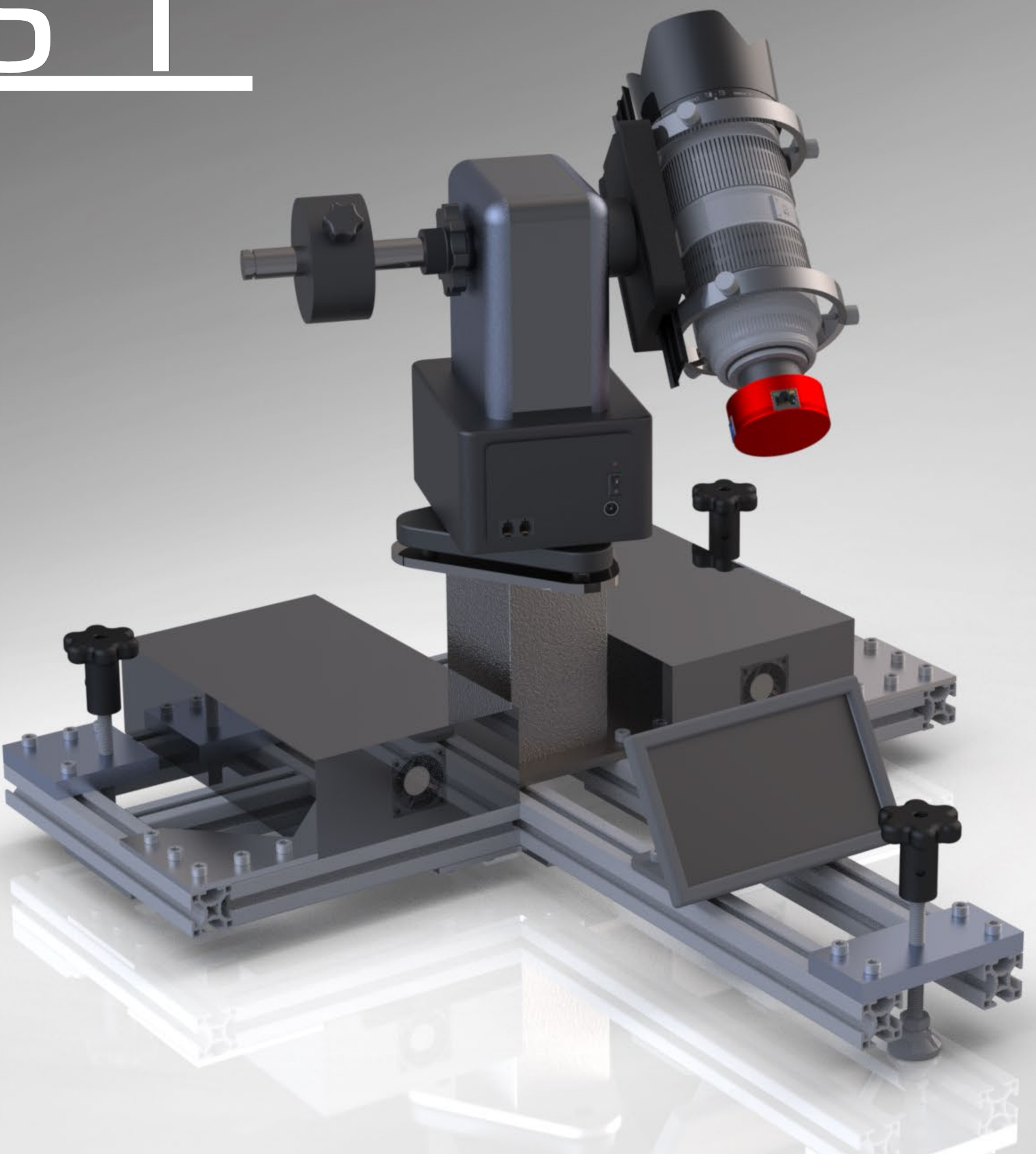


Limiting Stellar Magnitude (LSM)

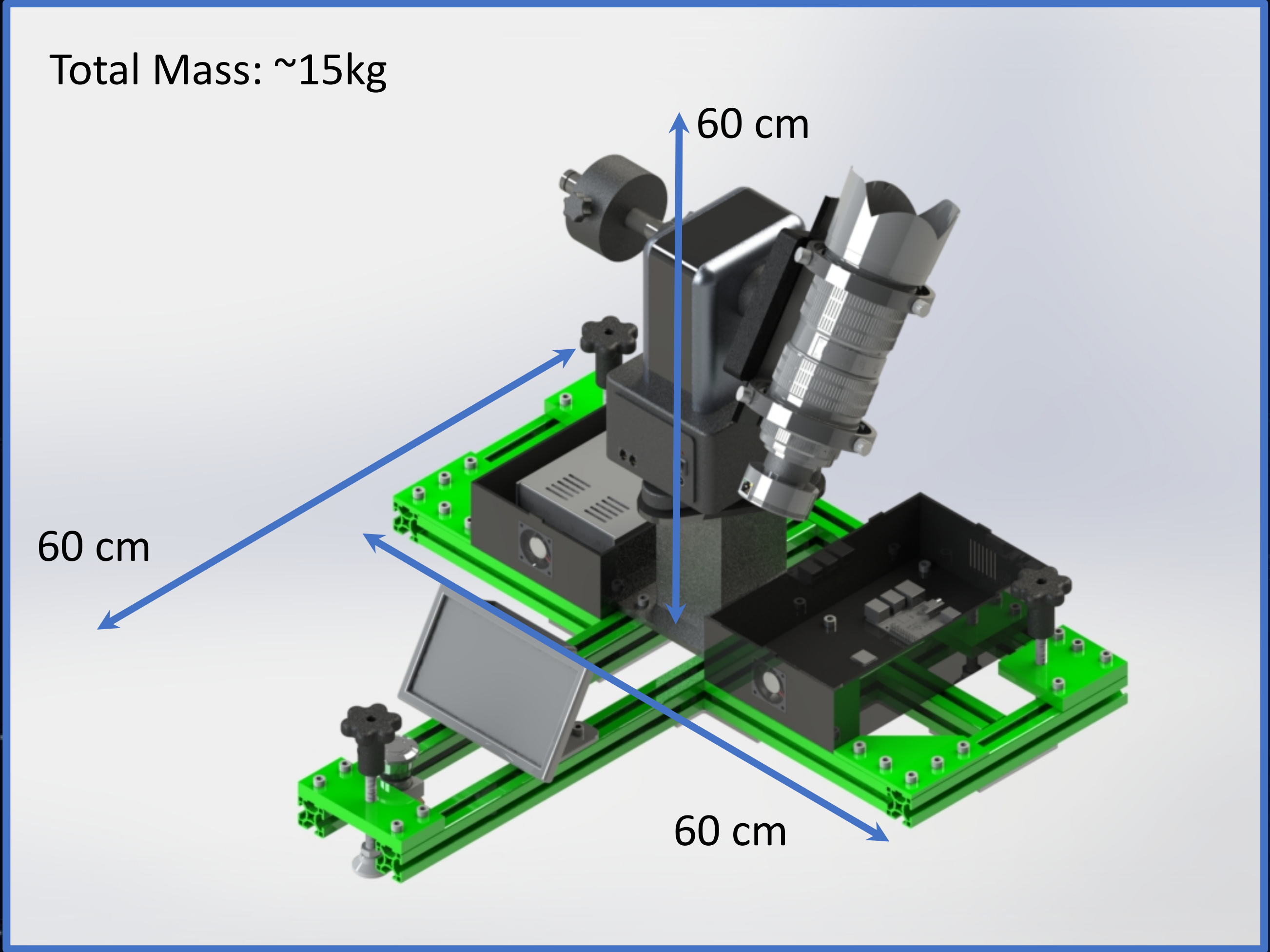


Design Solution

GHOST



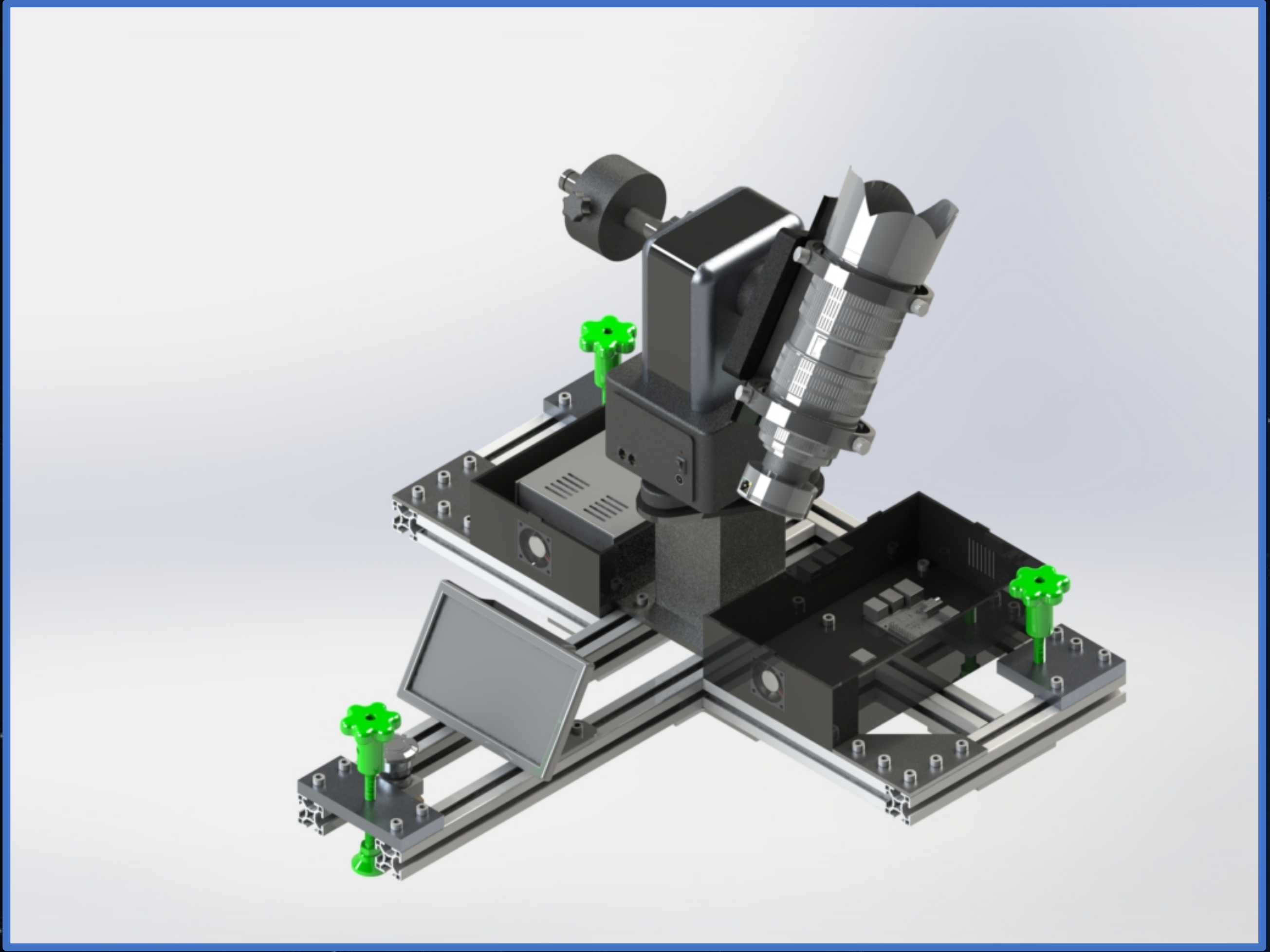
Hardware Design



Chassis

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

Hardware Design

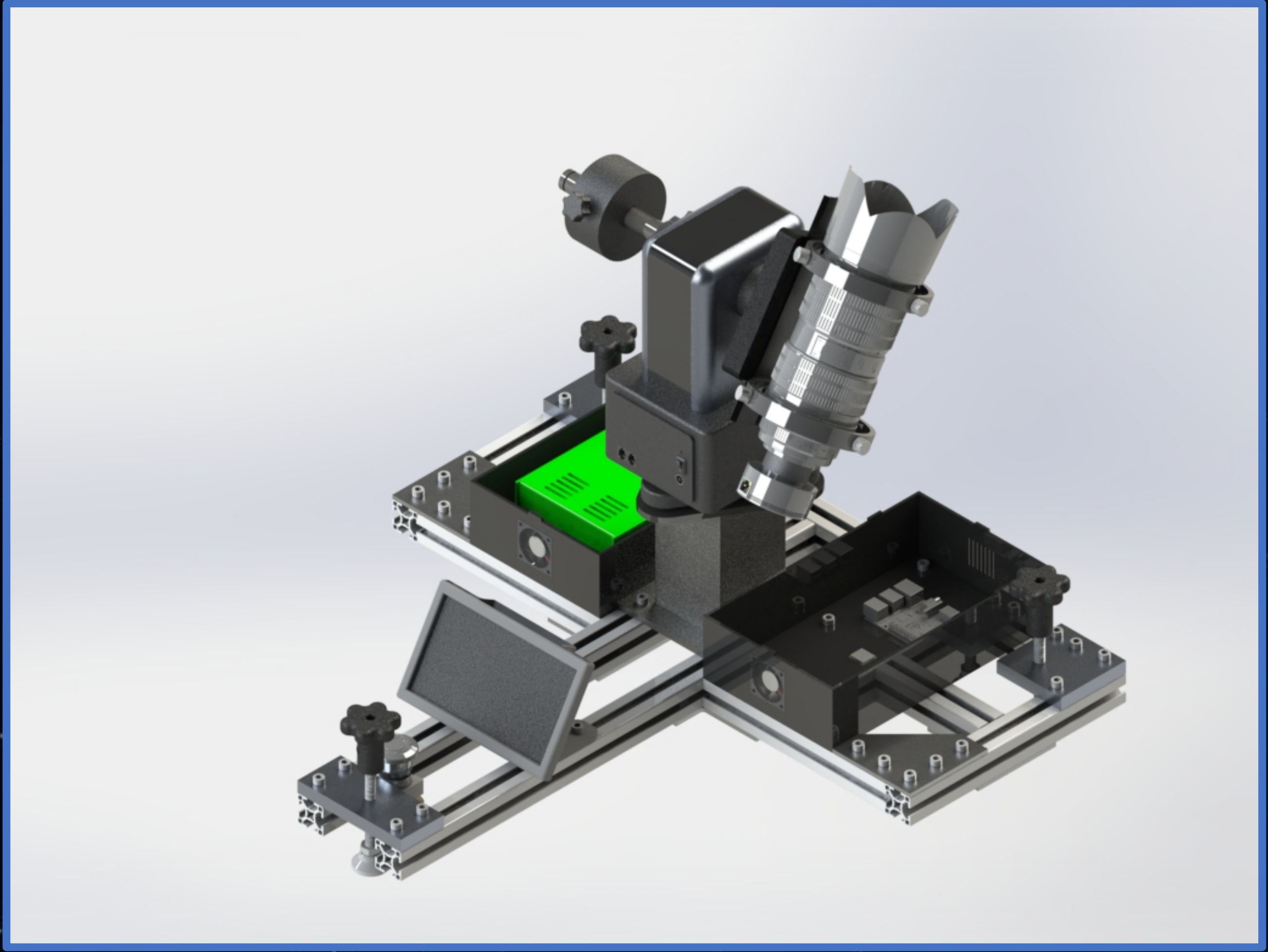


Chassis

Three Leveling Feet

- 3 points of contact for stability
- 4" screws allow for leveling to 10°

Hardware Design



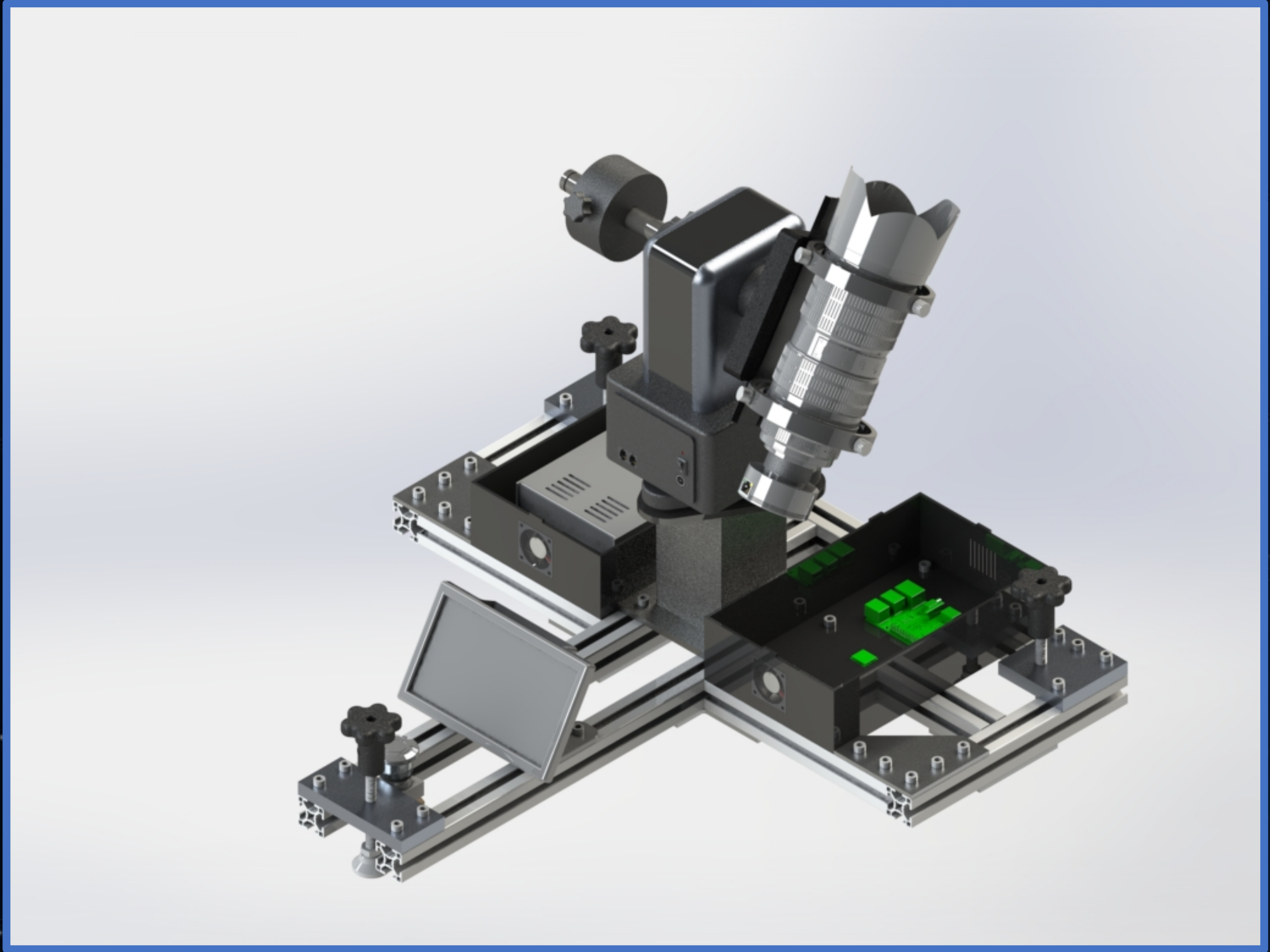
Chassis

Three Leveling Feet

Dual-Output Power Supply

- MEAN WELL 323741
- Powered by 120VAC (3-prong)
- Outputs 5V and 12V at up to 7A

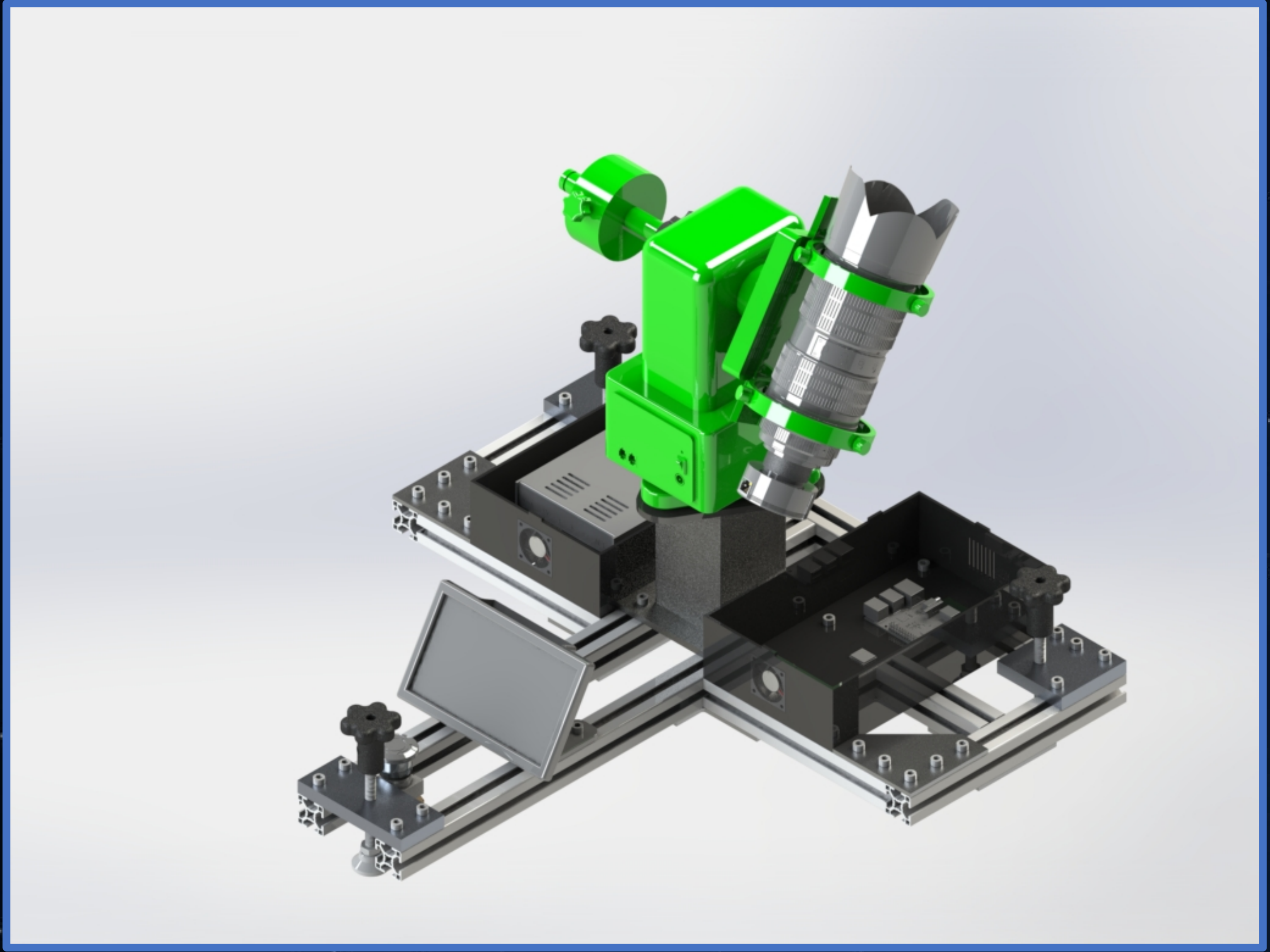
Hardware Design



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

- UDOO x86
  - 2.24Ghz processor
  - 4Gb RAM
  - 256Gb storage
- Adafruit Ultimate Module
  - PPS

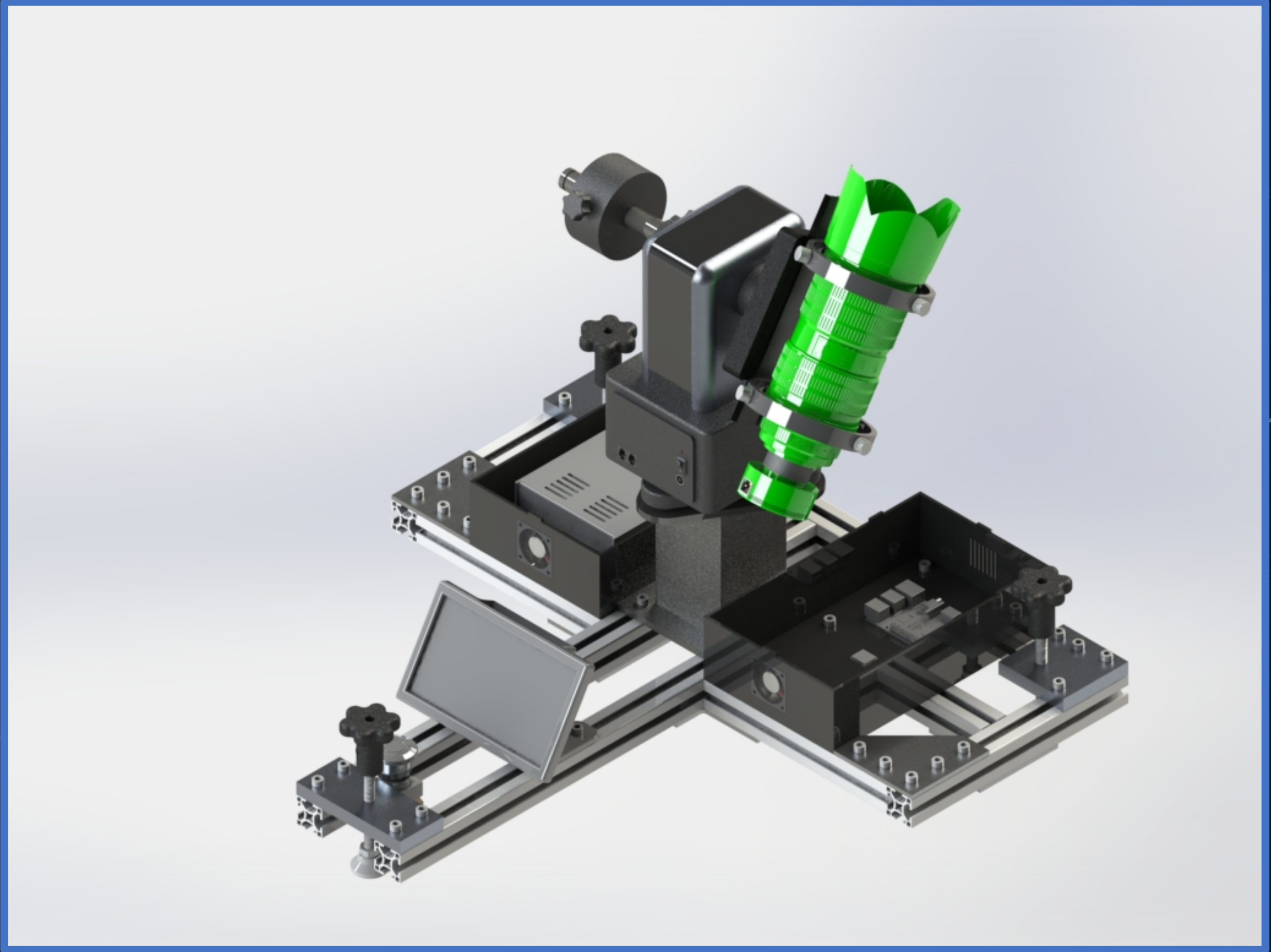
Hardware Design



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

- iOptron AZ Pro
  - Azimuth/Elevation
  - 10 deg/sec slewing
  - Sidereal tracking
  - 0.1 arcsecond resolution

Hardware Design



Chassis

Three Leveling Feet

Dual-Output Power Supply

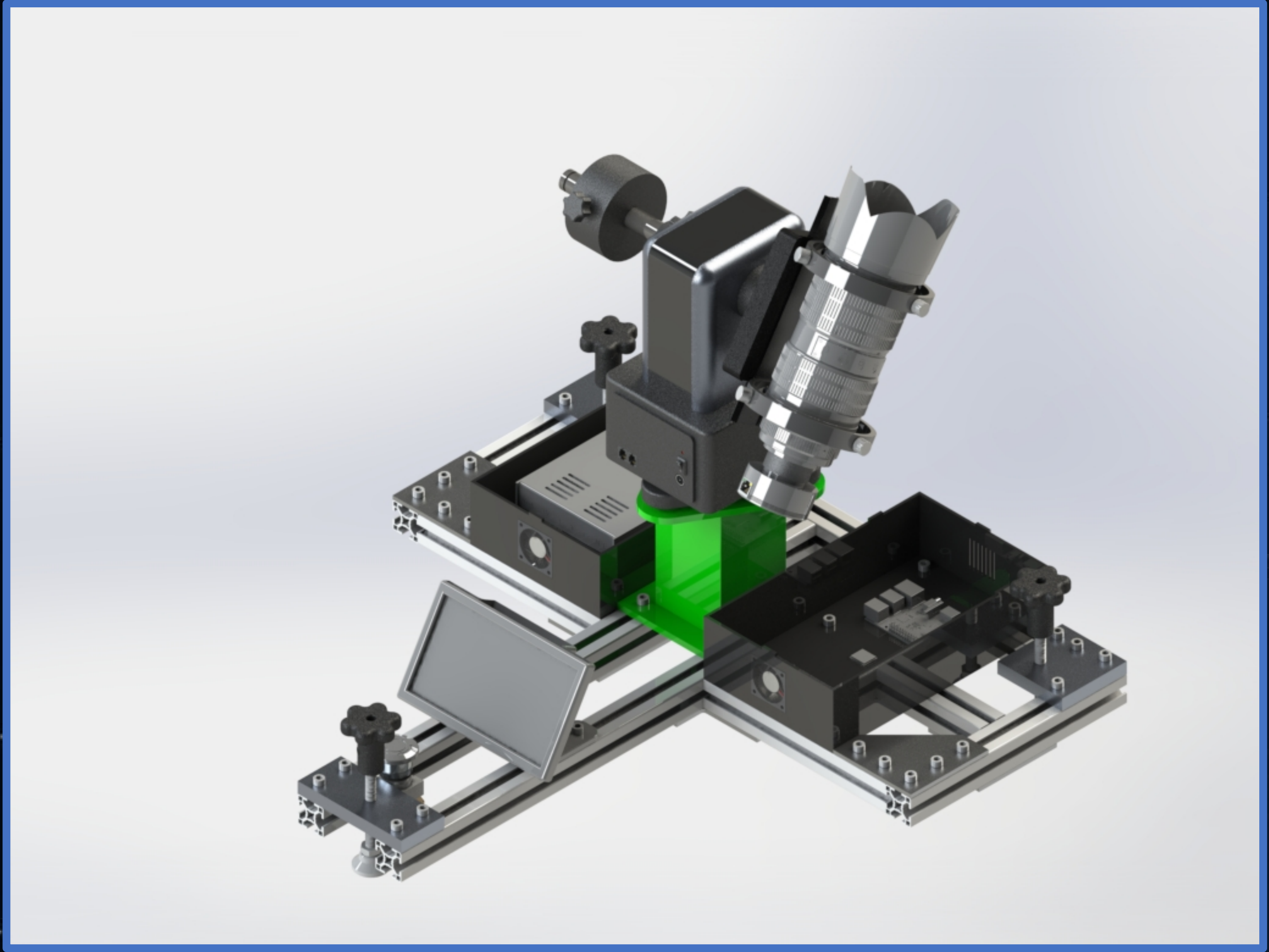
Computer and GPS

Actuation Mount

Camera and Lens

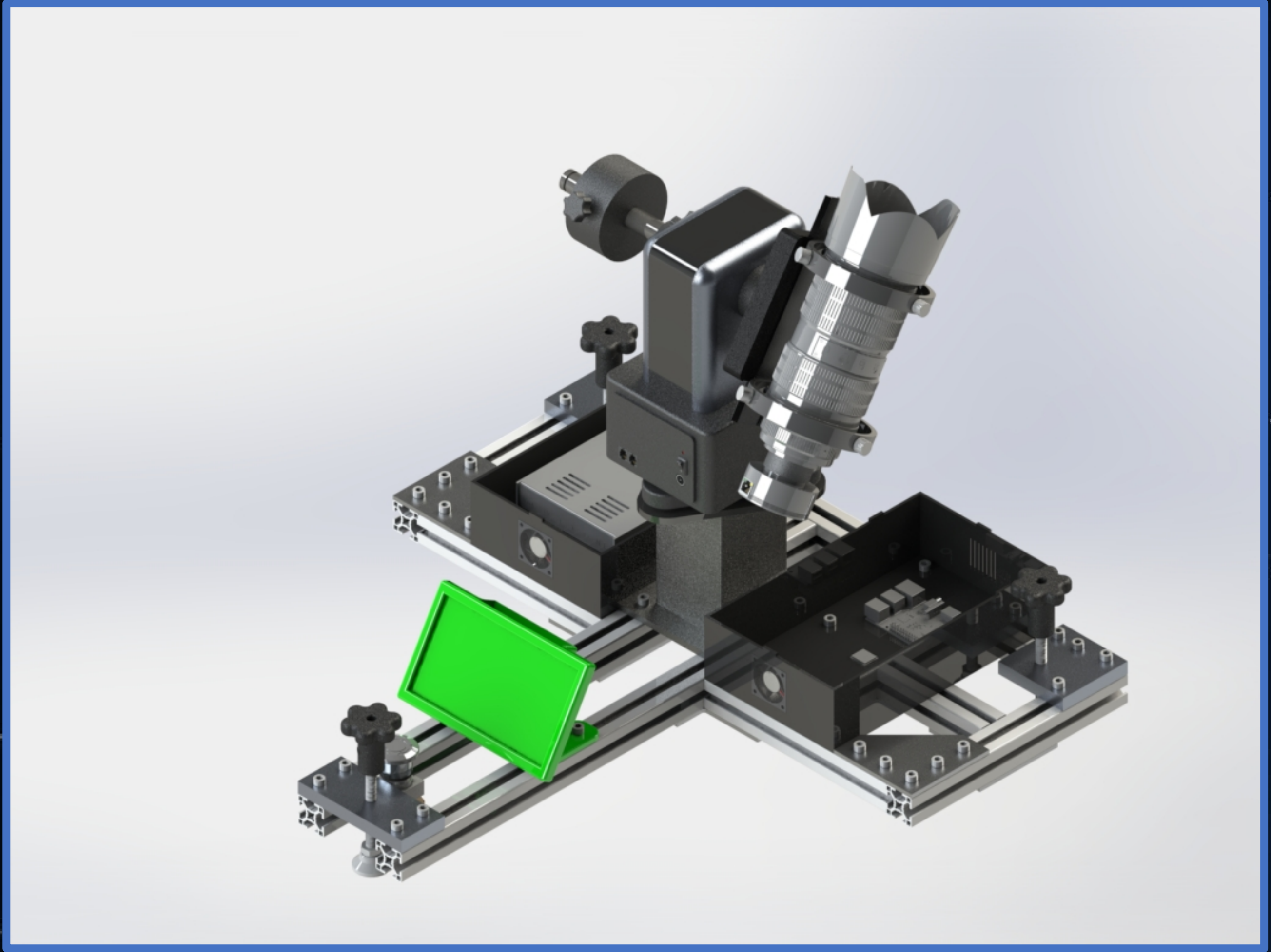
- ZWO ASI1600MM
  - 16.4MP - monochrome
- Canon EF 200mm f/2.8L
  - 4.5° effective circular FOV

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

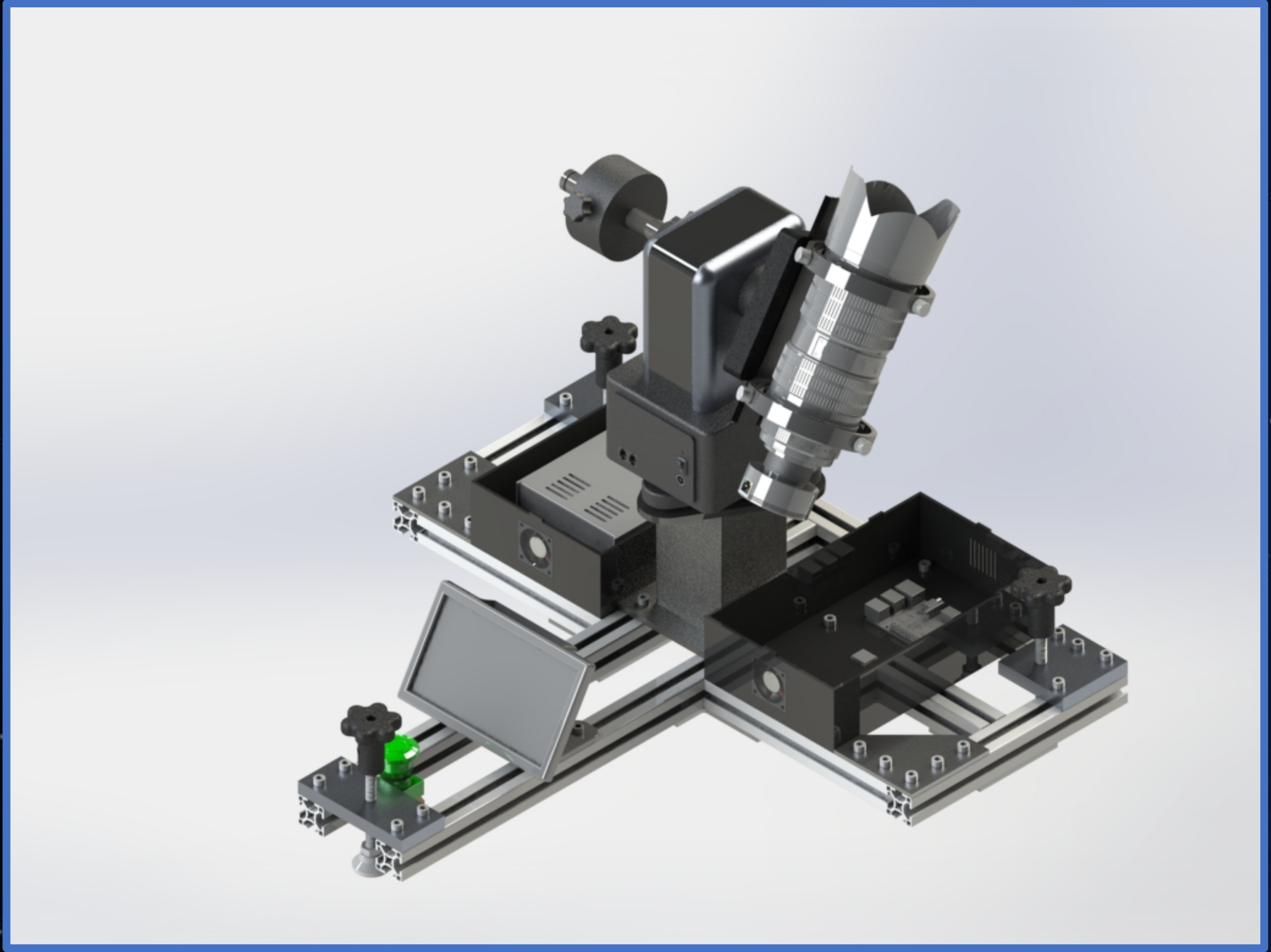
Hardware Design



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

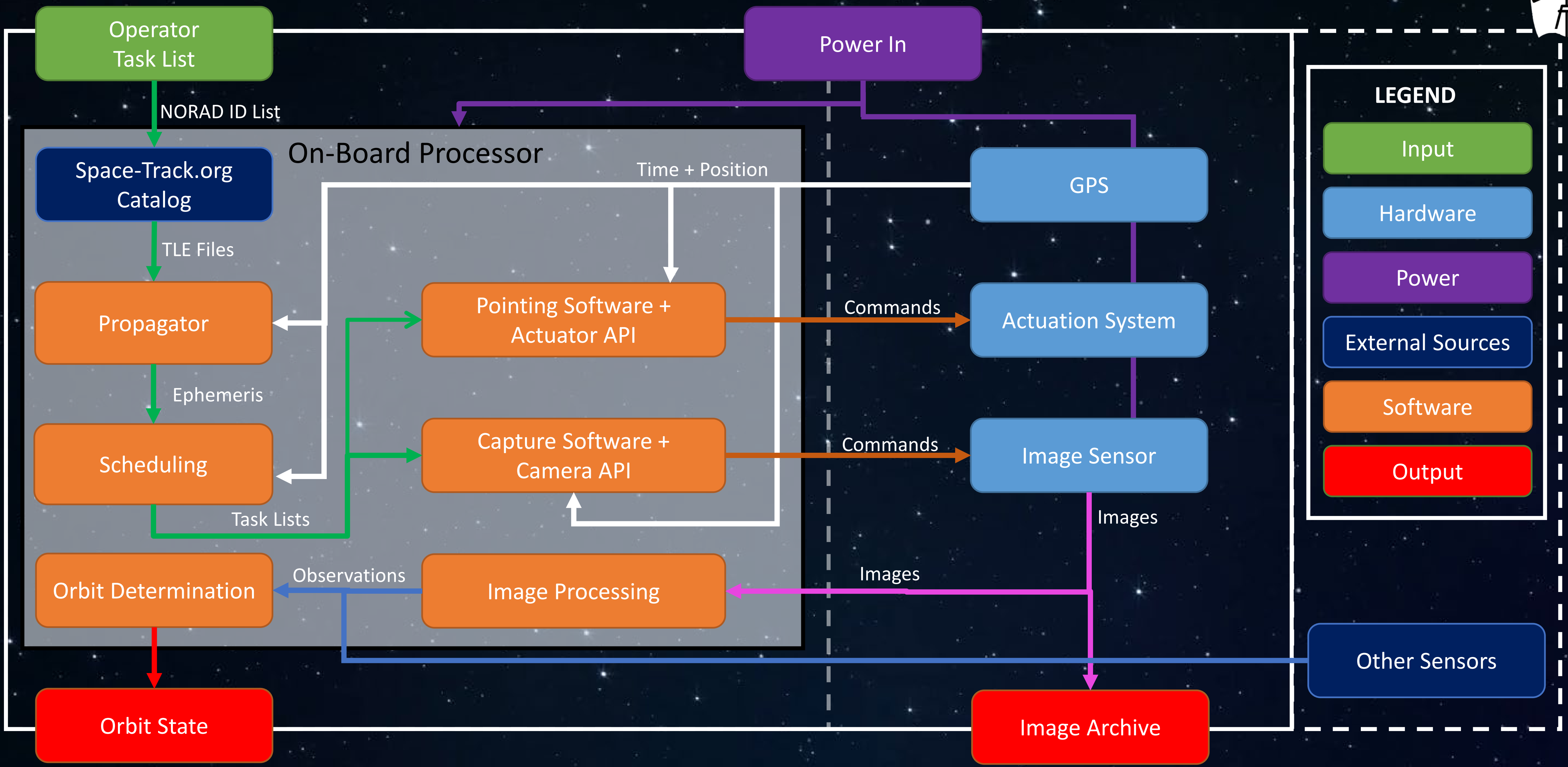
- GeekPi 7" 1024x600 LCD display
- HDMI input
- Used for calibration and output

Hardware Design

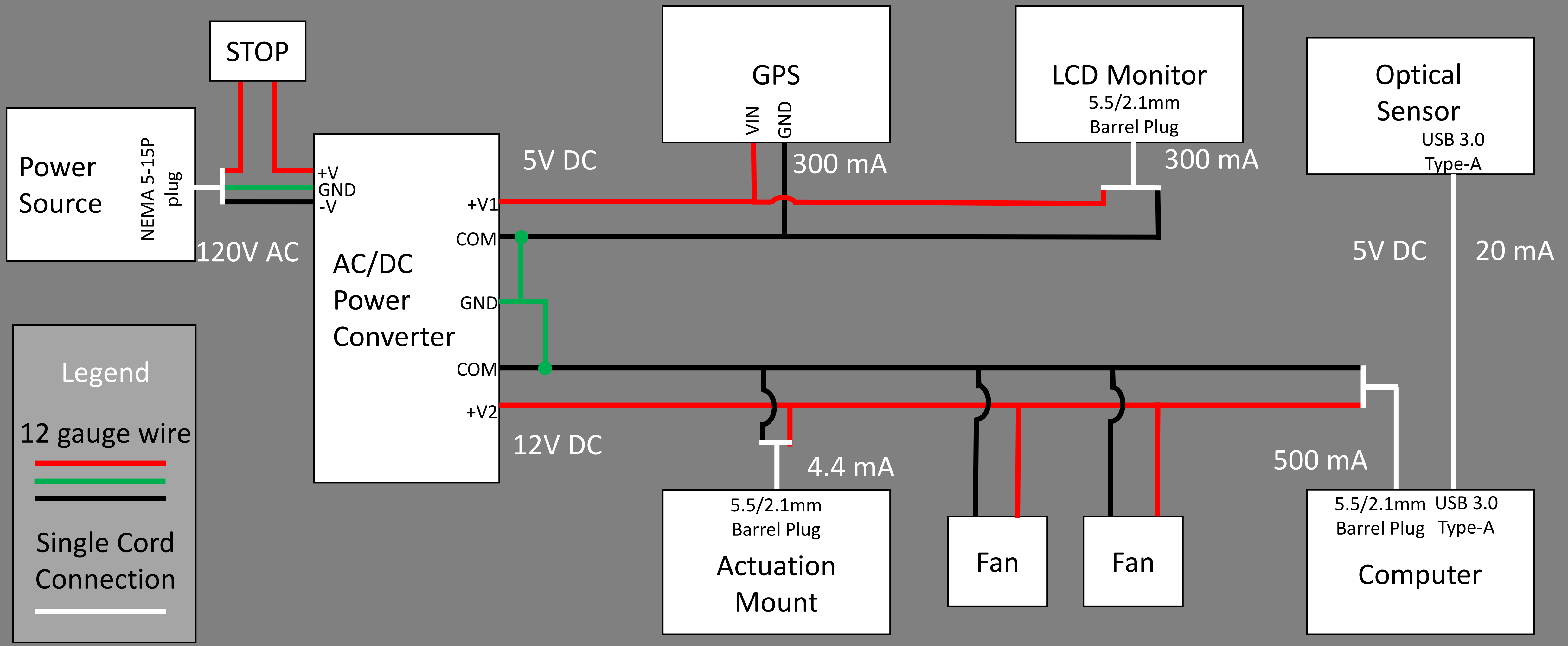


- Chassis
- Three Leveling Feet
- Dual-Output Power Supply
- Computer and GPS
- Actuation Mount
- Camera and Lens
- Pedestal
- Monitor
- Emergency Stop
  - Locking momentary switch
  - Cuts power to all subsystems

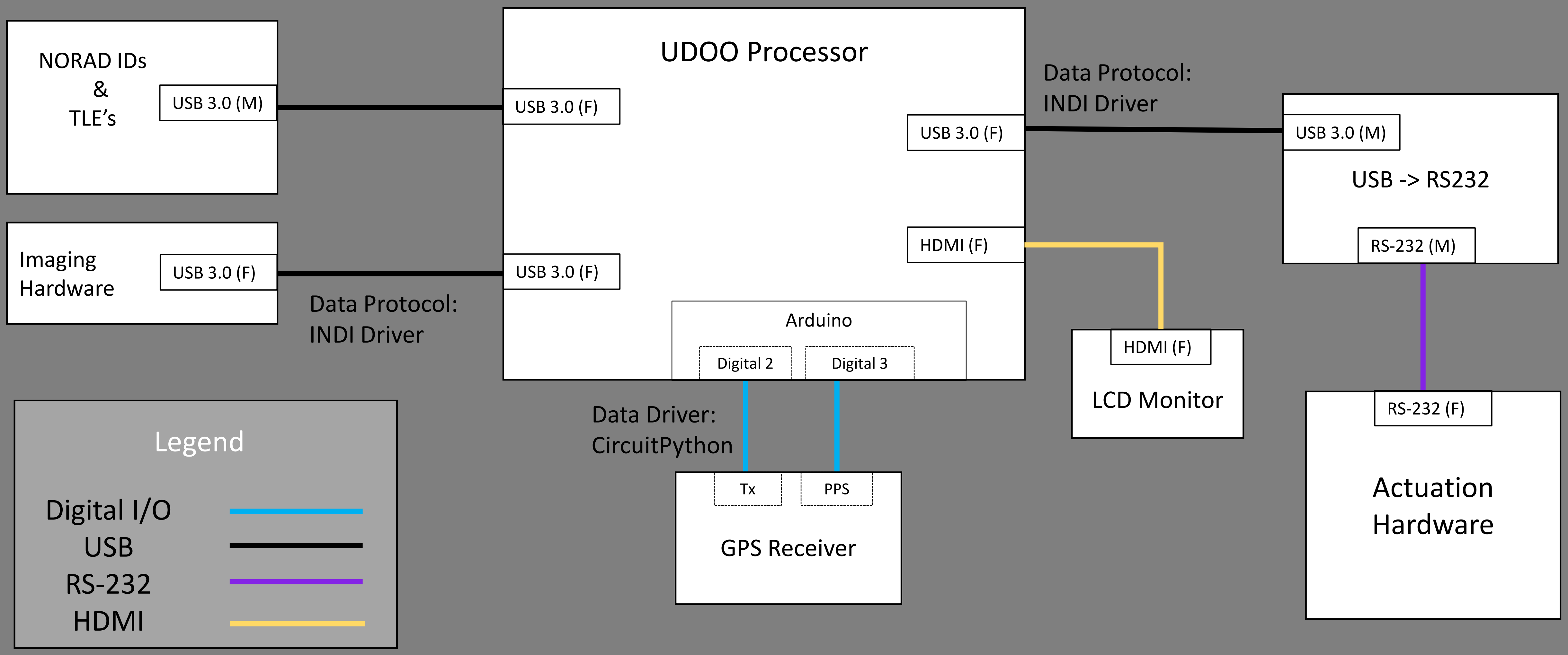
Functional Block Diagram



Power Distribution Wiring



Data Wiring



NORAD IDs & TLE's
USB 3.0 (M)
Imaging Hardware
USB 3.0 (F)
Data Protocol: INDI Driver
UDOO Processor
USB 3.0 (F)
USB 3.0 (F)
USB 3.0 (F)
HDMI (F)
Arduino
Digital 2
Digital 3
Data Protocol: INDI Driver
USB 3.0 (M)
USB -> RS232
RS-232 (M)
HDMI (F)
LCD Monitor
RS-232 (F)
Actuation Hardware
Data Driver: CircuitPython
Tx
PPS
GPS Receiver
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**

200Wh
Portable Battery
Outputs 120VAC

Anticipated Power On Time: **3+ hours**

*11W average

Critical Project Elements

Critical Project Elements

Structure	Actuation Hardware	Imaging Hardware	Electronics	Software
Chassis	Actuation mount	Camera & Lens	GPS	Scheduler
			Onboard Processor	Image Processing
			Power Supply	Orbit Determination

Critical Element

Non-Critical Element

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:

$$3.92\ \frac{\text{arcsec}}{\text{pixel}}$$

Assembled FOV:

$4.47° \times 6.75°$

FR 1.2 Verified

$FOV_{effective} \geq 4°$

Max LSM:

11.1

FR 1 Verified

$LSM_{Max} \geq 10$

Camera and Lens Requirements Met

FR 1	Selected camera and lens modeled to show LSM capabilities of 11.1 or dimmer in ideal conditions	✓
DR 1.1	Effective field of view is a 4.5° circle, allowing for flexibility in imaging	✓
FR 5	Optical system is COTS and available to ship within two days	✓

CPE Scheduler

Relevant Requirements:

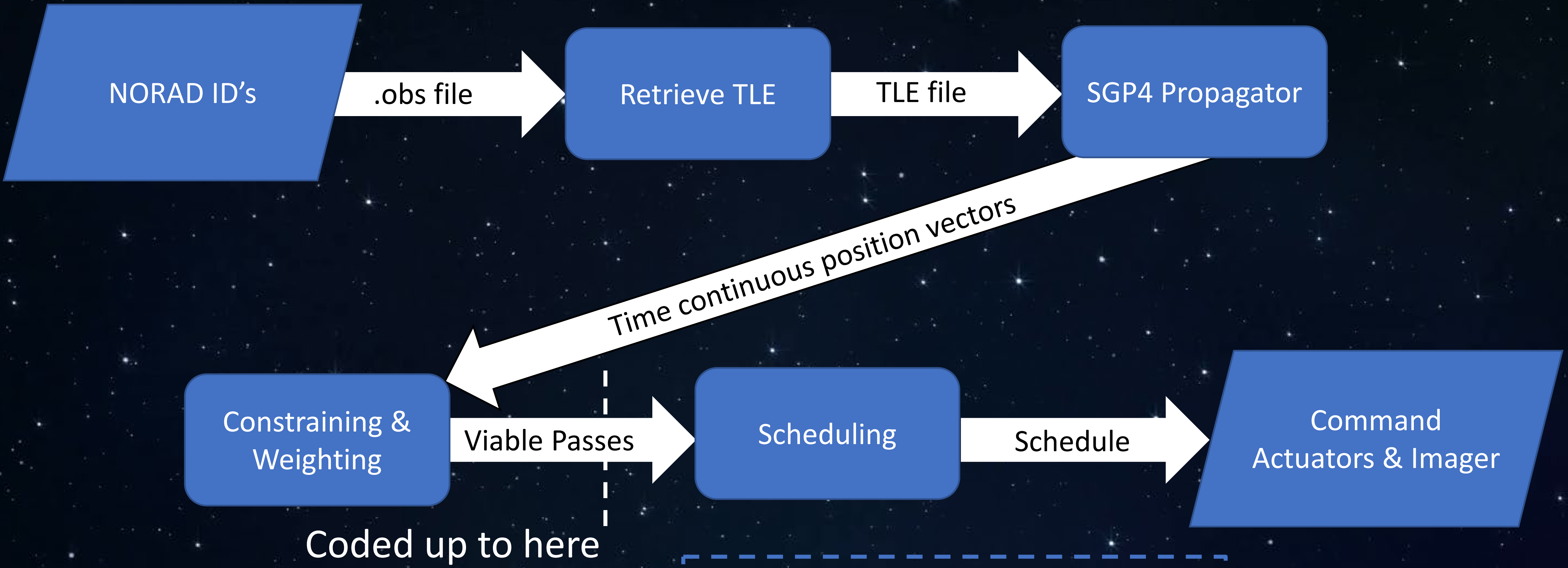
4.1 The system scheduling software shall be able to schedule imaging tasks given a list of NORAD IDs.

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



FR 4.1 Verified
Schedule observations

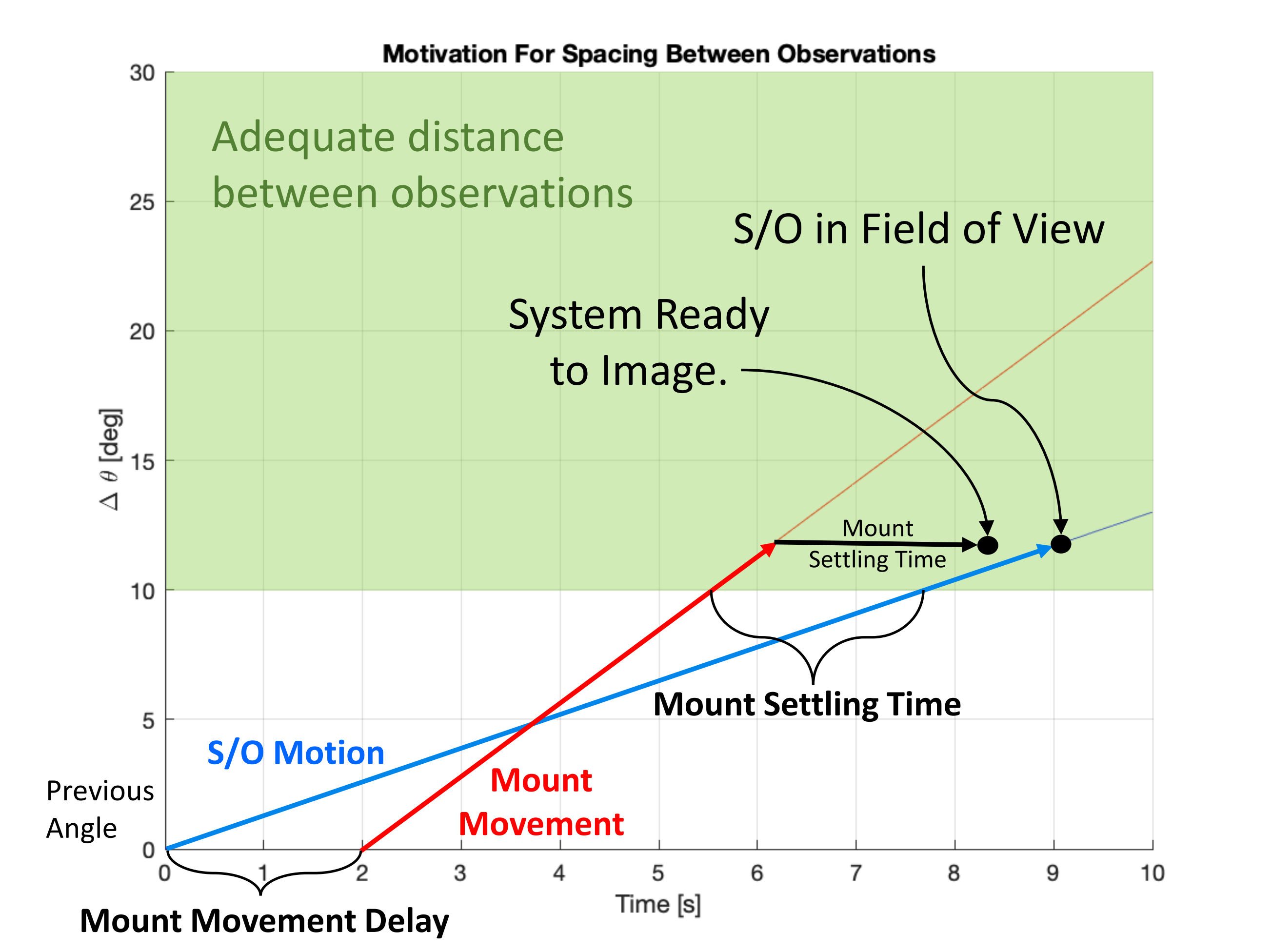
Scheduling Imaging Sequences

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

Command	Time (Julian Days)	Az (deg)	El (deg)	NORAD ID
M	2458432.500000	45	34	32711
B	2458432.500058	45	34	32711
E	2458432.500148	45	34	32711
M	2458432.500954	151	78	32711
B	2458432.501003	151	78	32711
E	2458432.501068	151	78	32711

- .cmd text file
  - Comma delimited

FR 4.2
Verified
Command observations

Command	Time	Az & El	NORAD ID
M - At time, t, **MOVE** to Az/El B - At time, t, **BEGIN** imaging E - At time, t, **END** imaging	Time at which the command is given	Pointing direction of actuation and imaging system	Current space object

Scheduler Requirements Met

DR 4.1	Method identified to prioritize and shift observations when conflicted across multiple satellites	✓
DR 4.2	Method identified for communicating between scheduling software and actuation hardware	✓

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

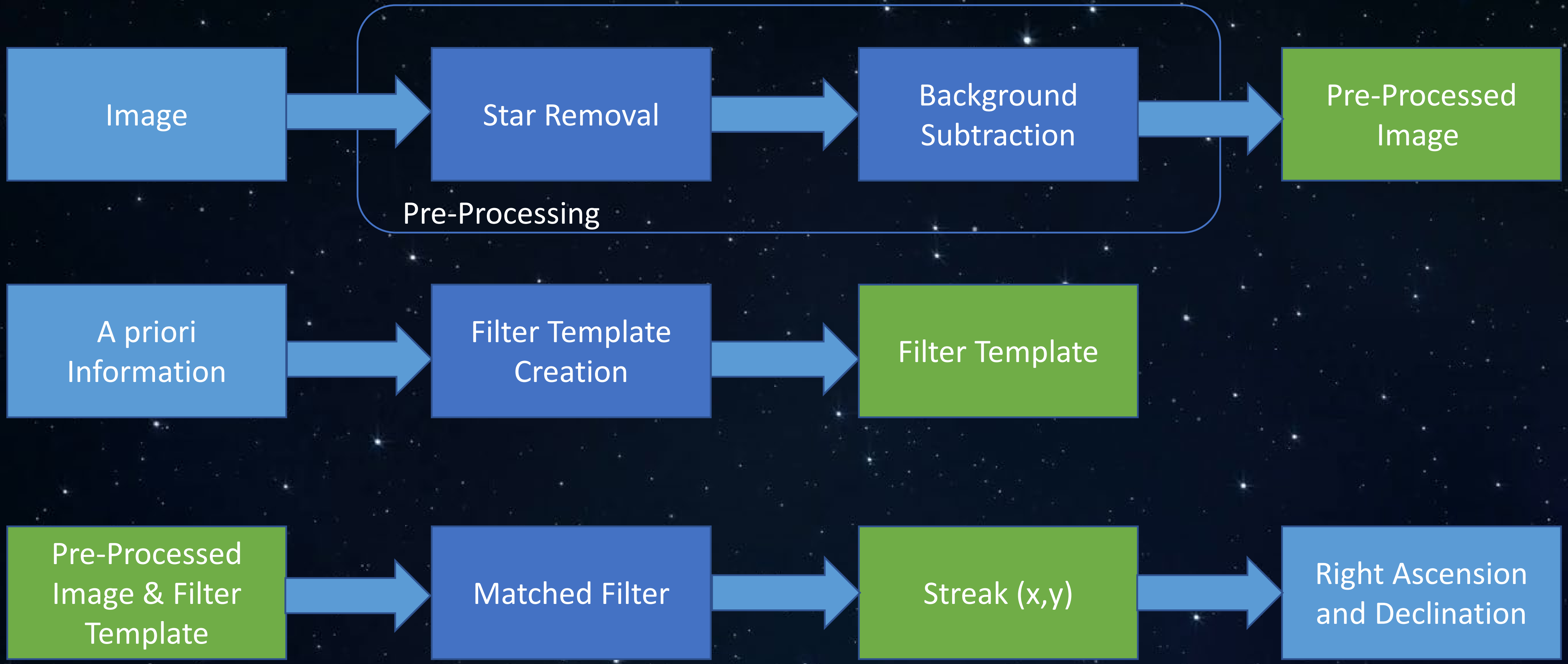
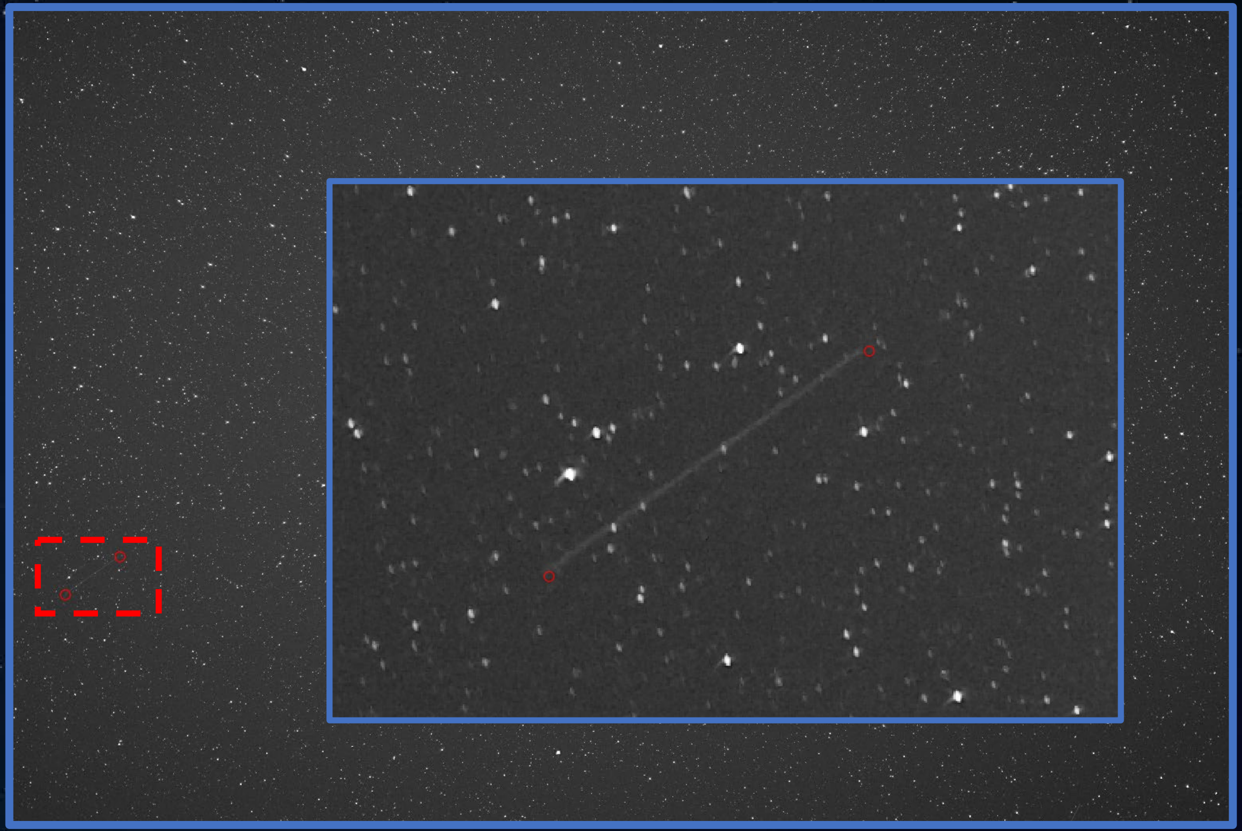


Image Processing Example

Initial raw image



Ends of streak identified

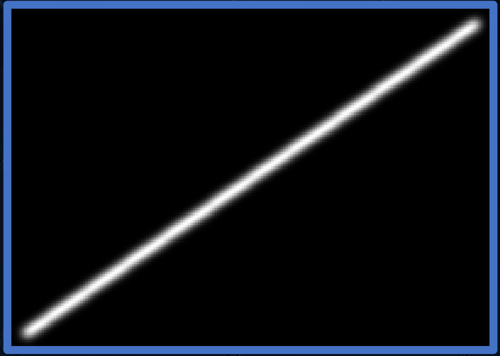
Image Processing Matched Filter

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

Image Processing Computing Time

- 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

FR 4.3 Verified
Onboard Processing

Image Processing Requirements Met

DR 3.3	Prototyped a matched filter, the optimal SNR filter, and tested on a representative image	✓
DR 4.3	Computation time has an order of magnitude FOS against computation time limit	✓

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

CPE Orbit Determination

Relevant Requirements:

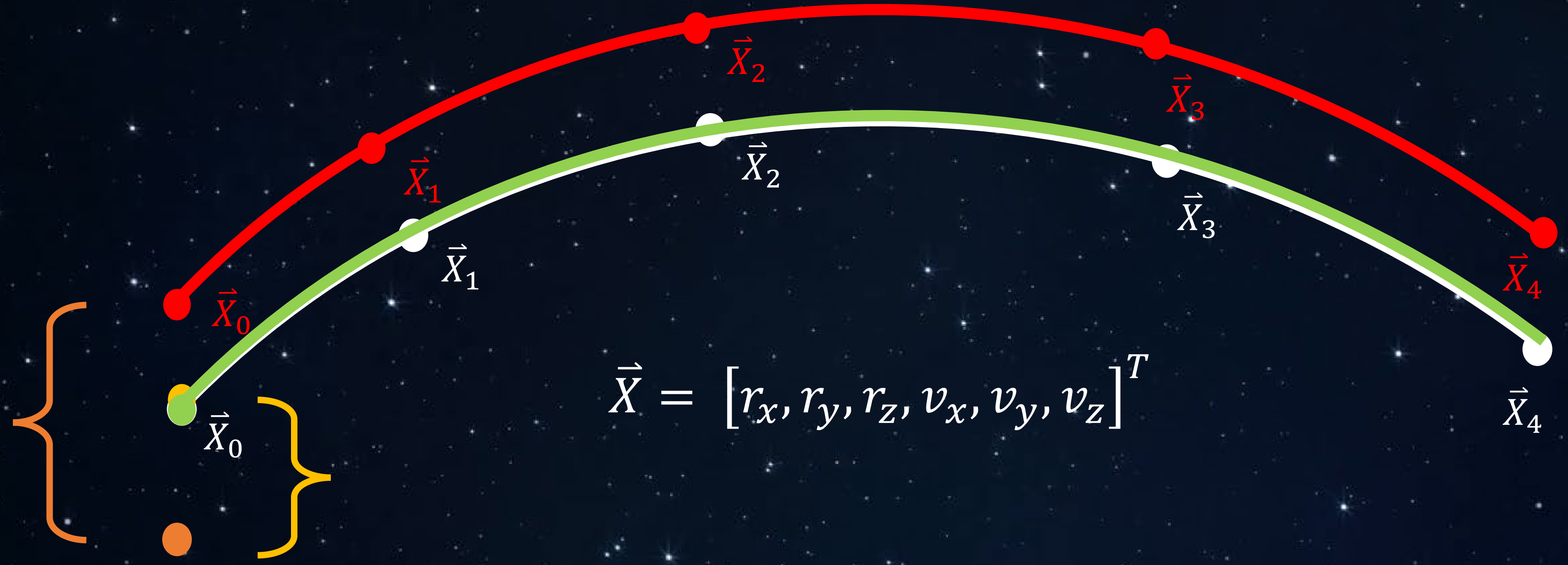
3 The system shall provide an orbit estimate if there are sufficient observations available

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.

Non-Linear Batch Background

Goal : Reduce residuals between the measured and estimated values



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

Textbook Example Orbital Elements

	Textbook Data*	Prototype Estimate
Position, km	$[8005, 2813, 5409]^T$	$[8007 \pm 29.88, 2823 \pm 29.76, 5410 \pm 10.20]^T$
Velocity, $\frac{km}{s}$	$[-2.924, 5.493, 2.764]^T$	$[-2.846 \pm 0.3110, 5.611 \pm 0.3980, 2.878 \pm 0.3604]^T$

Percent Error in Position: 0.1008%

Percent Error in Velocity: 2.671%

FR 3 Verified

Orbit estimate

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

Orbit Determination Requirements Met

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

Tracked Risks

Risk	Description	Likelihood of Related Problem	Severity	Total
SOFT-1	Accuracy of image processing has not yet been determined and may effect system output	5	4	**20**
TEST-1	Outdoor testing ability subject to weather, location, timing and ambient lighting conditions	5	4	**20**
CAM-1	LSM modeling not matching up with real-world performance	3	5	**15**
SOFT-2	Limited testing data available for software development before hardware available for testing	5	2	**10**
CHAS-1	Cables are required to connect moving camera assembly with chassis and could be damaged during rotation	2	5	**10**
TEST-2	Equipment must be transported regularly for testing and could be damaged while doing so	3	3	**9**
CAM-2	Camera timing latency between reported lens open/close and actual open/close unknown	3	3	**9**
CAM-3	Camera and actuation mount calibration to accuracy desired may be difficult to achieve	1	5	**5**

Highest Risks

		Severity				
		1	2	3	4	5
Likelihood	5		SOFT-2		SOFT-1, TEST-1	
	4					
	3			TEST-2, CAM-2		CAM-1
	2					CHAS-1
	1					CAM-3

Low (1-4)	Moderate (4-9)	High (10-14)	Extreme (15-25)

Risk Mitigation

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

Testing and Verification

Testing Levels

Fall 2018	Scheduler Prototype Testing ✓	Image Processing Prototype Testing ✓	Orbit Determination Prototype Testing ✓

Fall 2018

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

Jan

- Scheduler Unit Test
- Actuation Hardware Unit Test
- Imaging Hardware Unit Test
- Image Processing Unit Test
- Orbit Determination Unit Test

Feb

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

Mar

- Complete System Field Test

Preliminary System Testing

Pointing

Test Objectives:

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

Test Setup:

- GPS Disabled
- 120V Wall Power

Processing

Test Objectives:

1. Complete image processing on sample images
2. Perform OD using data from image processing on sample images

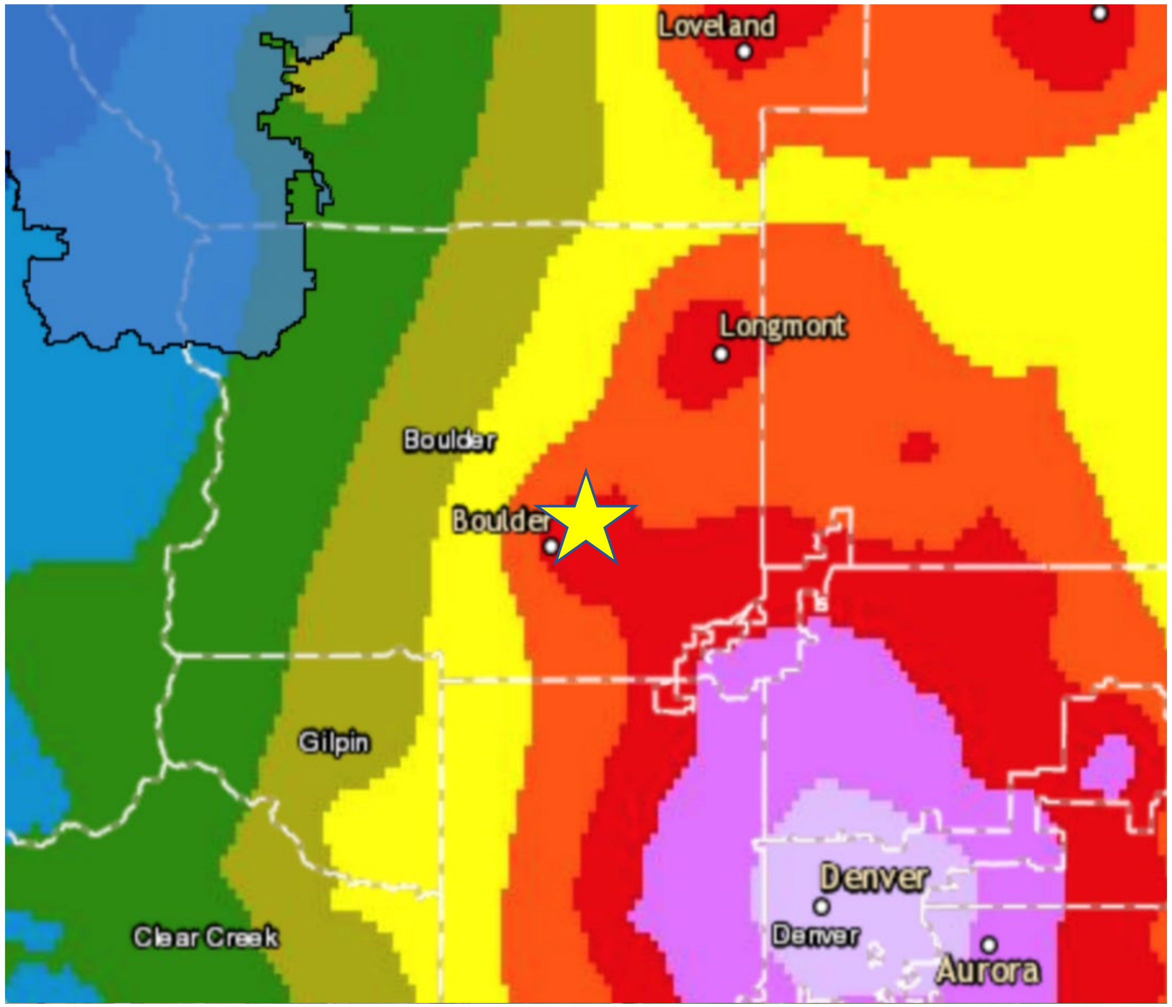
Field System Testing

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

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.

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.

Requirement Specific Testing

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.

Requirement Specific Testing

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

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

Organizational Chart

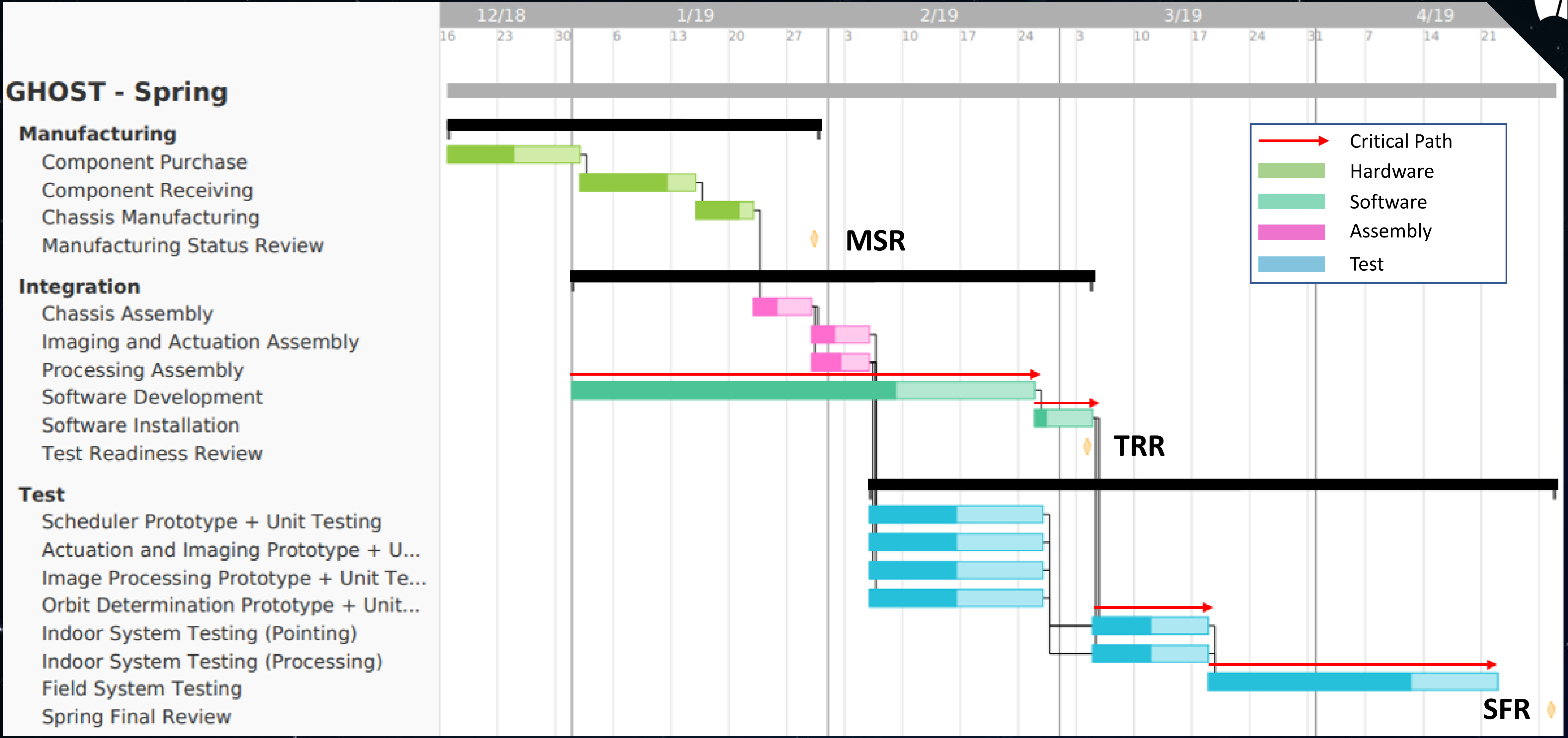
- **Jack Toland** — Project Manager
  - **Jacob Vendl** — Hardware Lead
    - **Kira Altman** — GPS and Timing
    - **Lucas Calvert** — Electronics
    - **Seth Hill** — Integration
    - **Duncan McGough** — Manufacturing
  - **Ginger Beerman** — Software Lead
    - **Connor Ott** — Image Process. & Scheduler
    - **Connie Childs** — Scheduler
    - **Blaine Covington** — Image Processing
    - **Rachel Mamich** — Orbit Determination

Work Breakdown Structure

Hardware			Software		
Chassis Fabrication	System Integration	Test	Scheduler	Image Processing	Orbit Determination
Lead: Lucas, Duncan **Tasks:** - Manufacture frame components - Assemble 80/20 chassis	**Lead:** Kira, Seth **Tasks:** - Add electronics and hardware to chassis - Complete chassis wiring	**Lead:** Jack, Jake **Tasks:** - Create test procedures - Schedule testing for system	**Lead:** Connie, Connor **Tasks:** - Code scheduler in Python - Interface w/ other software	**Lead:** Blaine, Connor **Tasks:** - Code image processing in Python - Interface w/ other software	**Lead:** Rachel, Ginger **Tasks:** - Code orbit determination in Python - Interface w/ other software

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
12/18
1/19
2/19
3/19
4/19
16
23
30
6
13
20
27
3
10
17
24
3
10
17
24
31
7
14
21
MSR
TRR
SFR
Critical Path
Hardware
Software
Assembly
Test

Cost Plan

Component	Cost	Budget Allocation	Margin
Chassis	$436.07	$600	27.3%
Actuation	$1078	$1500	28.1%
Imaging	$1943.59	$2000	2.8%
Processing	$285.55	$400	28.6%
GPS	$39.95	$100	60.1%
Power	$243.90	$400	39.0%
Total	**$4027.06**	**$5000**	**19.5%**

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

Backup Index

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

PDR	CDR
SNR = 6	SNR = 30

- Switched type of Actuation Mount

PDR	CDR
RA/Dec	Az/El

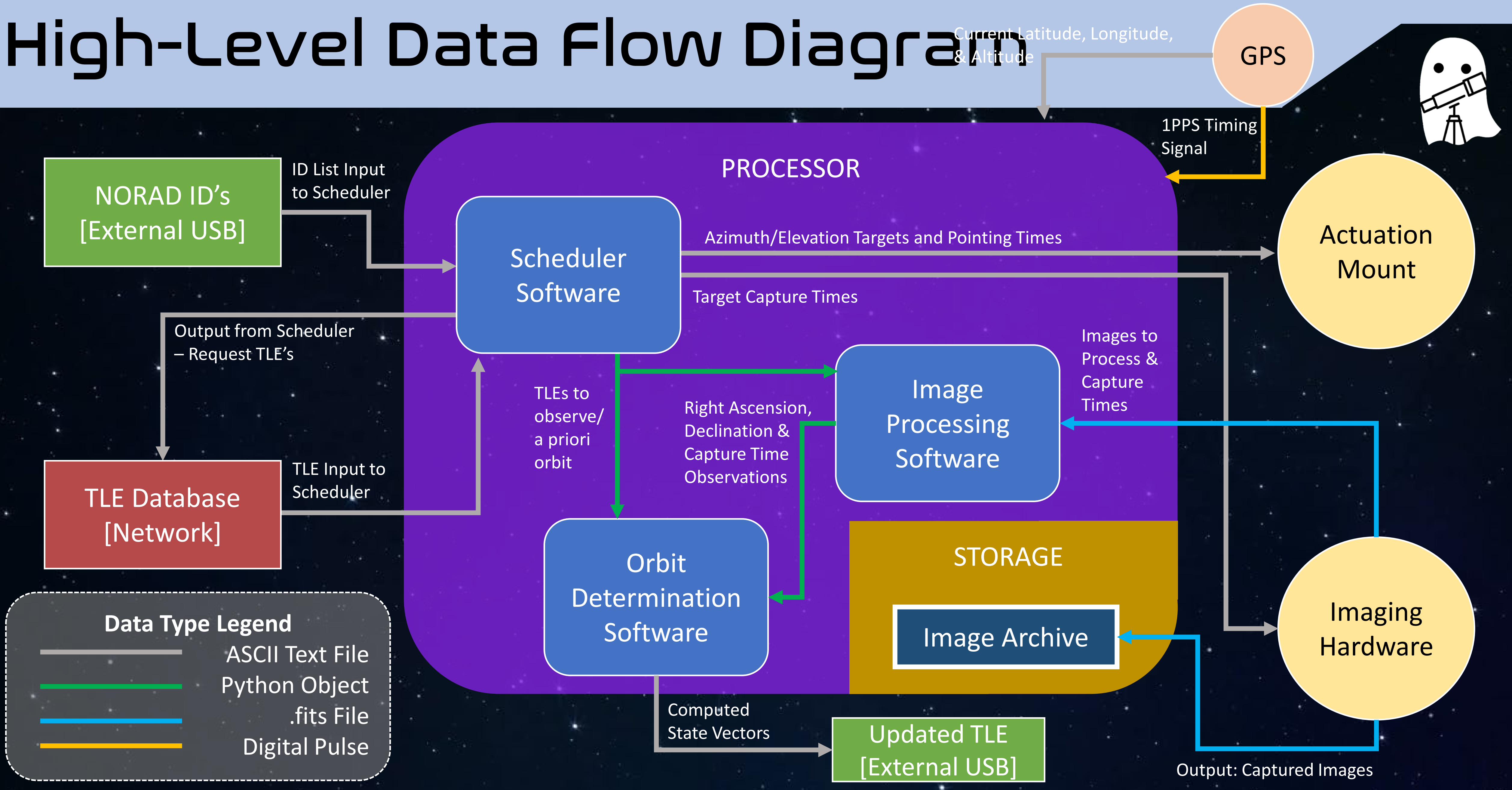
Critical Project Elements
Justification

Critical Project Element	Justification
Camera & Lens	**Determines quality of the data.** The optical system must be capable of capturing images of space objects.
Scheduler	**Allows for system automation.** The software must schedule observation periods.
Image Processing	**Extraction of the data.** The software must be able to change captured images into quantitative measurements.
Orbit Determination	**Final output of the system.** Filtering data to enhance the orbital update is paramount to system success.

Requirements Satisfied – Hardware

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

High-Level Data Flow Diagram



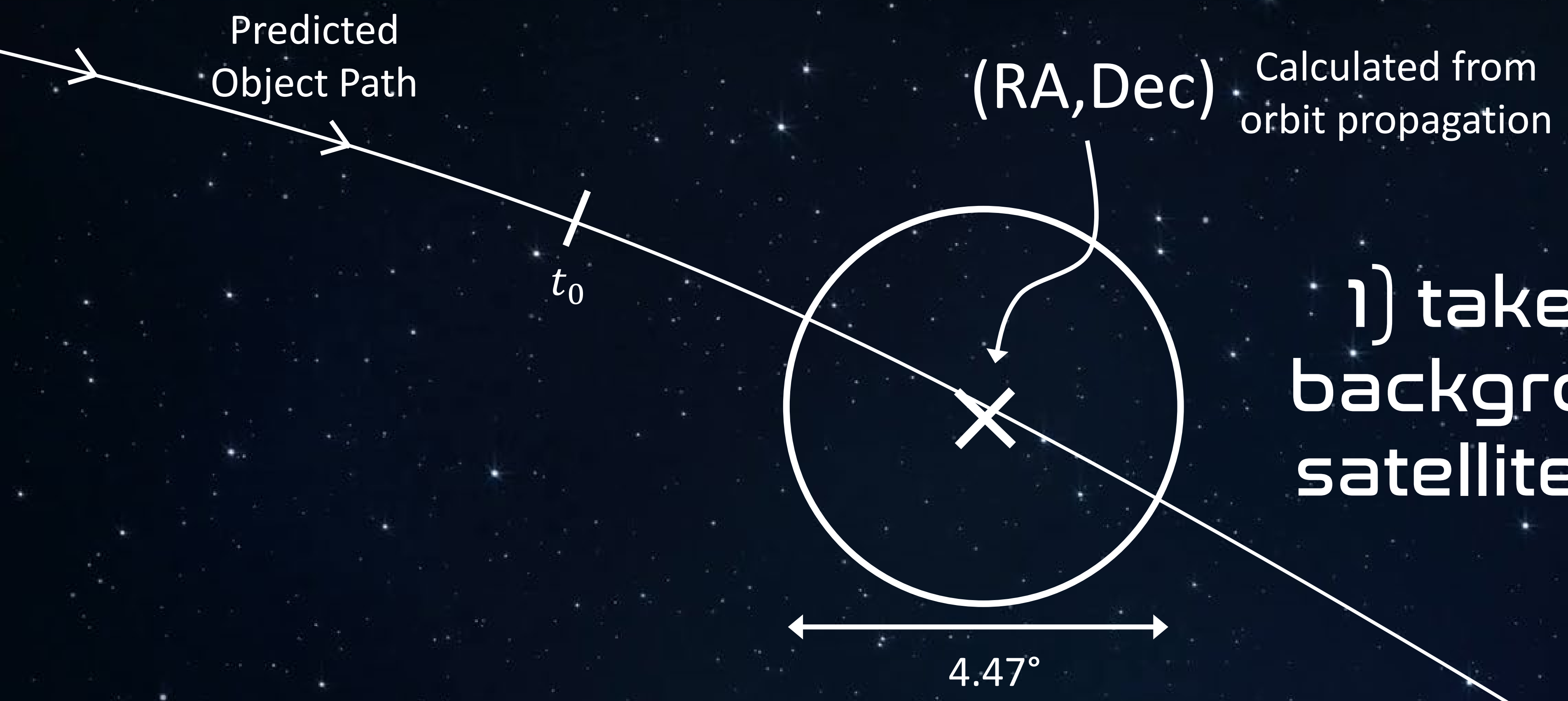
Backup - Imaging Procedure

Camera & Lens FOV Simplification

Orientation of sensor unknown

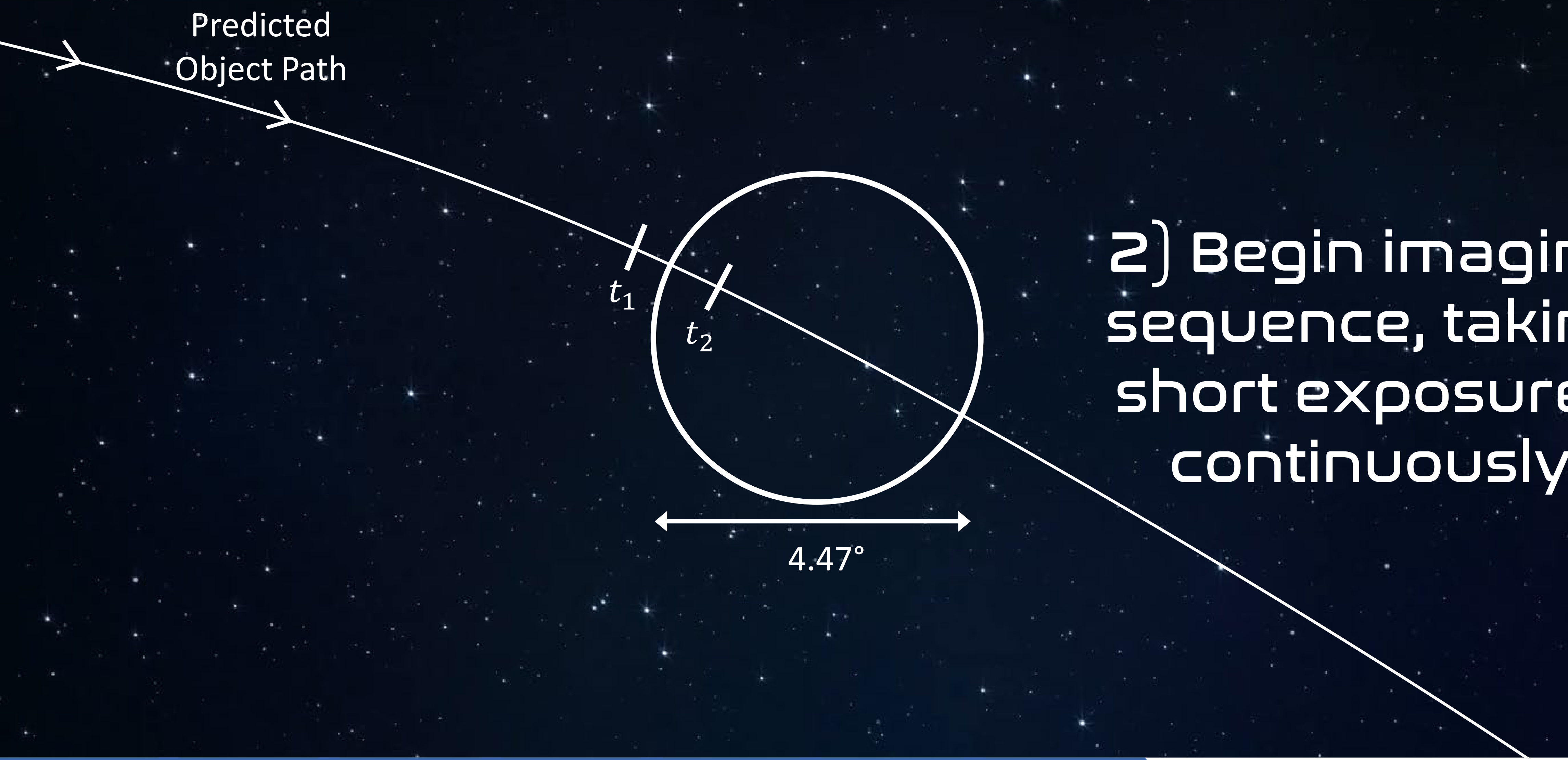
Assume 4.47deg circular FOV

Camera and Lens Selection Exposure Plan



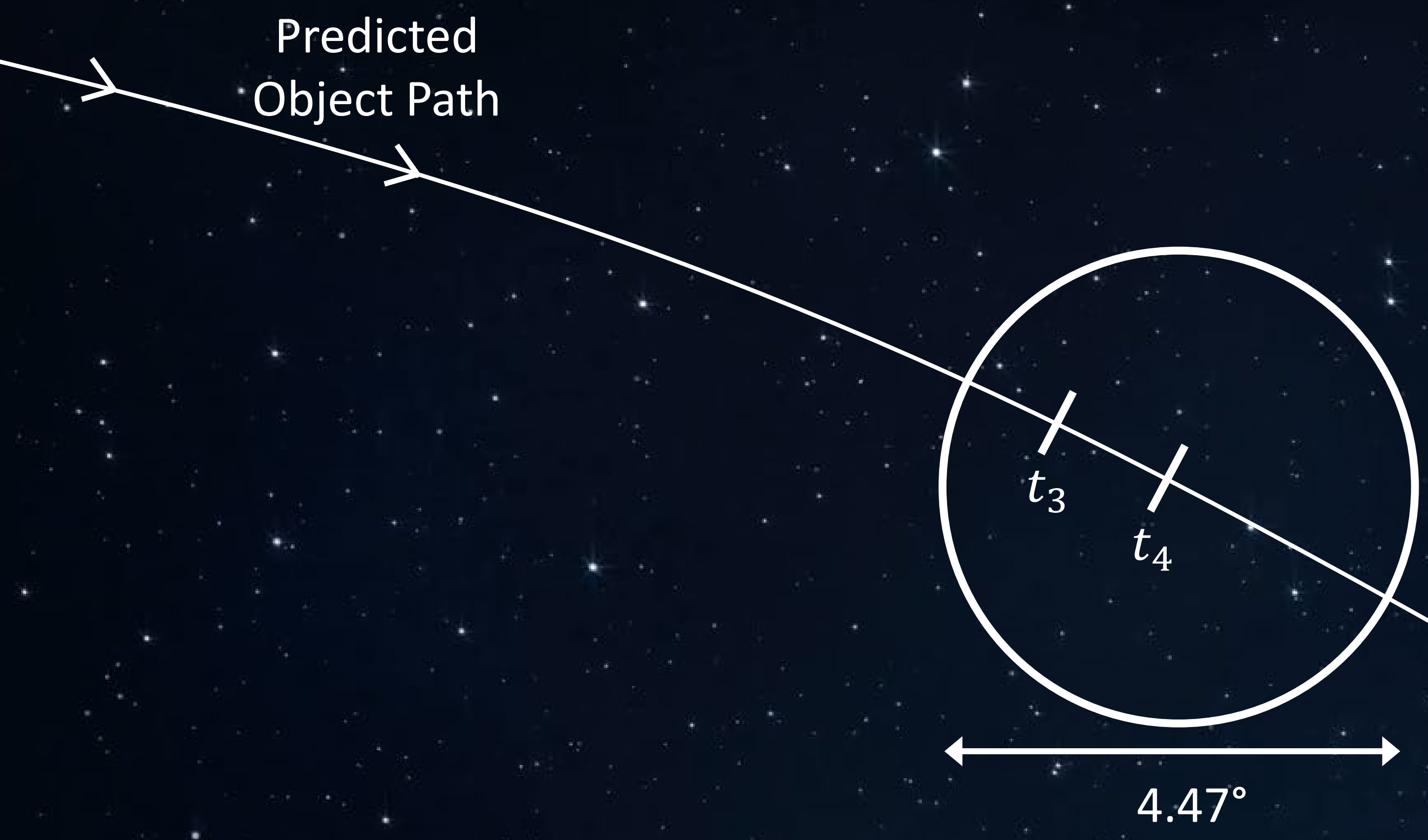
1) take picture of background before satellite arrival into FOV

Camera and Lens Selection Exposure Plan



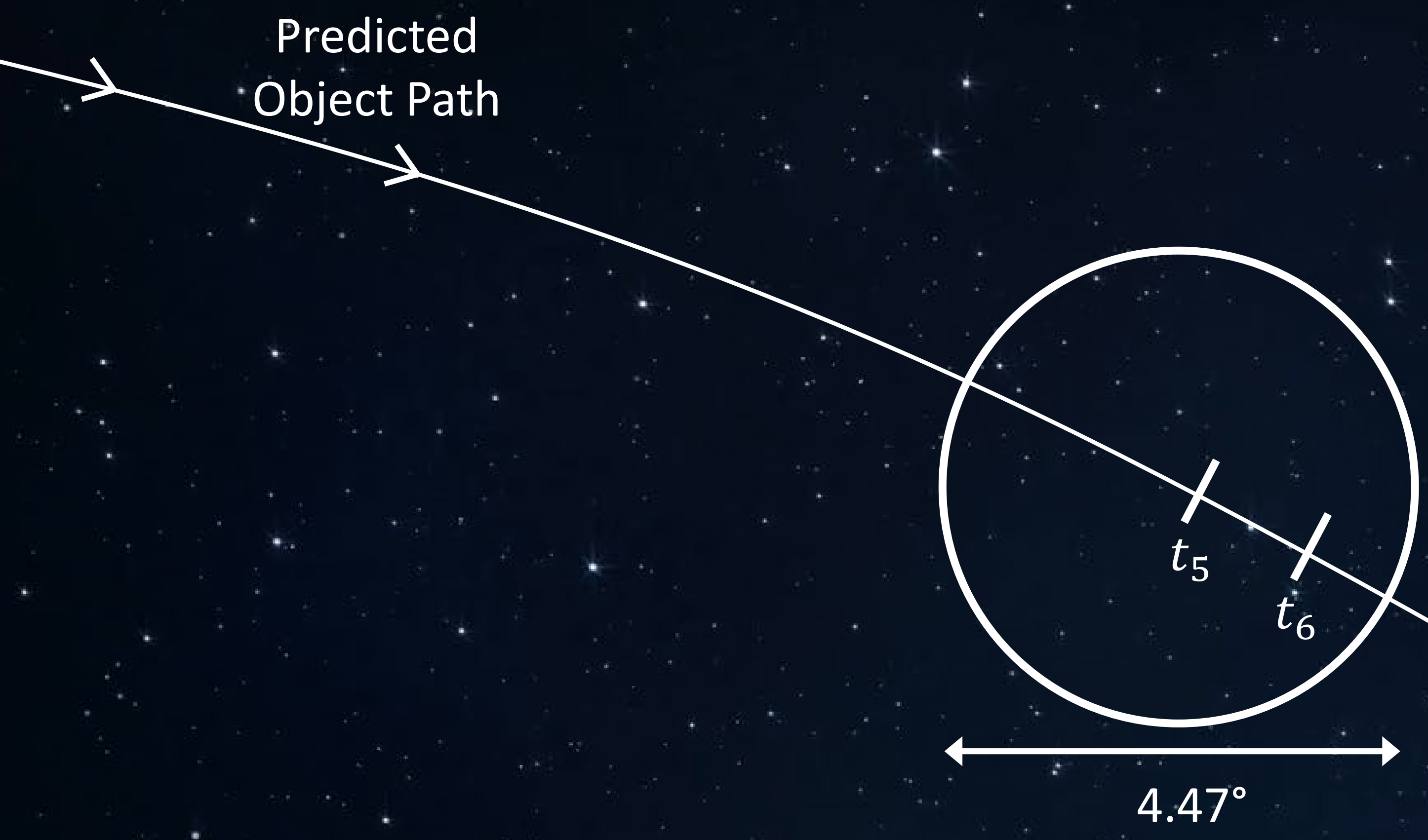
2) Begin imaging sequence, taking short exposures continuously

Camera and Lens Selection Exposure Plan



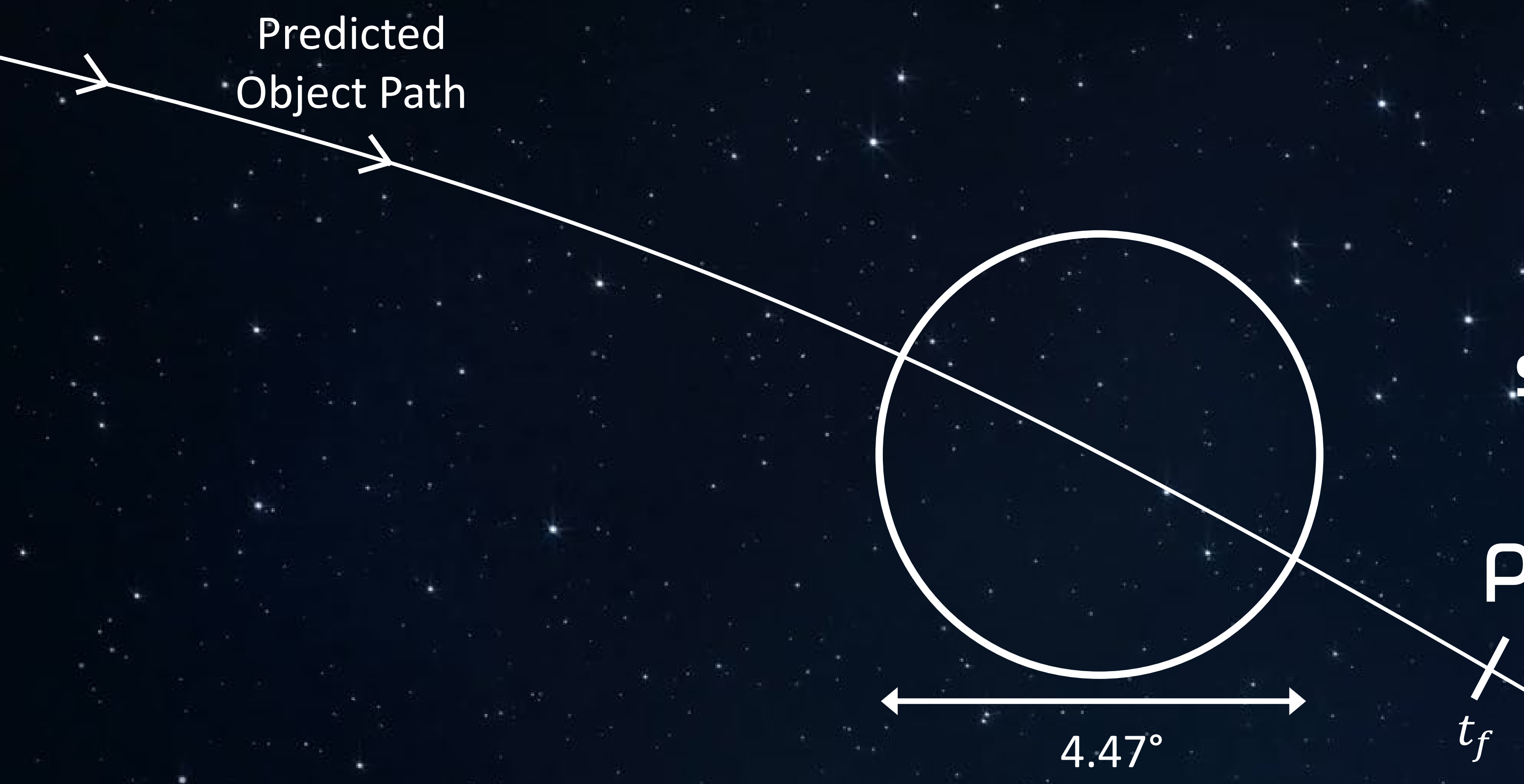
3) Continue short exposures as space object passes through the field of view

Camera and Lens Selection Exposure Plan



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

Camera and Lens Selection Exposure Plan



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

Camera and Lens Selection Exposure Plan

	1	2	3	4
Image Taken				
Info Gathered	Empty celestial background for image processing	None. Partial streaks will be discarded	$(\alpha_1, \delta_1, t_1)$ and $(\alpha_2, \delta_2, t_2)$	$(\alpha_3, \delta_3, t_3)$ and $(\alpha_4, \delta_4, t_4)$

Backup - Budget

Hardware Budget

Component	Cost	PDR Budget	Margin
Chassis	$395.48	$500	20.9%
Actuation	$1078	$1500	28.1%
Imaging	$1943.59	$2000	2.8%
GPS	$39.95	$100	60.1%
Power	$250.36	$400	39.0%

Chassis BOM

Component	Cost	Supplier
1/8" Acrylic plates (12"x48")	$55.94	McMaster
3" x 3" Steel Square Tube	$20.13	McMaster
Leveling Feet	$54.48	McMaster
1/2" Aluminum Plate (8"x8")	$33.07	McMaster
1/4" Steel Plate (8"x8")	$30.63	McMaster
80/20 x 210mm	$15.74	80/20 Inc
80/20 x 540mm	$7.05	80/20 Inc
80/20 x 250mm	$8.62	80/20 Inc

Component	Cost	Supplier
80/20 x 570mm	$7.34	80/20 Inc
80/20 30-4480	$53.64	80/20 Inc
80/20 30-4351	$15.16	80/20 Inc
80/20 14062	$13.60	80/20 Inc
80/20 M6 T-nut	$17.28	80/20 Inc
[M6x1] x 12mm	$11.09	McMaster
[M6x1] x 20mm	$14.12	McMaster
Display	$37.59	Amazon (GeeekPi)

Actuation Hardware BOM

Component	Cost	Supplier
iOptron AZ Mount Pro	$999	iOptron
iOptron SkyTracker Pro CW Package	$79	iOptron

Imaging Hardware BOM

Component	Cost	Supplier
ZWO ASI1600MM	$999	Zwo
Canon EF 200mm f/2.8L	$749	Amazon (Canon)
RS232 to USB cable	$18.60	Amazon (Letotech)
Lens Hood	$35	Amazon (Canon)
EOS-T2 Adapter	$48	Zwo
Scope Rings	$72.99	Amazon (Astomania)
8" Dovetail Rail Plate	$21	Amazon (ORION)

Processing BOM

Component	Cost	Supplier
UDOO x86 2.24GHz	$190.64	Mouser
UDOO memory SD card	$57.94	Amazon (Samsung)
UDOO Power Adapter	$8.90	UDOO
Fan	$7.50	UDOO
USB Drive (64 gb)	$13.34	Amazon (SanDisk)
USB Bulkhead Port	$7.23	Amazon (StarTech)

GPS BOM

Component	Cost	Supplier
Adafruit Ultimate GPS Module	$39.95	Adafruit

Power BOM

Component	Cost	Supplier
Portable Power Source	$165.99	CHAFON
12V/5V Switching Power Supply	$25.49	Jameco
12 gauge wire (black)	$8.48	Amazon (BestConnections)
12 gauge wire (red)	$8.48	Amazon (BestConnections)
Kill Button	$7.01	Amazon (uxcell)
120V Plug and Lead (6ft)	$11.99	Amazon (Hanvex)

Backup - Actuation Hardware

Specifications iOptron AZ Pro

iOptron AZ Mount 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

Mount Selection Capabilities

Slew Rate:
10°/sec

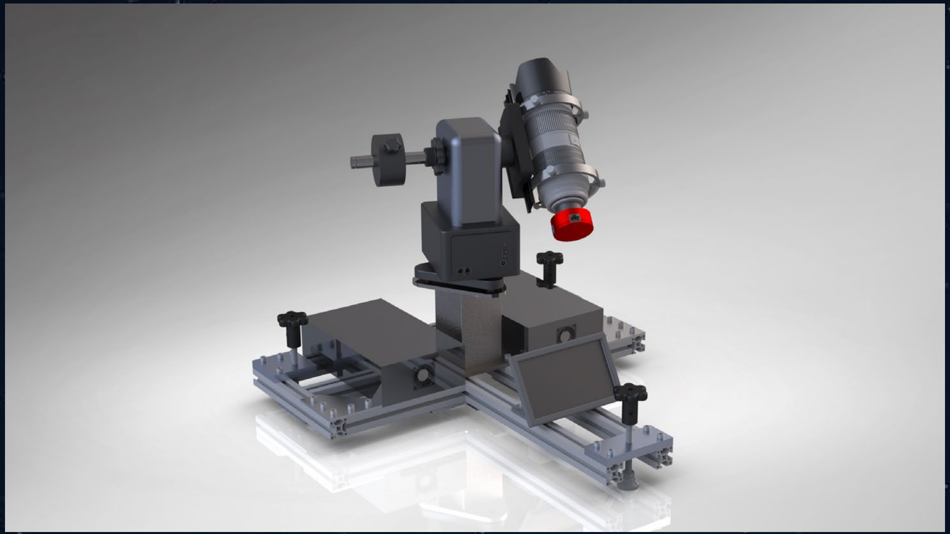
Angular Pointing Resolution:
0.1 arcseconds

Tracking Type:
Sidereal

iOptron AZ Mount Pro

Mount Calibration

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

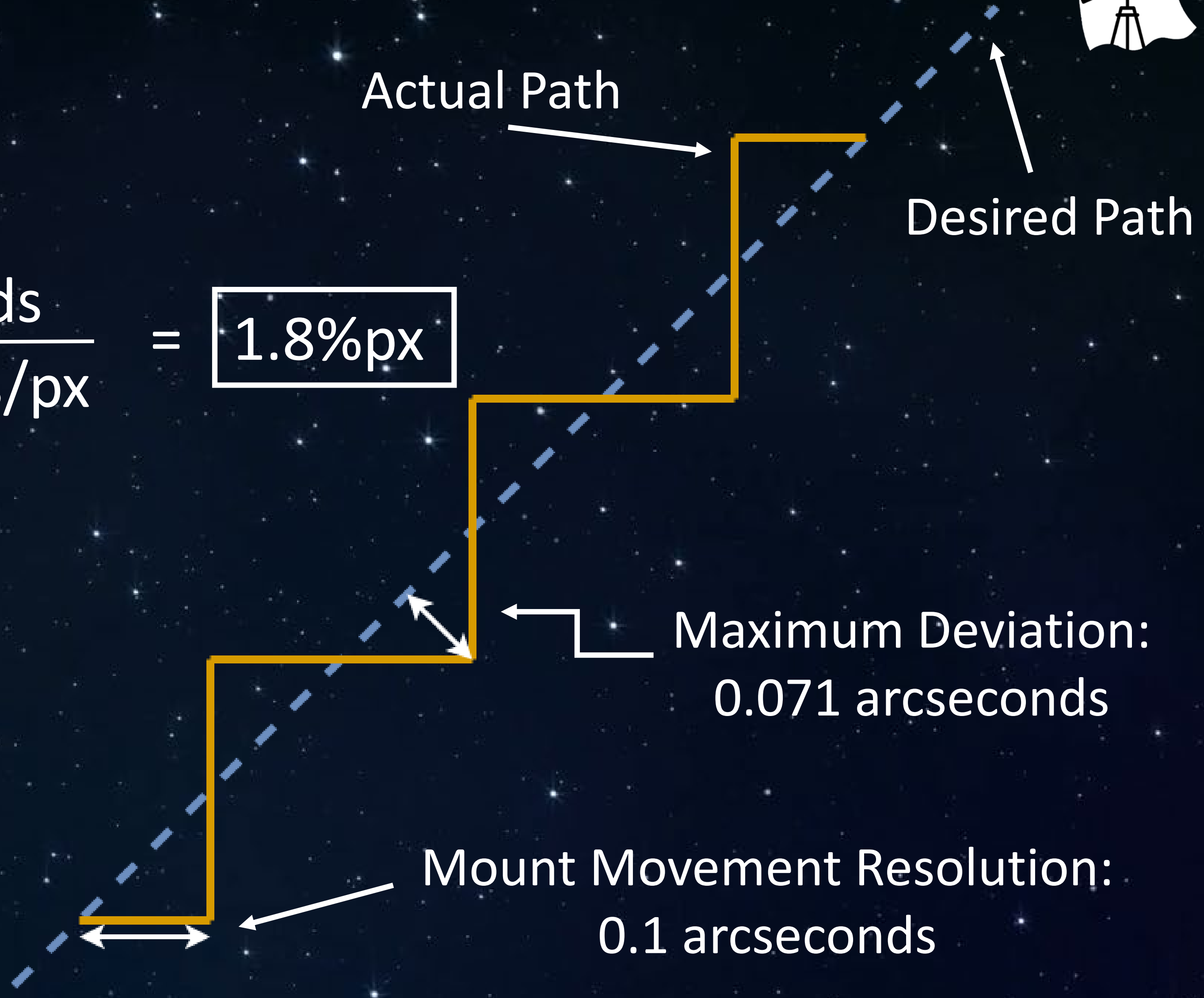


1) Onboard GPS and angle sensors will predict alignment

3) Onboard geometric algorithm completes the calibration process

Mount Jitter Analysis

$$\frac{\text{Max Motor Deviation}}{\text{Angular Pixel Resolution}} = \frac{0.071\text{arcseconds}}{3.92\text{ arcseconds/px}} = \boxed{1.8\%\text{px}}$$



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 ZWO 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: 3.8μm
- Where to Buy: ZWO 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

+

+

EOS-T2 Adapter ($48)

INDI Protocol

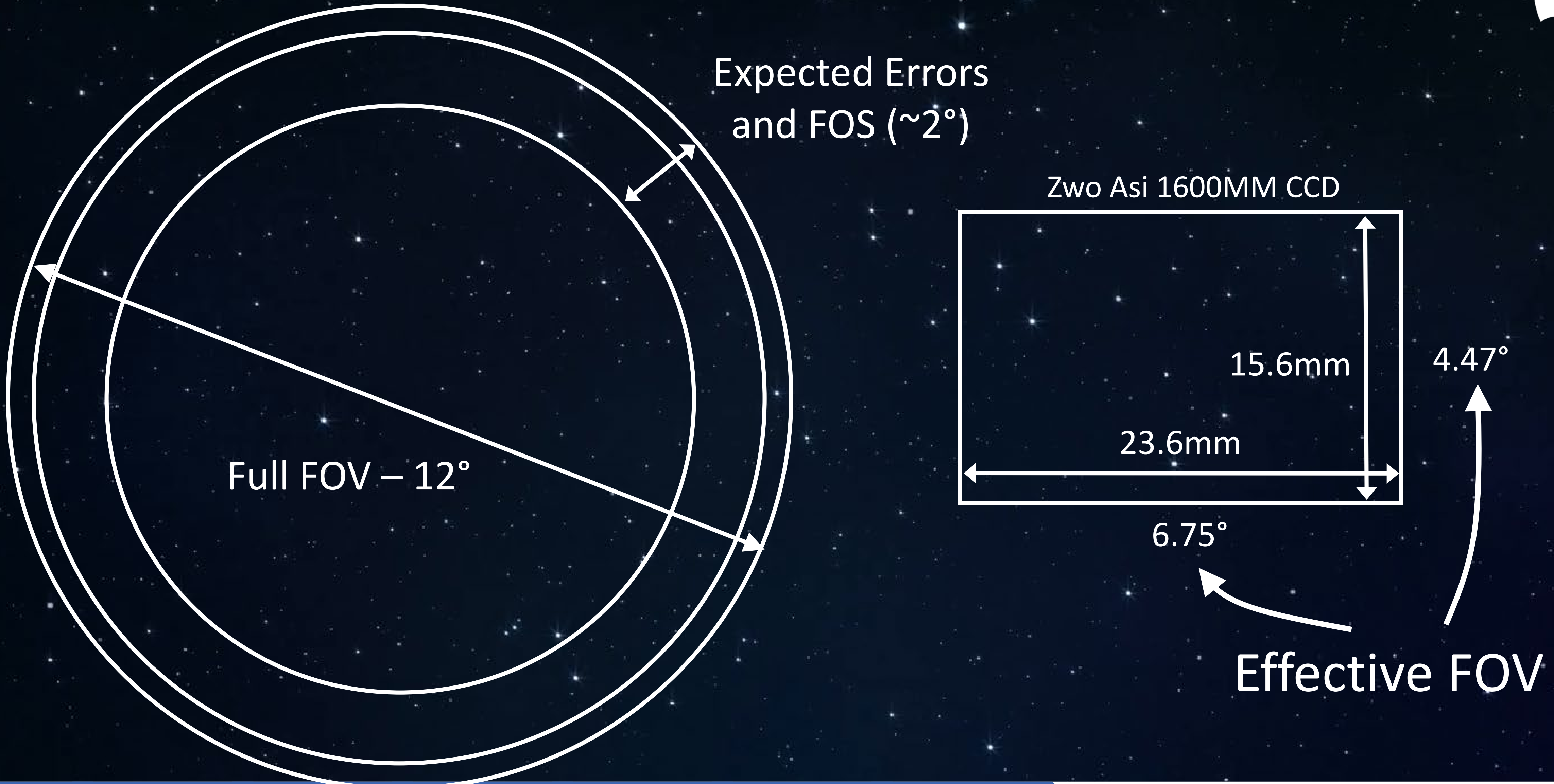
Vello Collar for Mounting ($50)

To UDOO

1.5W Power

To Actuation Mount

Camera and Lens Selection Field of View



Imaging Hardware Modeling

Limiting Stellar Magnitude (LSM)

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

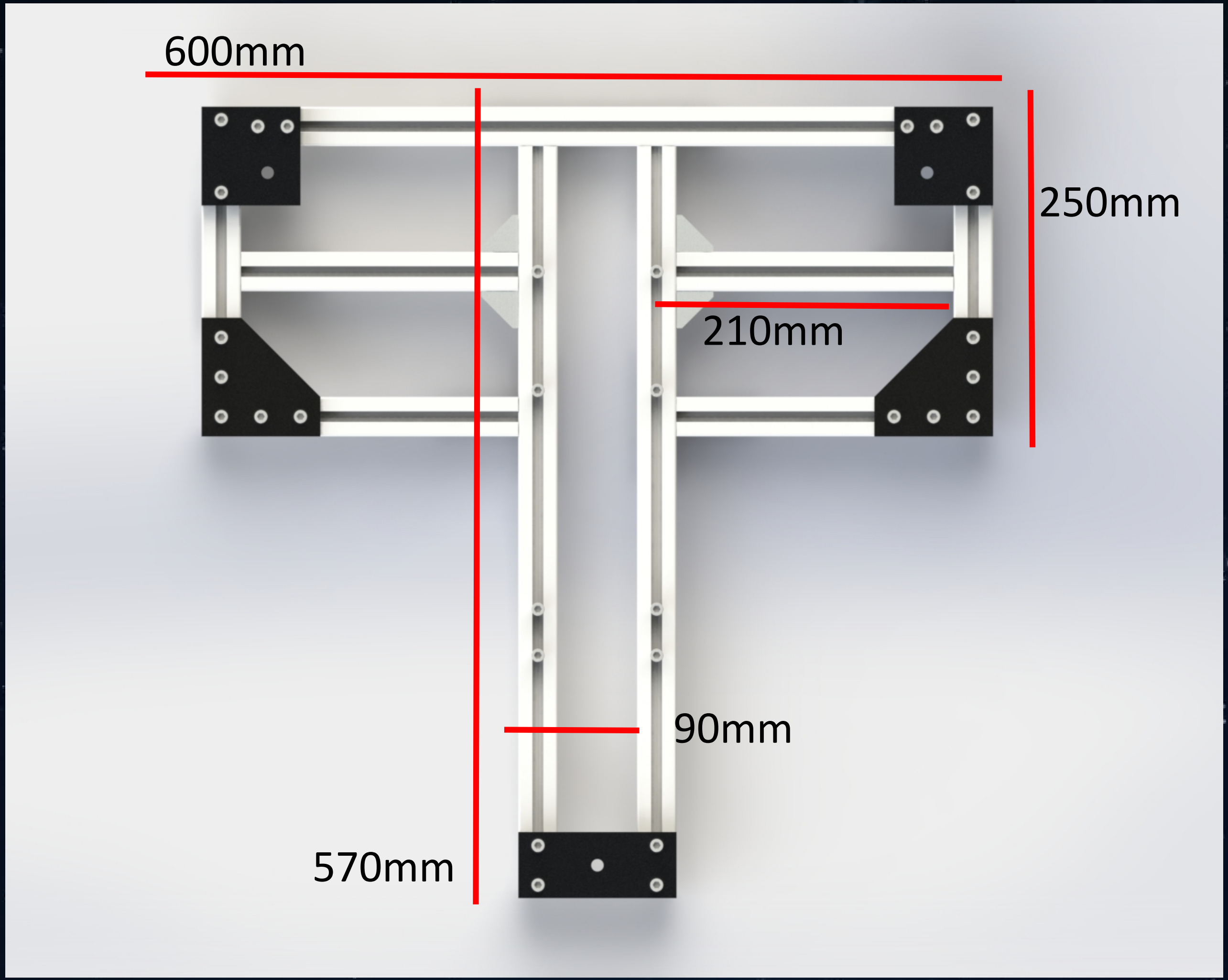
- D – aperture diameter
  - 10mm - 100mm
- p – pixel size
  - 2.4μm - 8.3μm square
- N – f-number
  - 1.4 - 5.6

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

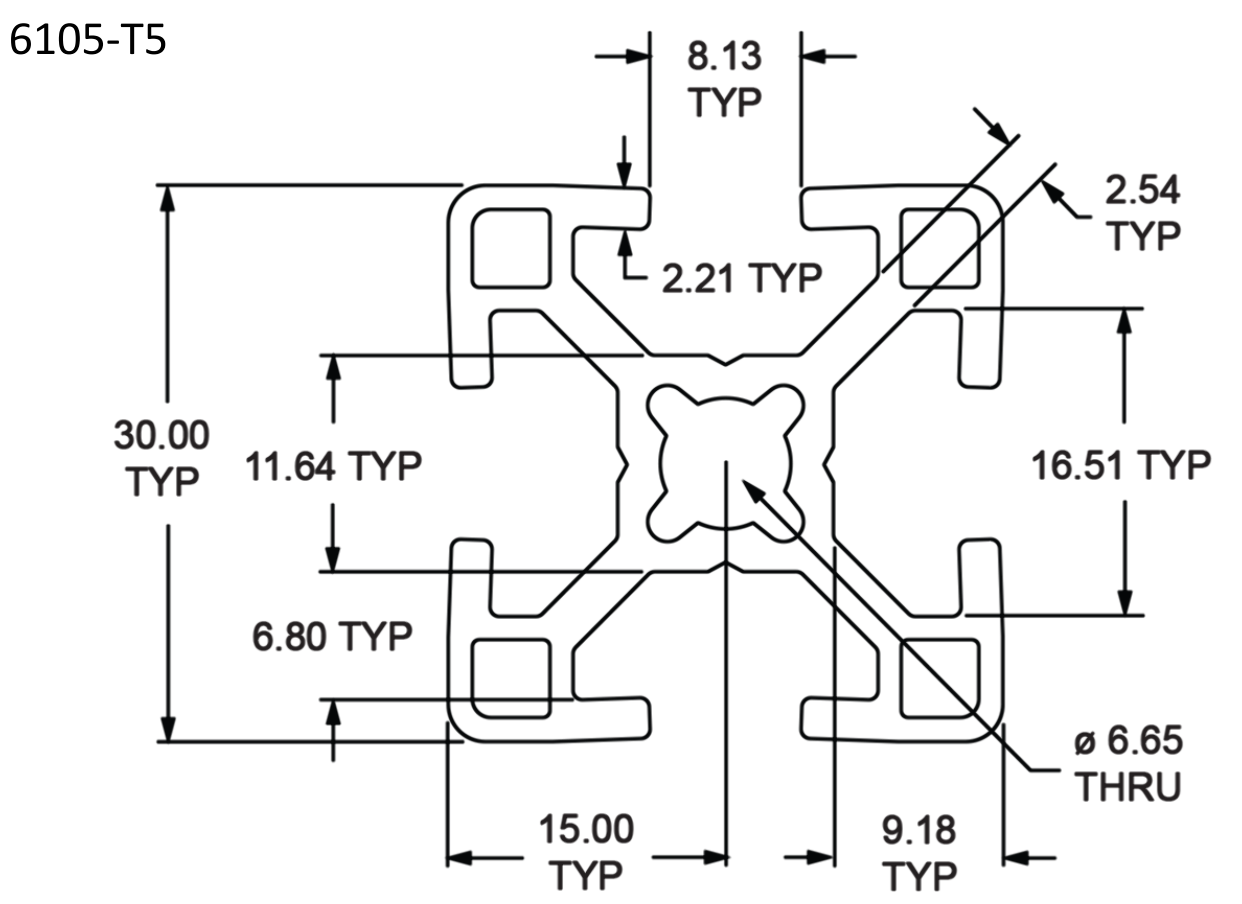
$$m_v(N, D, p) = -2.5\log_{10}\left[\frac{\mathrm{SNR}_{alg}\left[\sqrt{m_i}\,\omega N D\,\left(q_{p,sky} + q_{p,dark}\right)\right]^{1/2}}{\Phi_0 \tau_{atm}\tau_{opt}\left(\frac{\pi D^2}{4}\right) QE\sqrt{p}}\right]$$

Backup – Chassis

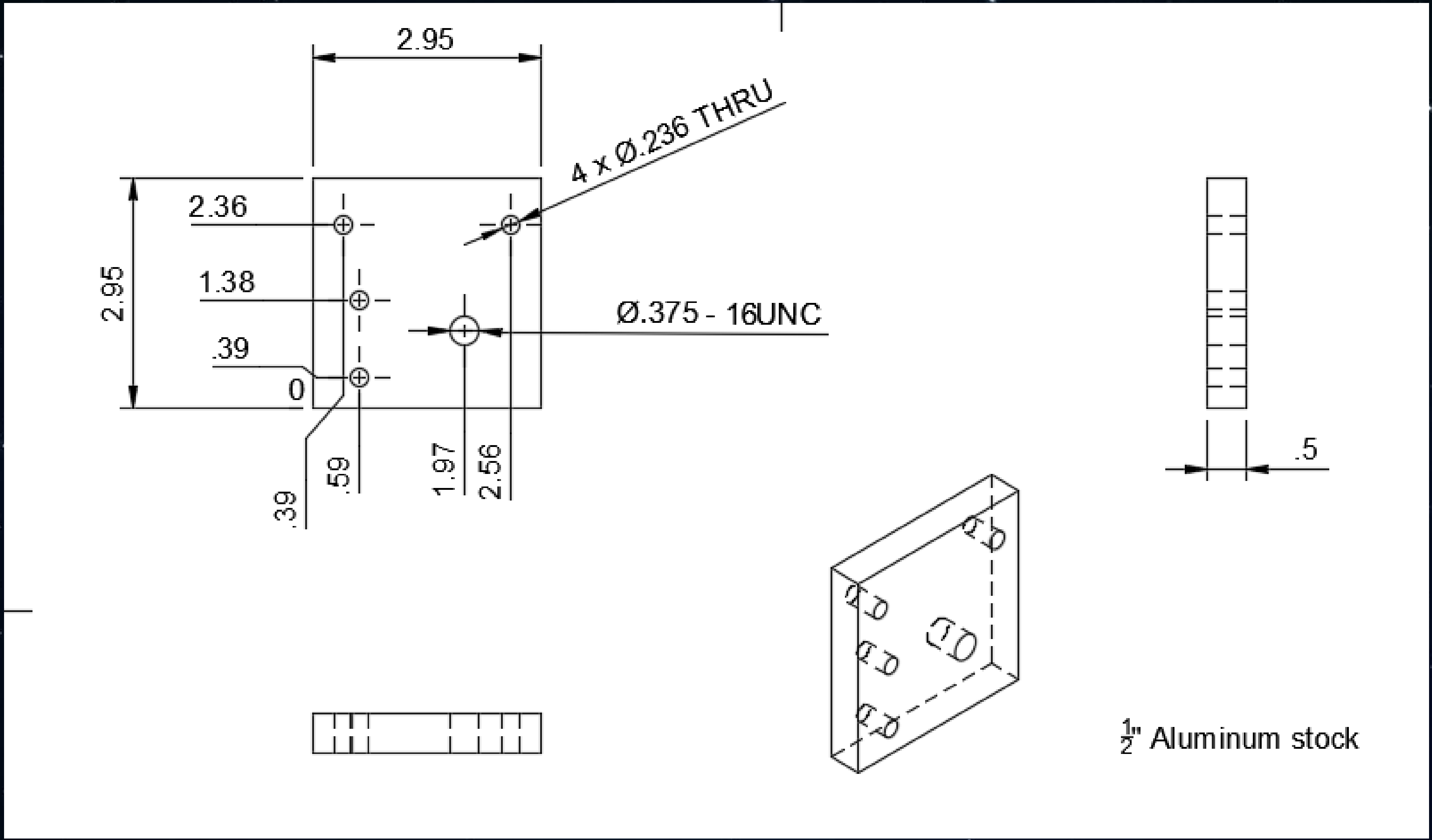
Drawings Frame Overview



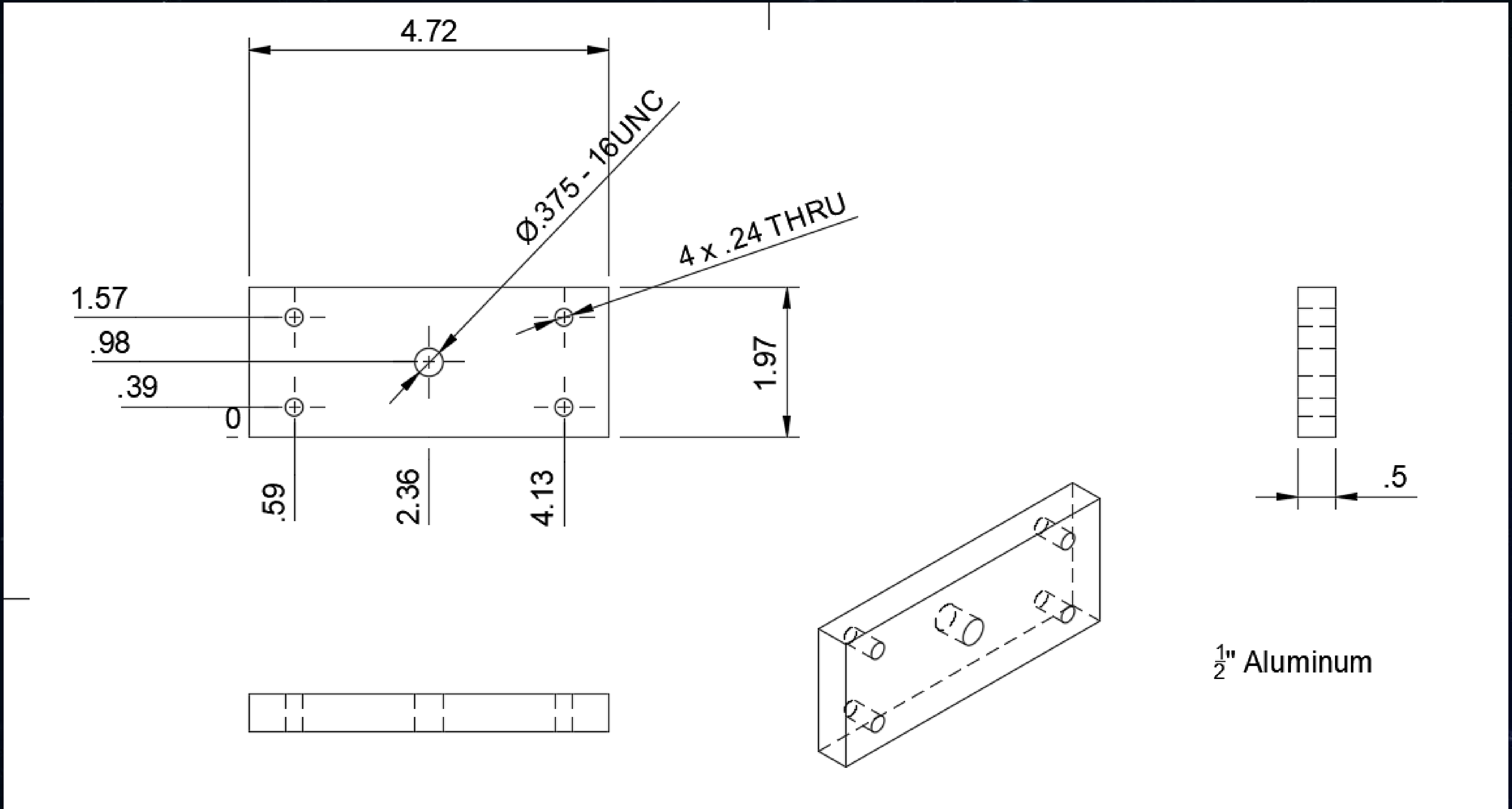
Drawings 8020 Profile



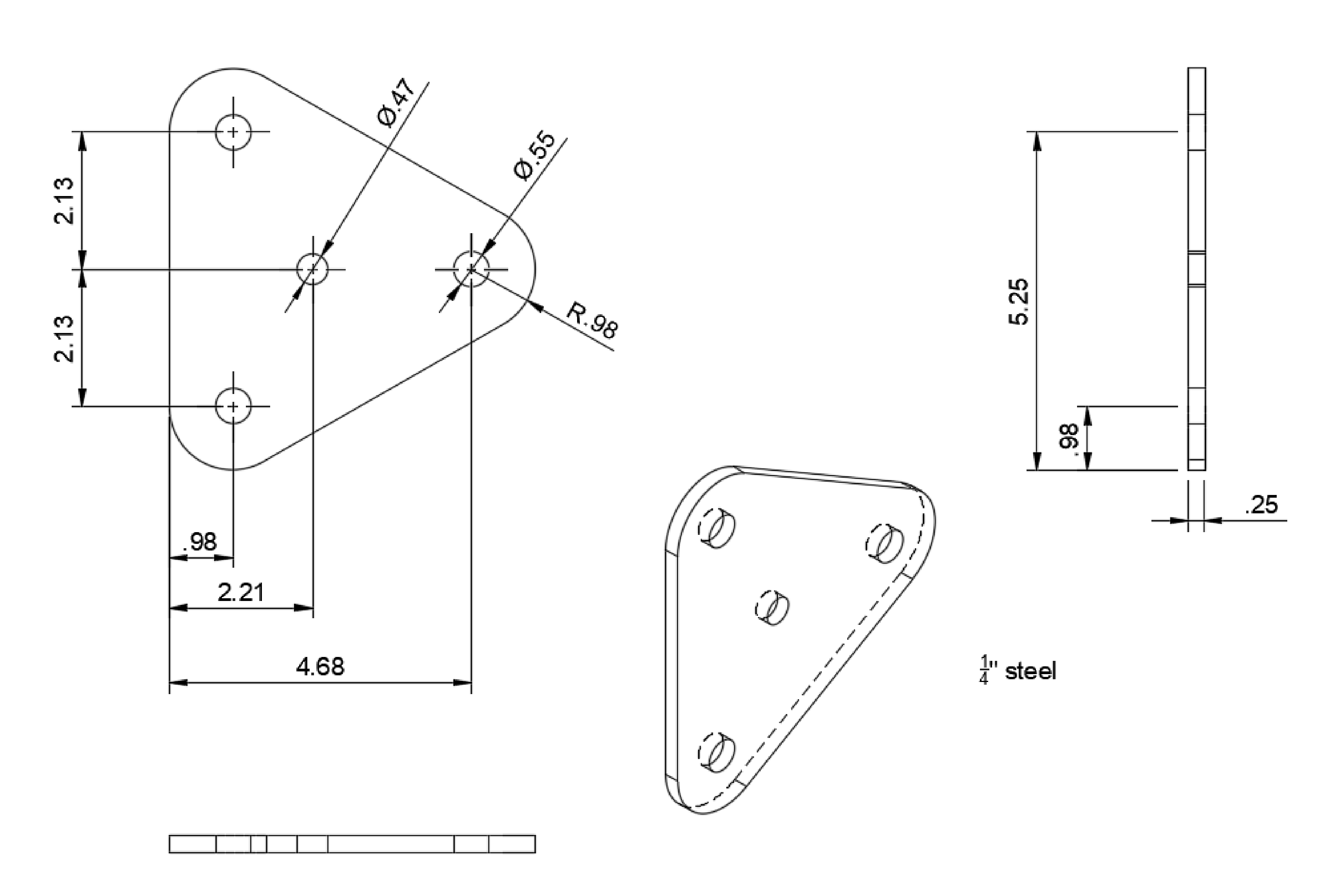
Drawings Corner Leveling Plate



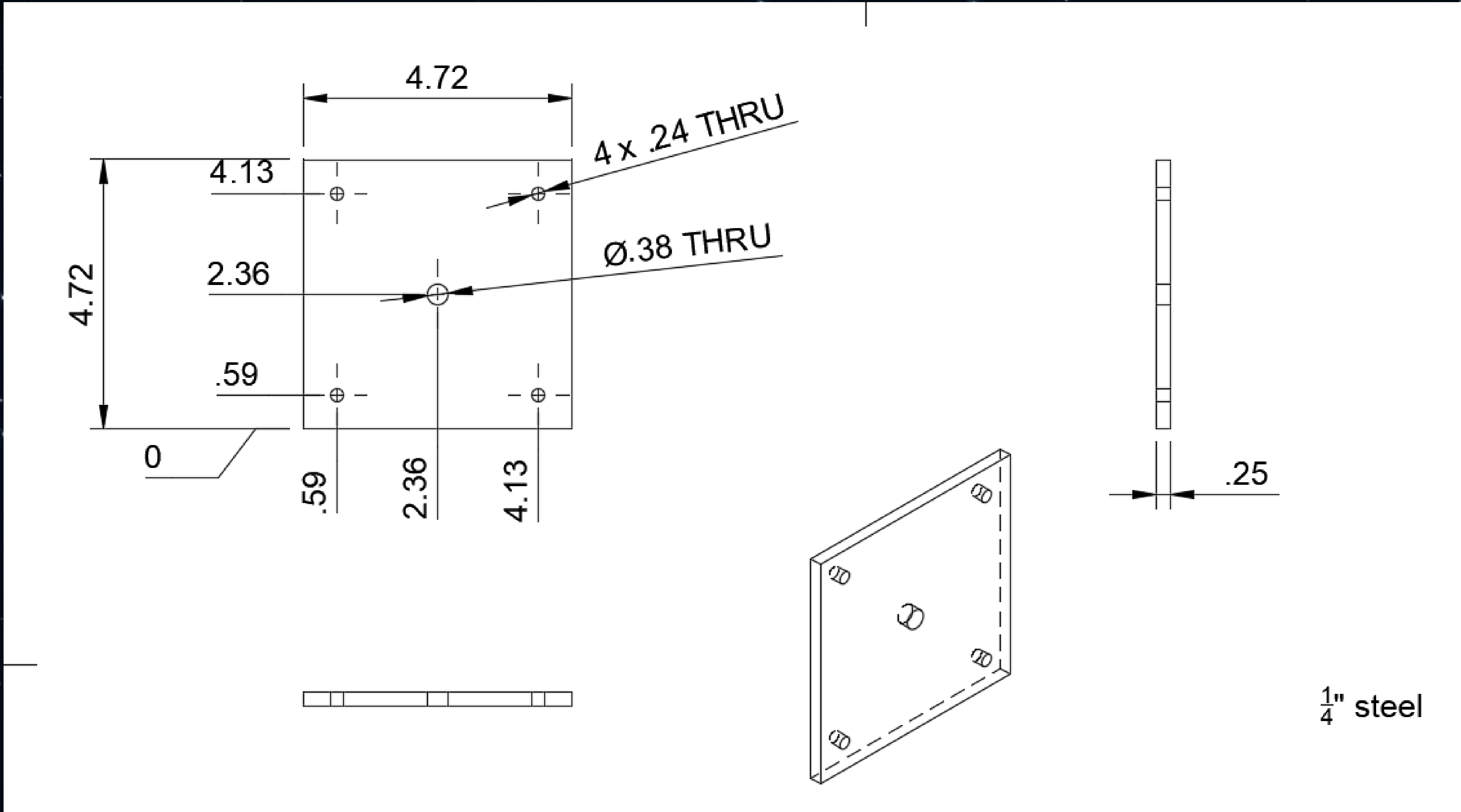
Drawings Gap Leveling Plate



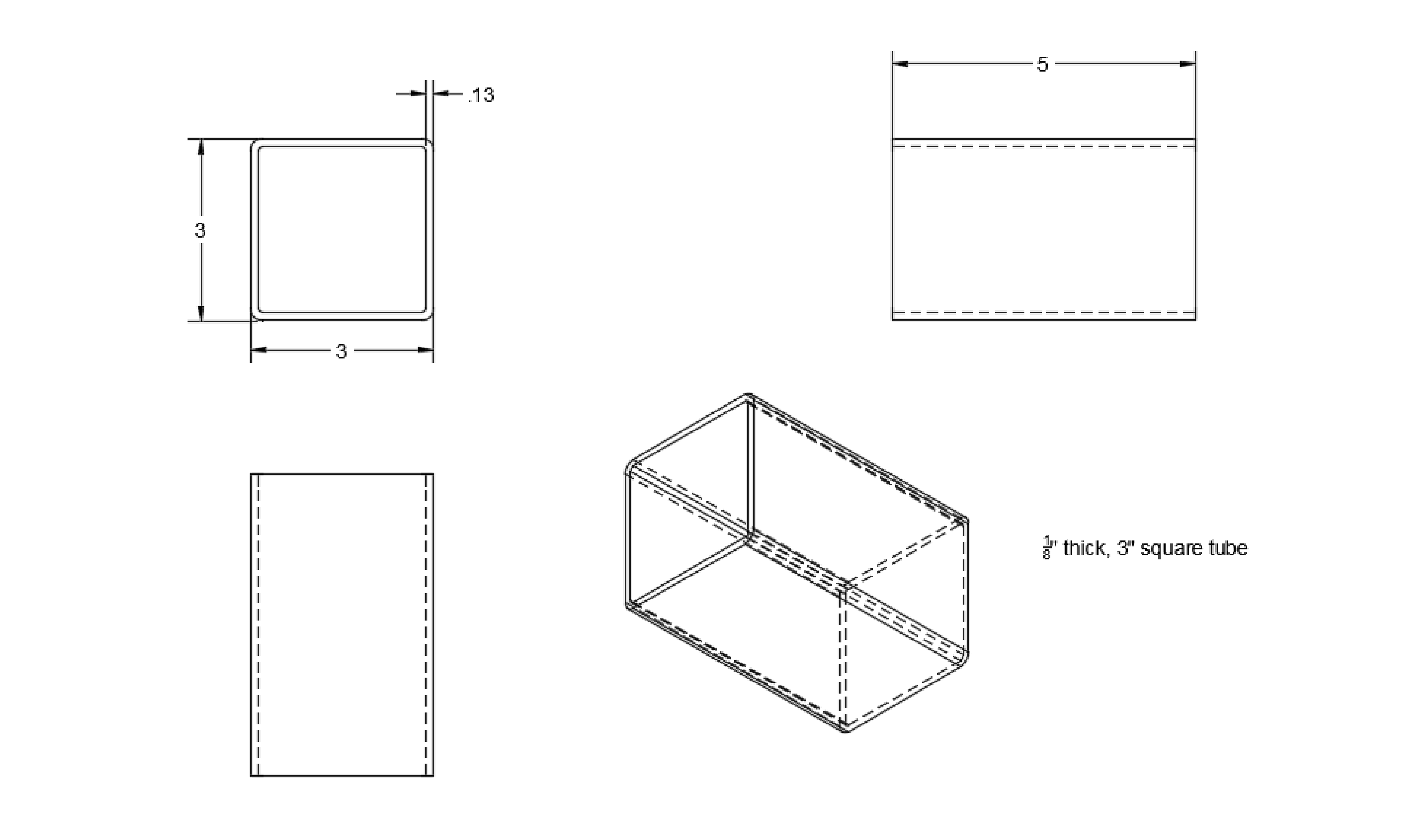
Drawings Top Flange



Drawings Base Flange

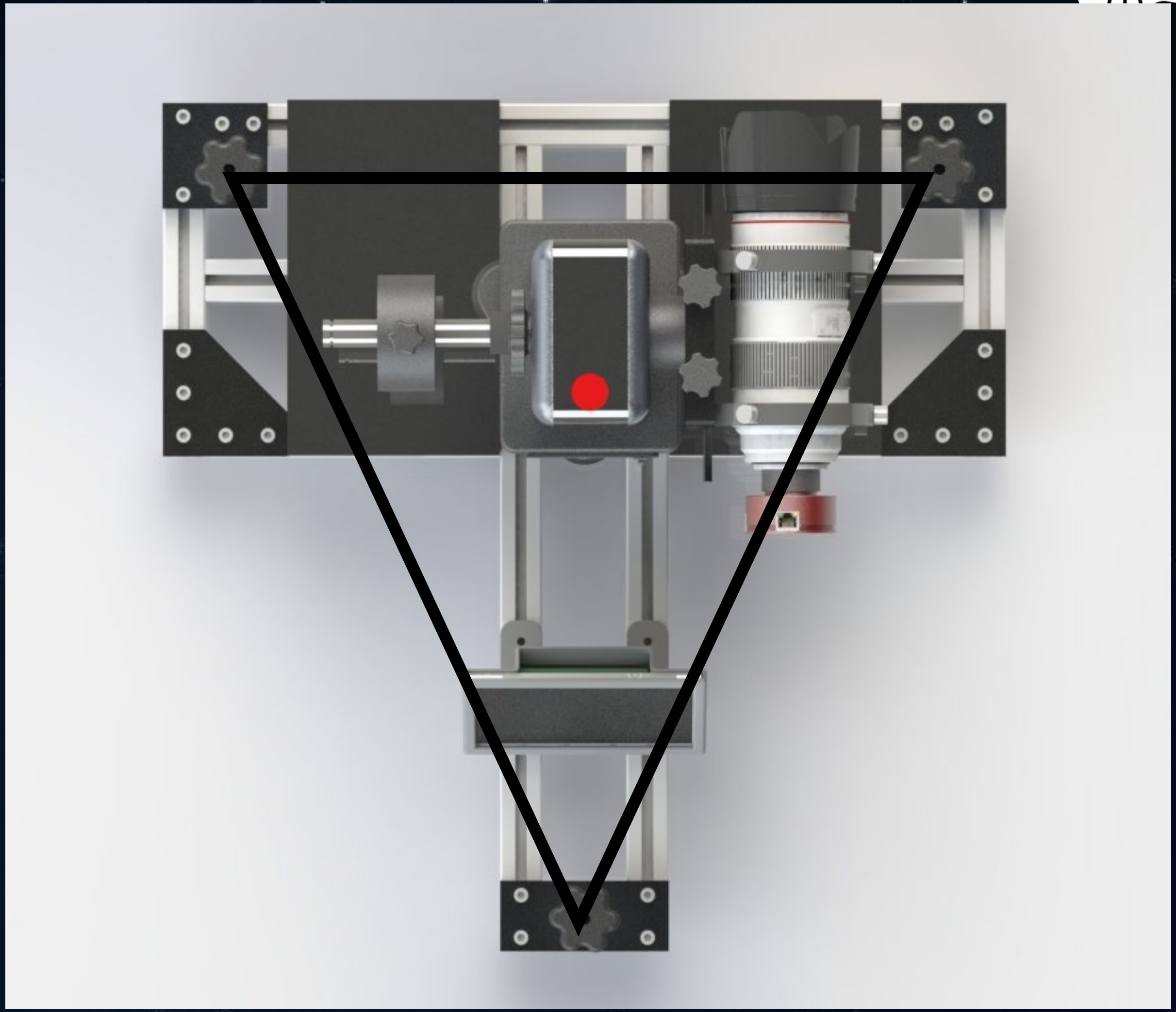


Drawings Riser Tube



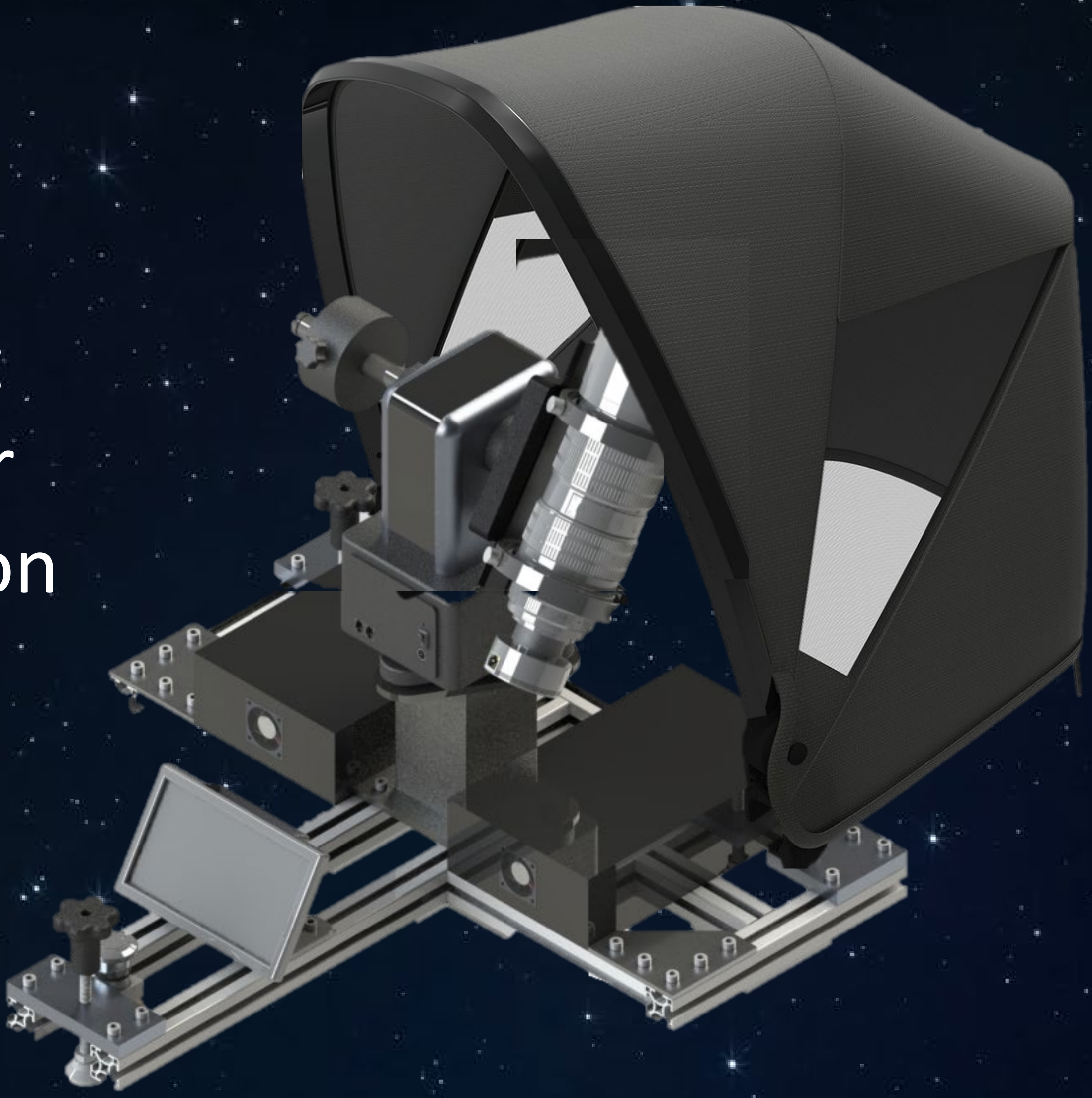
Chassis Center Of Mass Analysis

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

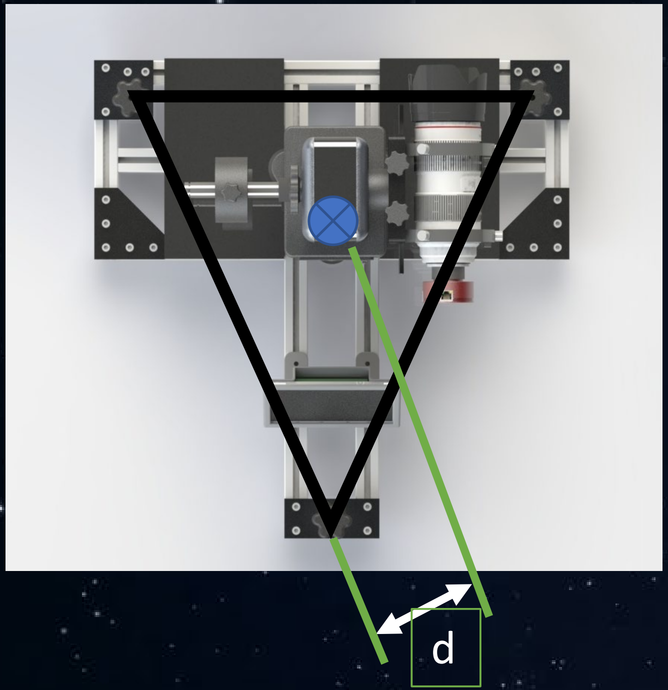


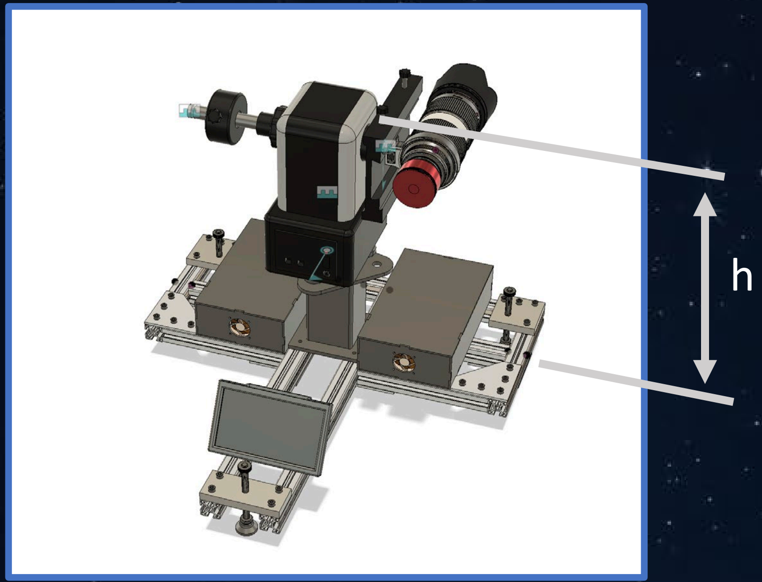
Chassis Future Weatherproofing

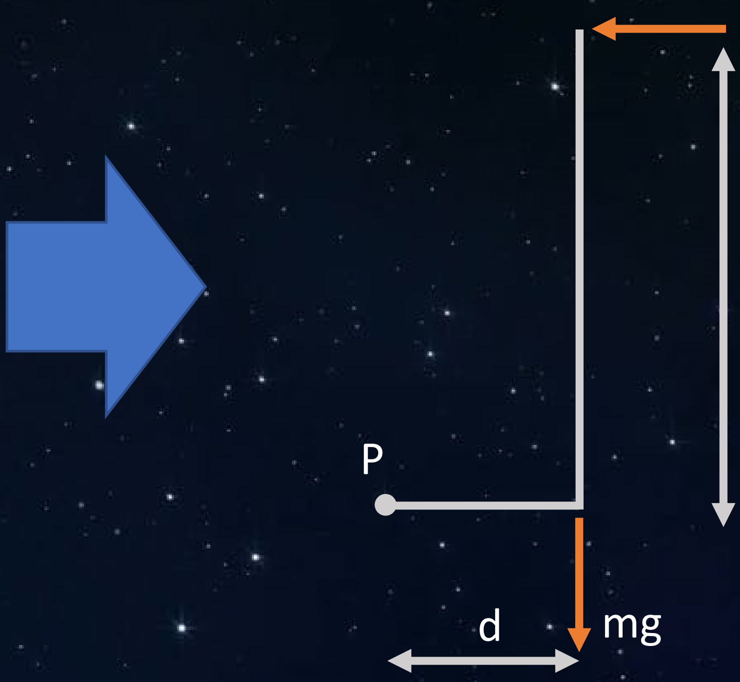
Out of scope for current project, but Chassis designed for future implementation



Chassis Tipping Force







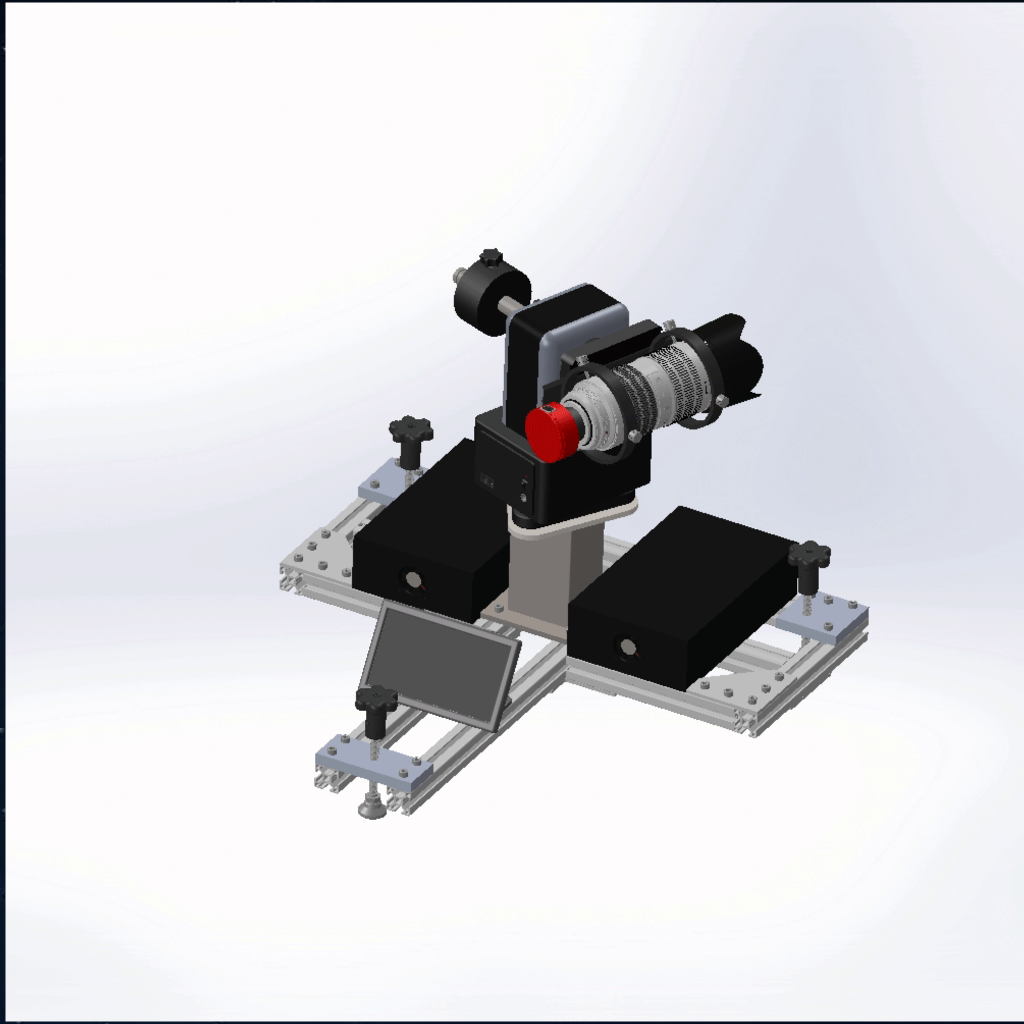
Given
h = 450mm
d = 184mm
m = 15.8kg

$$\sum M_P = 0$$
$$= Fh - mgd$$
$$\Longrightarrow F = {}^{mgd}/_{h}$$
$$\Longrightarrow Tipping\ Force, F = 63.4N = 14.2\ lbf$$

Chassis Motion Study

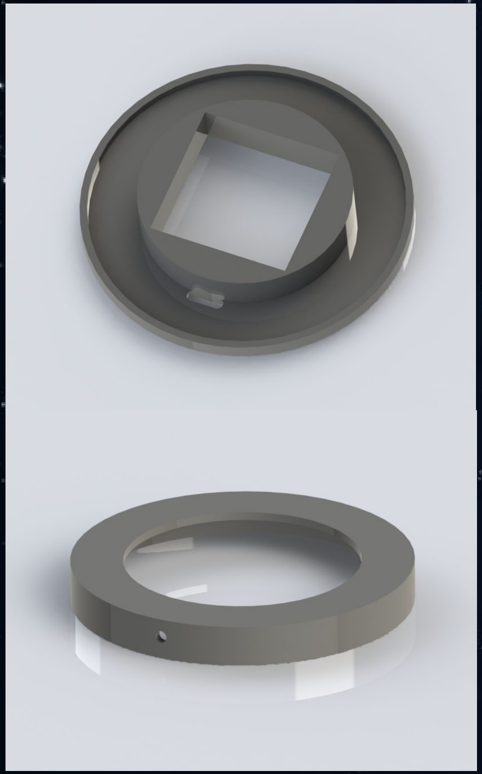
- No interference between optics and chassis

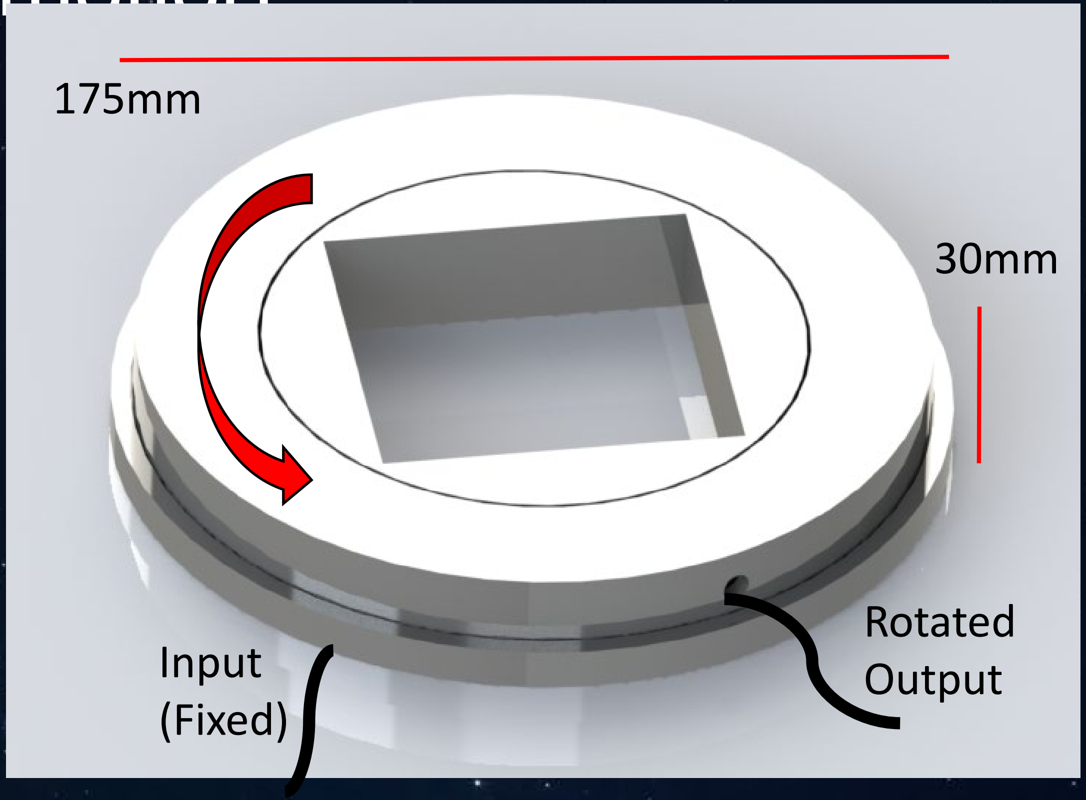
- Full range of motion accessible



Chassis Wire Management

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





Chassis Accident Prevention

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

Chassis Electronics Box Thermal Analysis

- 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

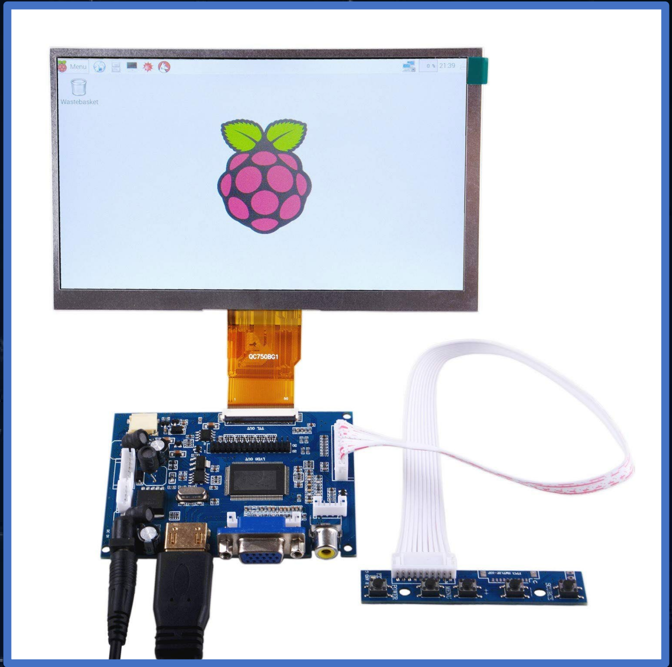
- Size: 198mm x 99mm x 38mm
- Ripple and Noise: 80 mV p-p
- Load Regulation: 3.0%
- Line Regulation: 1.0%
- Input: 88-264VAC
- Output: 5V @ 7A or 12V @ 7A
- Short circuit / overload protection

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

GPS Receiver Timing Output

NMEA text file

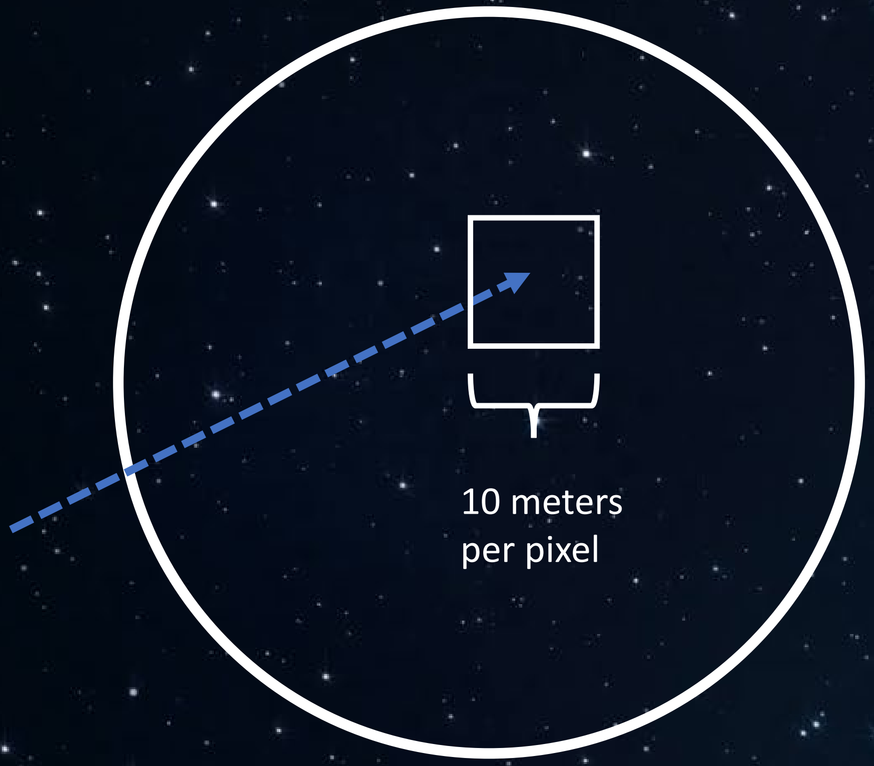
- Sent through I/O output to Arduino every second
- Contains current position ~1 meter accuracy
    - Processor pulls longitude/latitude data
- Contains current time ~1 ms accuracy

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

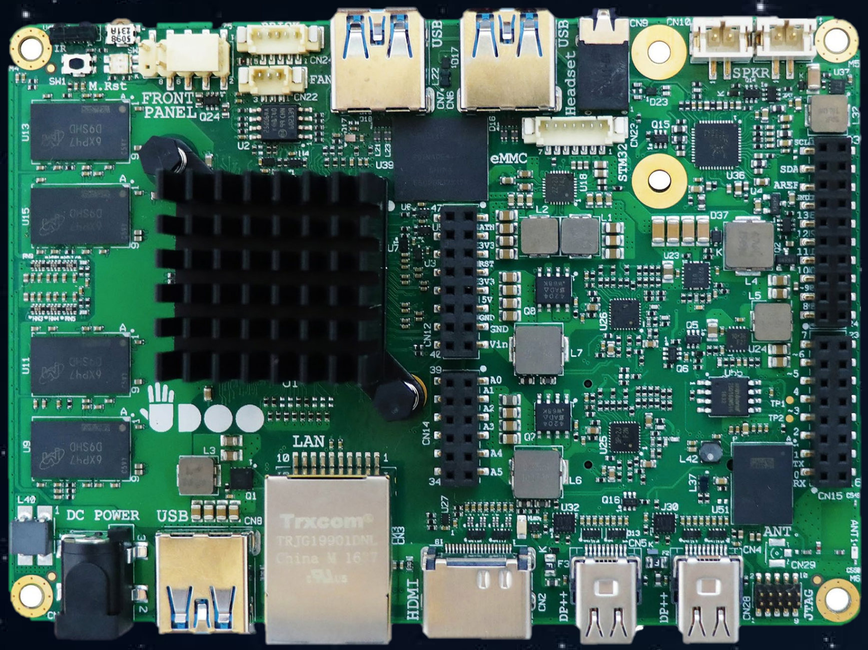
IMAGE TIMESTAMP:

ACTUAL IMAGE:

--> Compare timestamp record to which LED is lit to extract latency

Backup – Computer

Specifications UDOO x86



UDOO X86 Advanced Plus

CPU: 4-core 2.24GHz Intel Celeron N3160

Microcontroller: Intel Curie

RAM: 4GB DDR3L

I/O: Gigabit Ethernet

3 x USB type-A

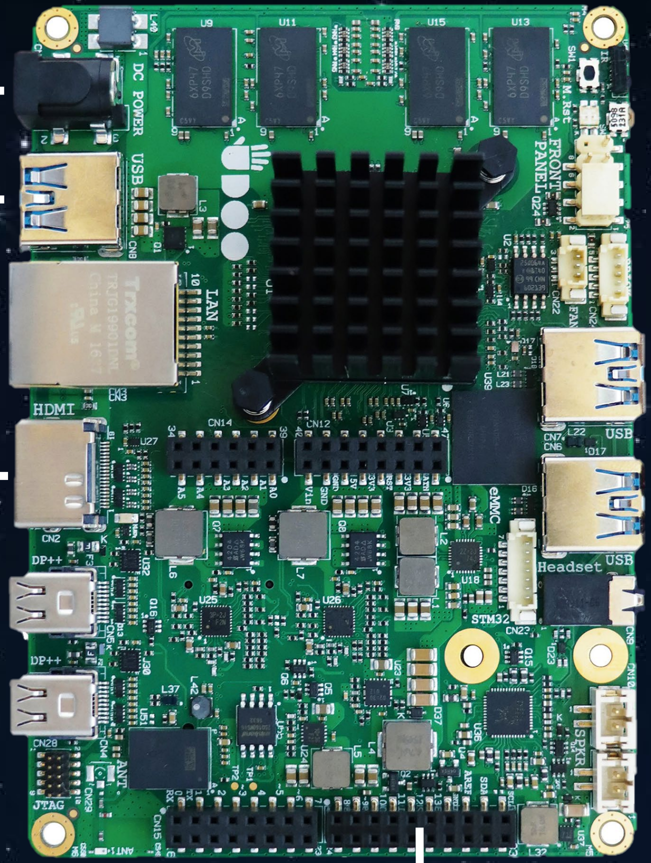
Arduino Pinout (from onboard M/C)

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)

USB3 Type A to ZWO Camera

USB3 Type A to iOptron Mount

Arduino pinout to Arduino shield

Arduino shield to GPS header

Backup – Scheduler

TLE Retrieval

.obs file

Module Name
NORAD ID 1, override #
NORAD ID 2
NORAD ID 3
.
.
.
Module Name 2
NORAD ID 4
NORAD ID 5, override #
.
.

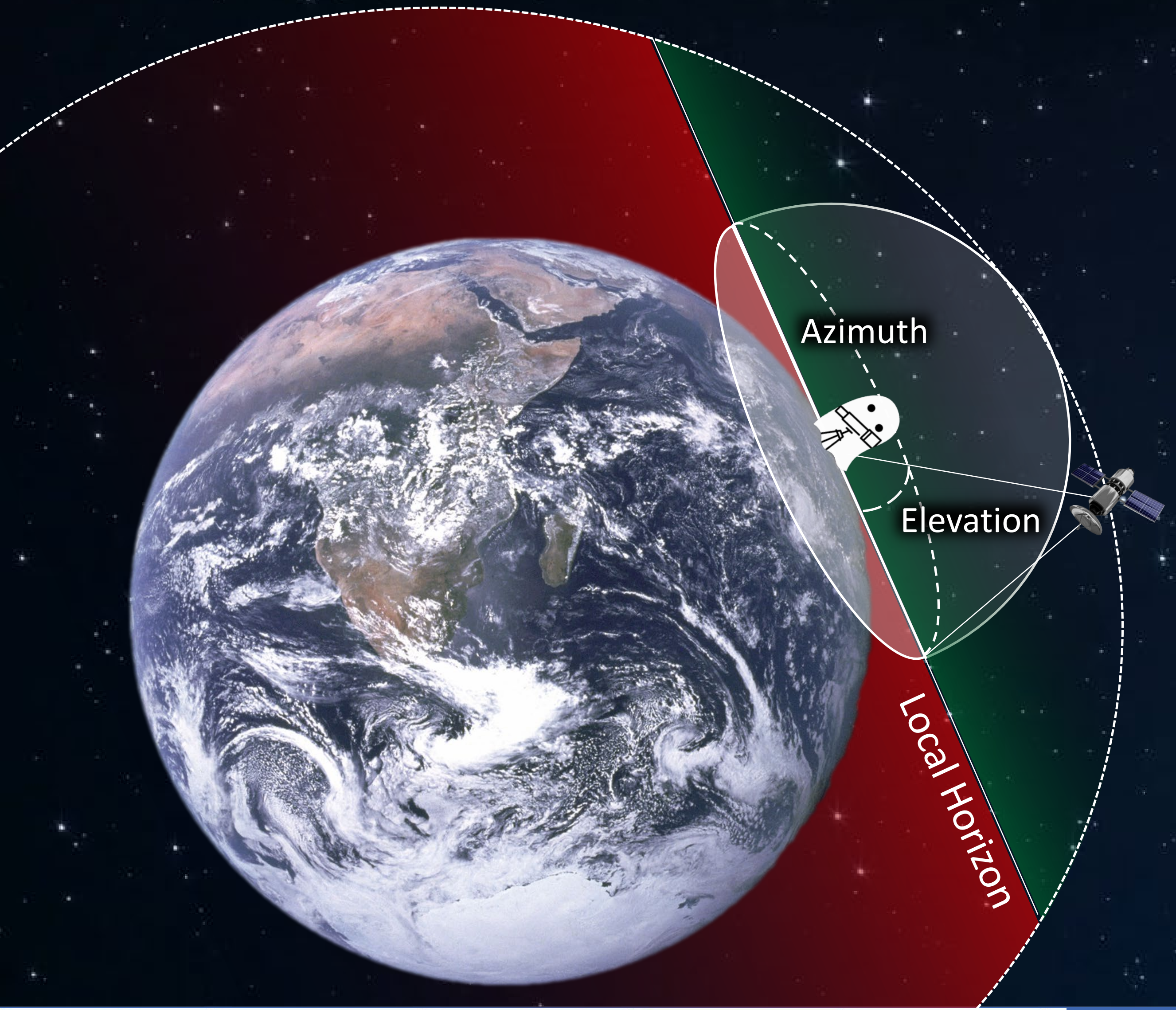
TLE catalog downloaded from Space-track.org

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

Latest TLE file

- .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

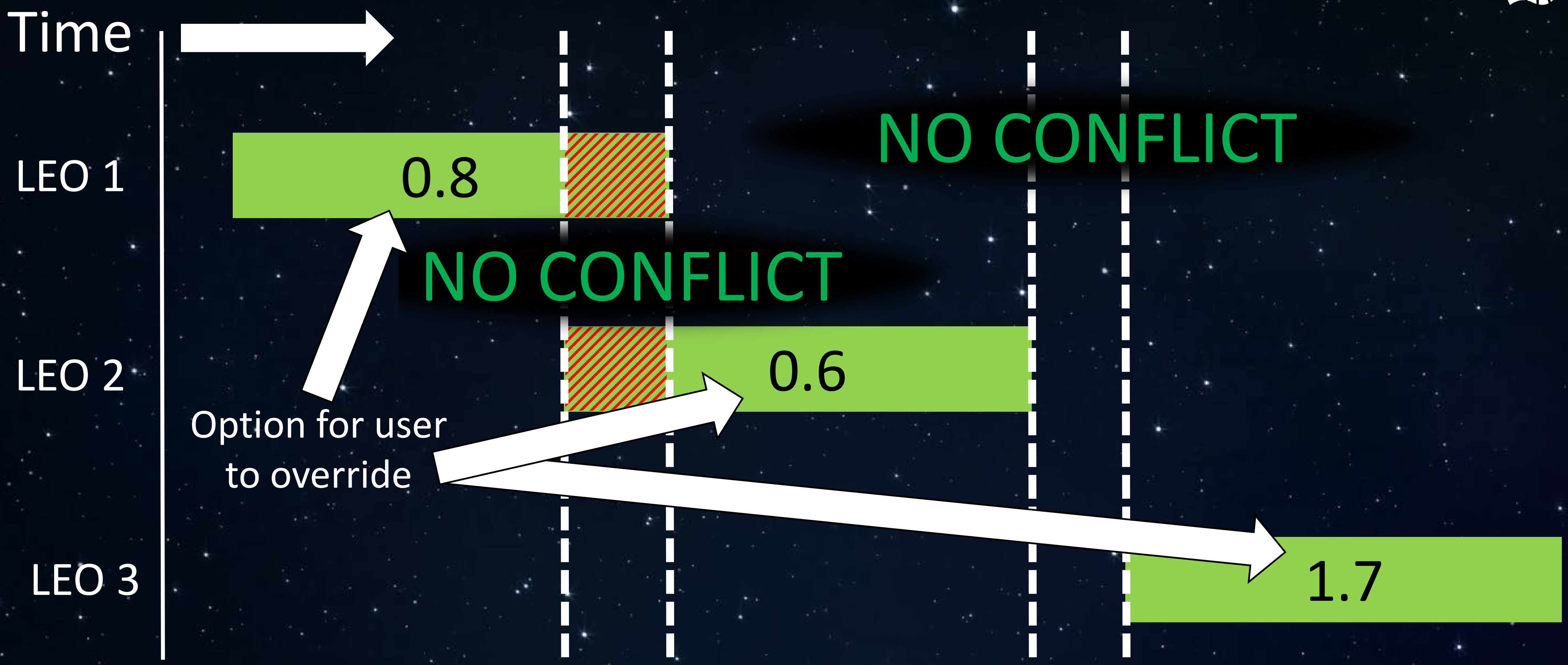
SGP4 Propagation



- 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

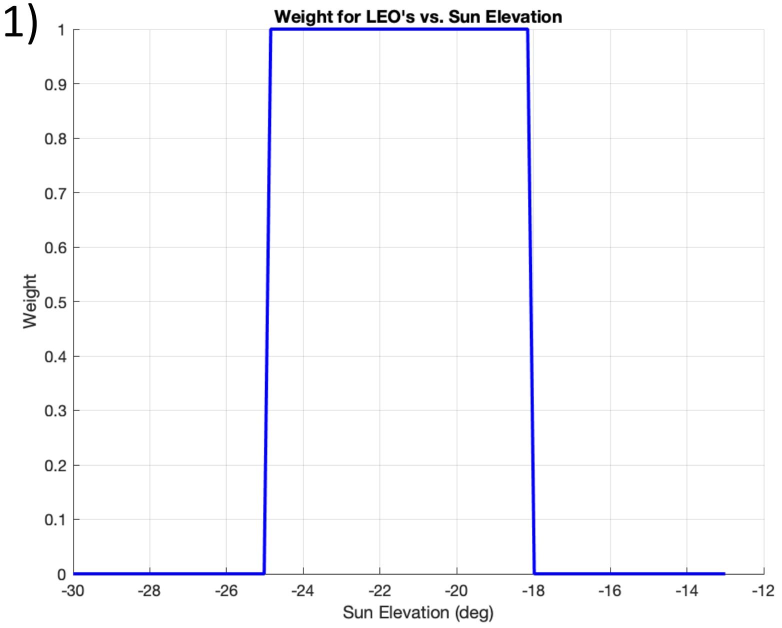
Weighting Priority to Observations

LEOs

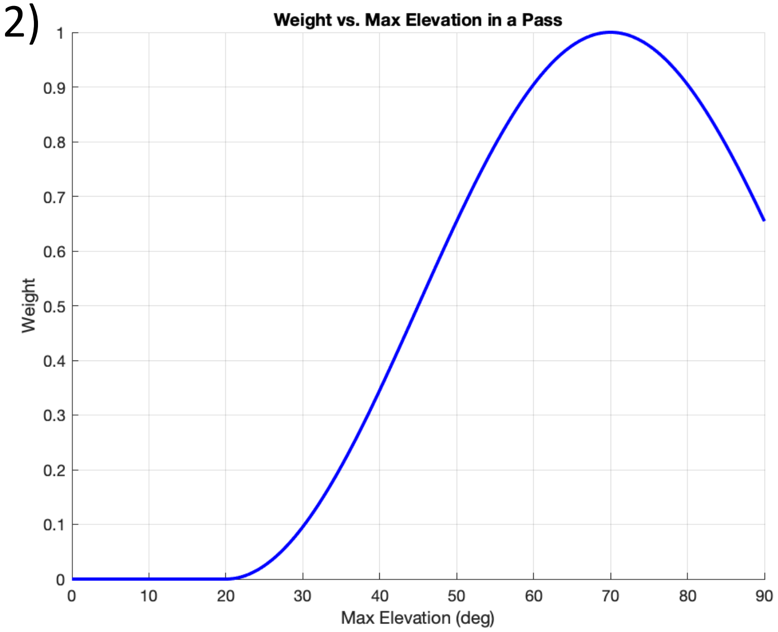


Weighting Priority to Observations

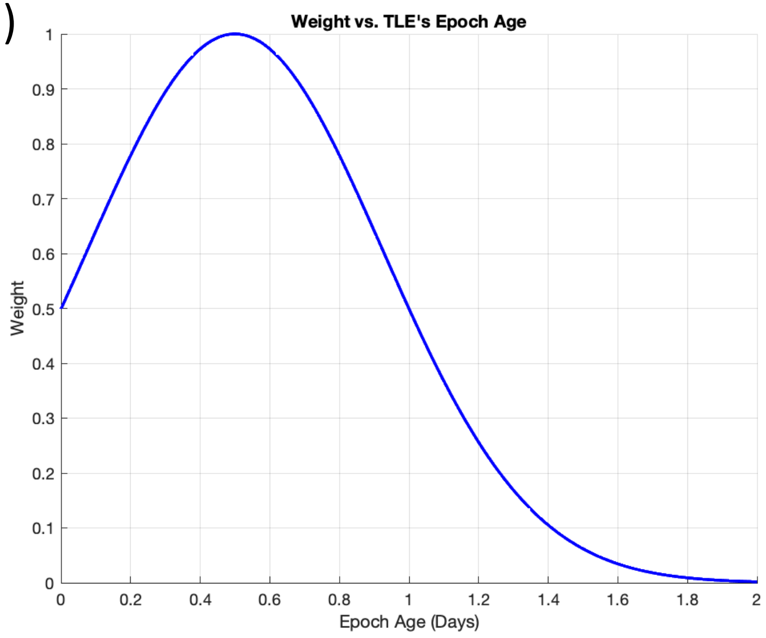
(1)



(2)



(3)



(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

$$(1)\ f(x) = step(x+25) - u(x+18)$$

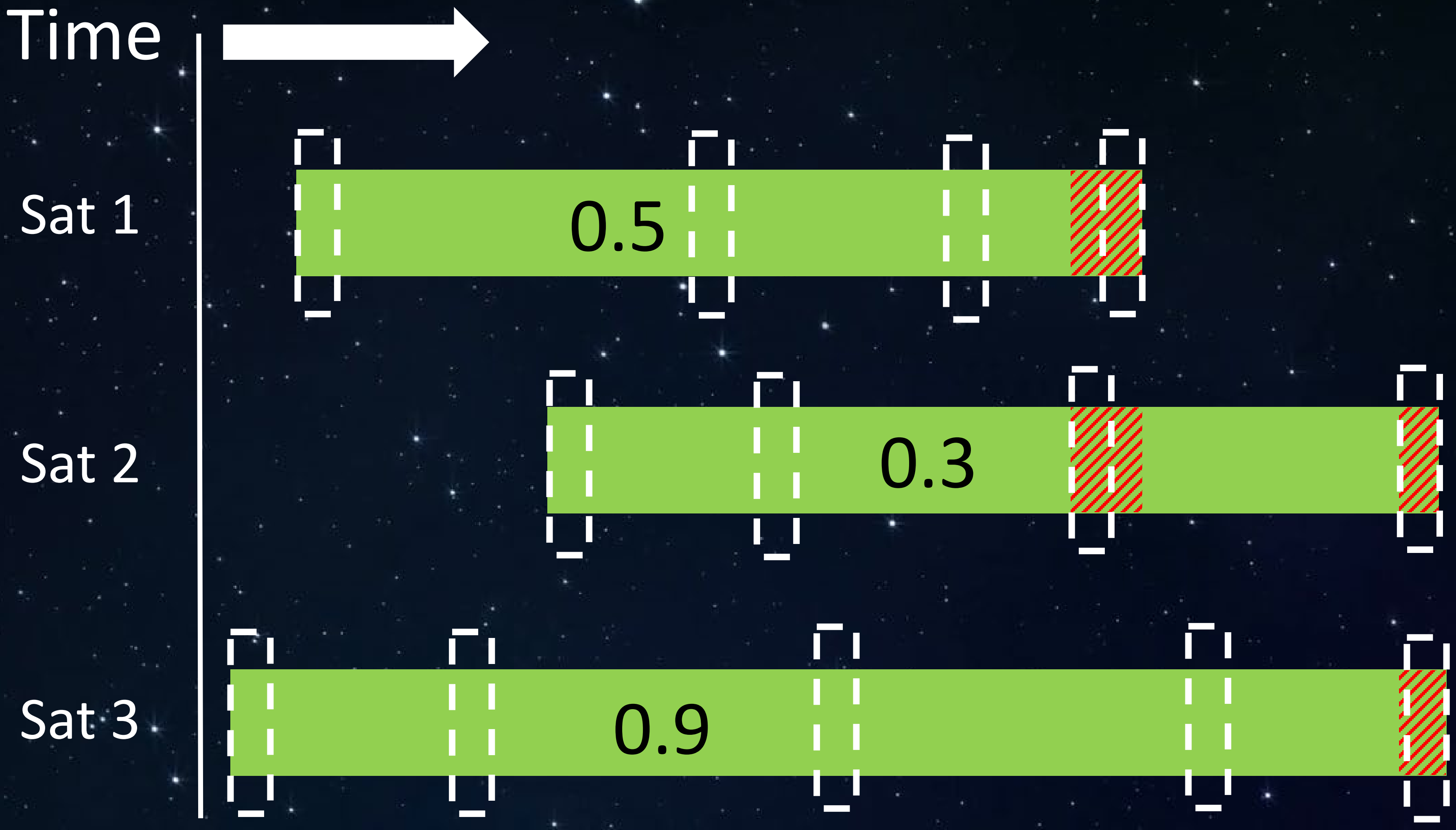
$$(2)\ f(x) = \left(0.5 - 0.5\cos\left(1.4\pi\frac{20-x}{90-20}\right)\right)u(x-20)$$

$$(3)\ f(x) = \exp((-2.78(x-0.5))^\wedge 2)$$

Creating Actuation/Imaging Commands

Key to image near horizon and near max elevation

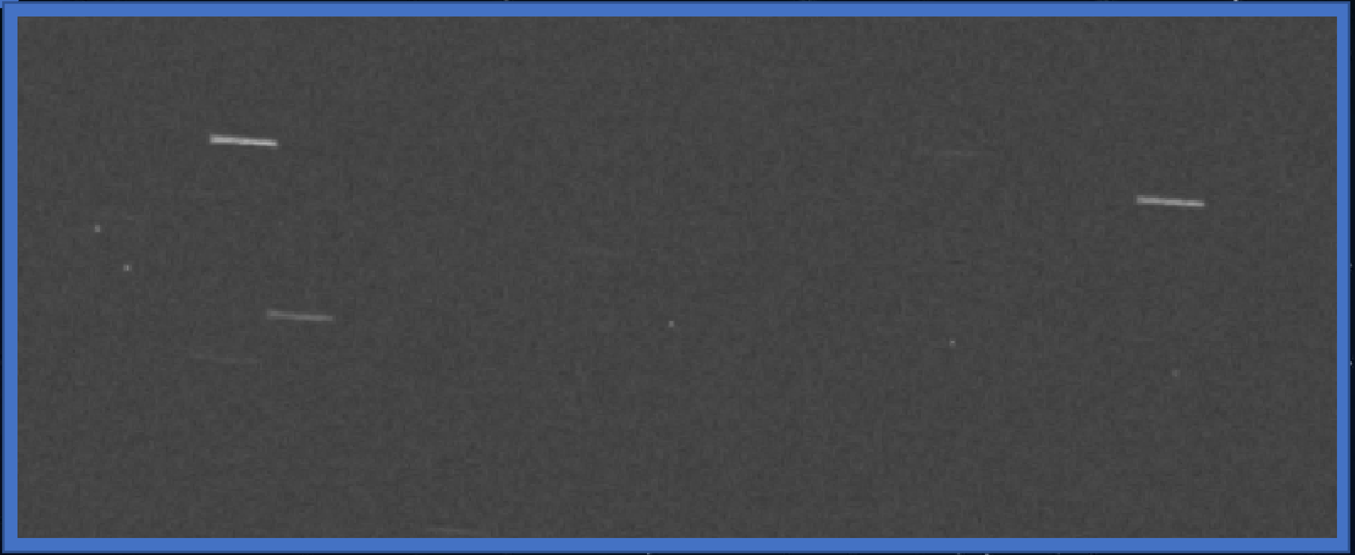
- Do not continuously track
- Add in more imaging sequences where possible



Backup – Image Processing

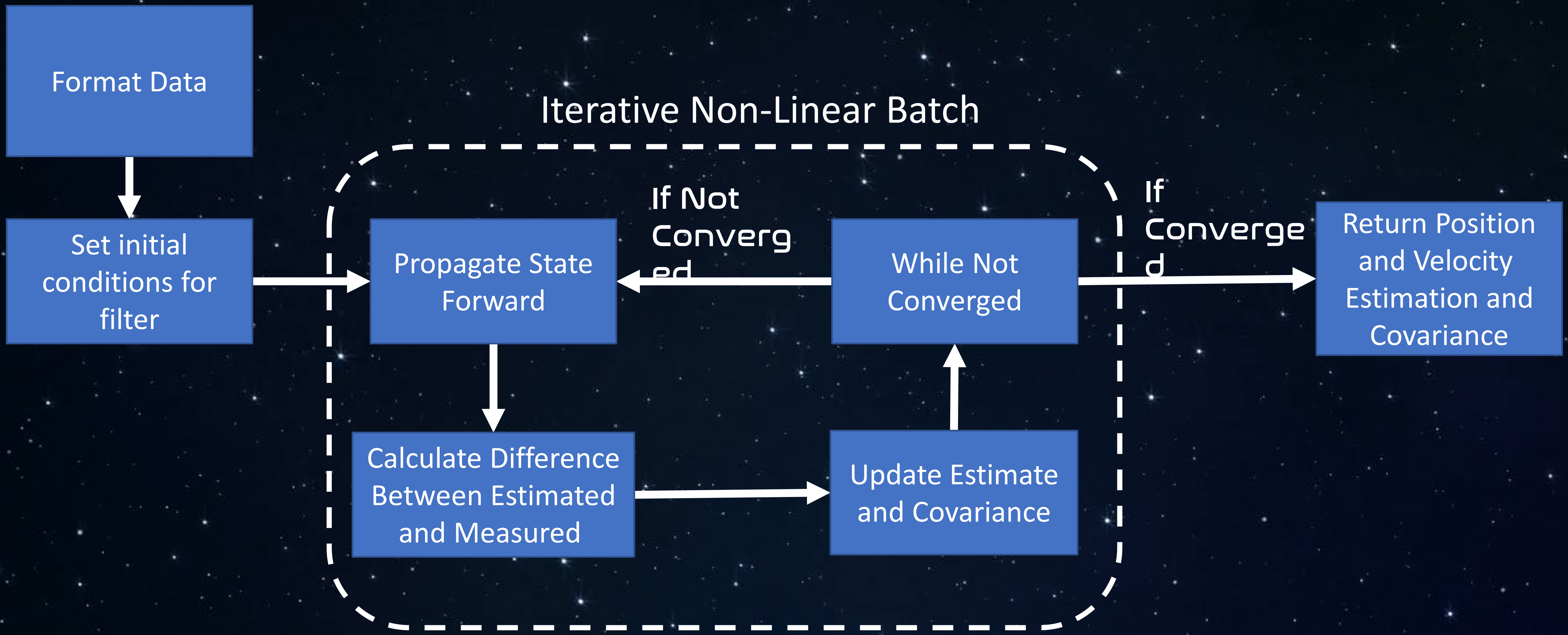
Image Processing Object Tracking

Image Processing Object Tracking



Backup – Orbit Determination

Batch Process Algorithm Breakdown

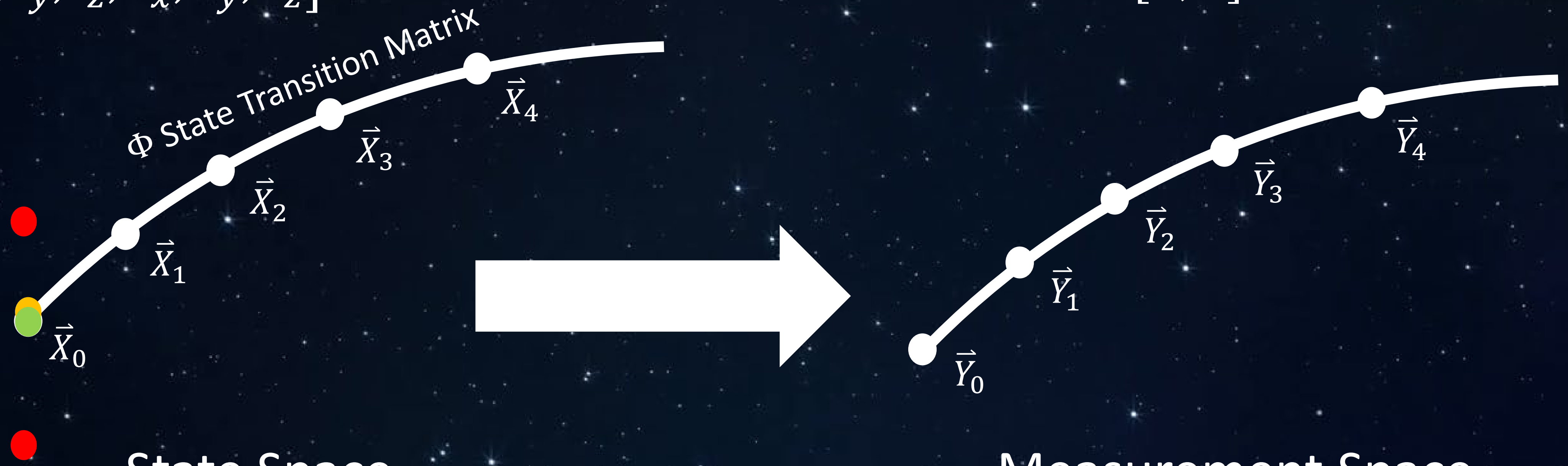


Non-Linear Batch Filtering
Background

Goal : Reduce residuals between the estimation and the measured values

$\vec{X} = \left[r_x, r_y, r_z, v_x, v_y, v_z\right]^T$

$\vec{Y} = [\alpha, \delta]^T$



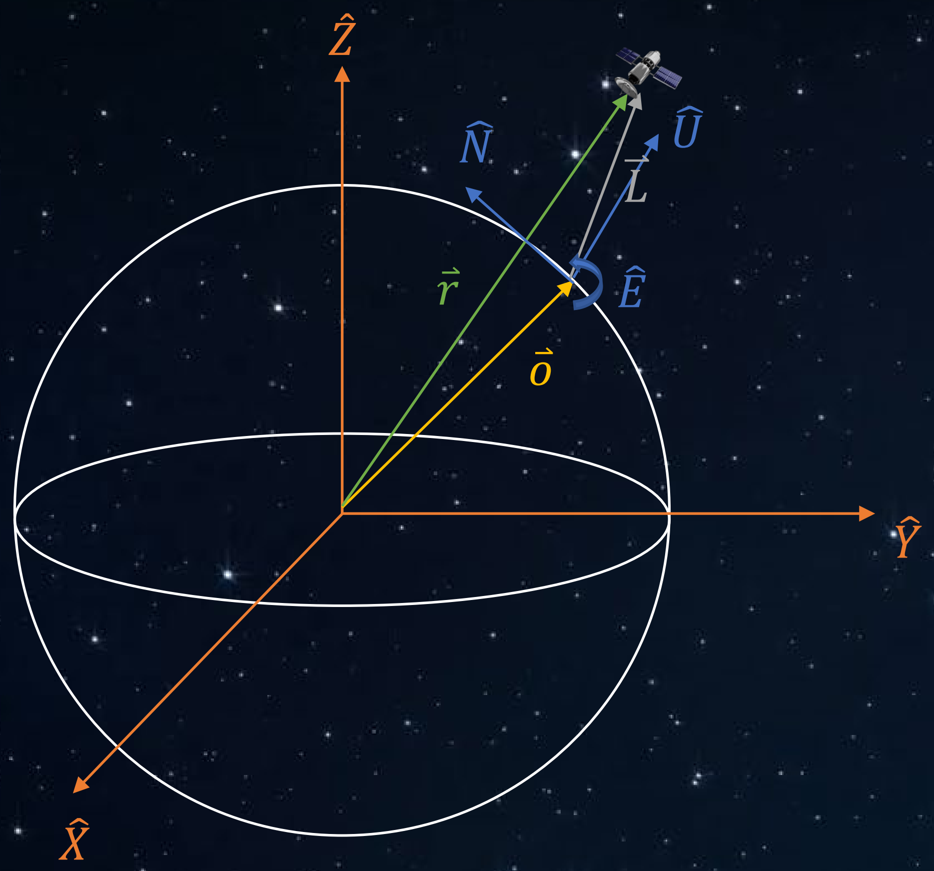
State Space

$\vec{x} \in \mathbb{R}^6$

Measurement Space

$\vec{y} \in \mathbb{R}^4$

Coordinate Transformations



$$\vec{r} = \vec{o} + \vec{L}$$

$\hat{X}\hat{Y}\hat{Z}$, Earth's Center: *Earth Centered Inertial Frame*

$\hat{N}\hat{E}\hat{U}$, Observation Site: *Topocentric Frame*

$\vec{o}$: Position vector in the ECI frame

$\vec{L}$: Line of sight vector in the topocentric frame

$\vec{r}$: *Position vector of the space object in the ECI frame*

Equations of Motion

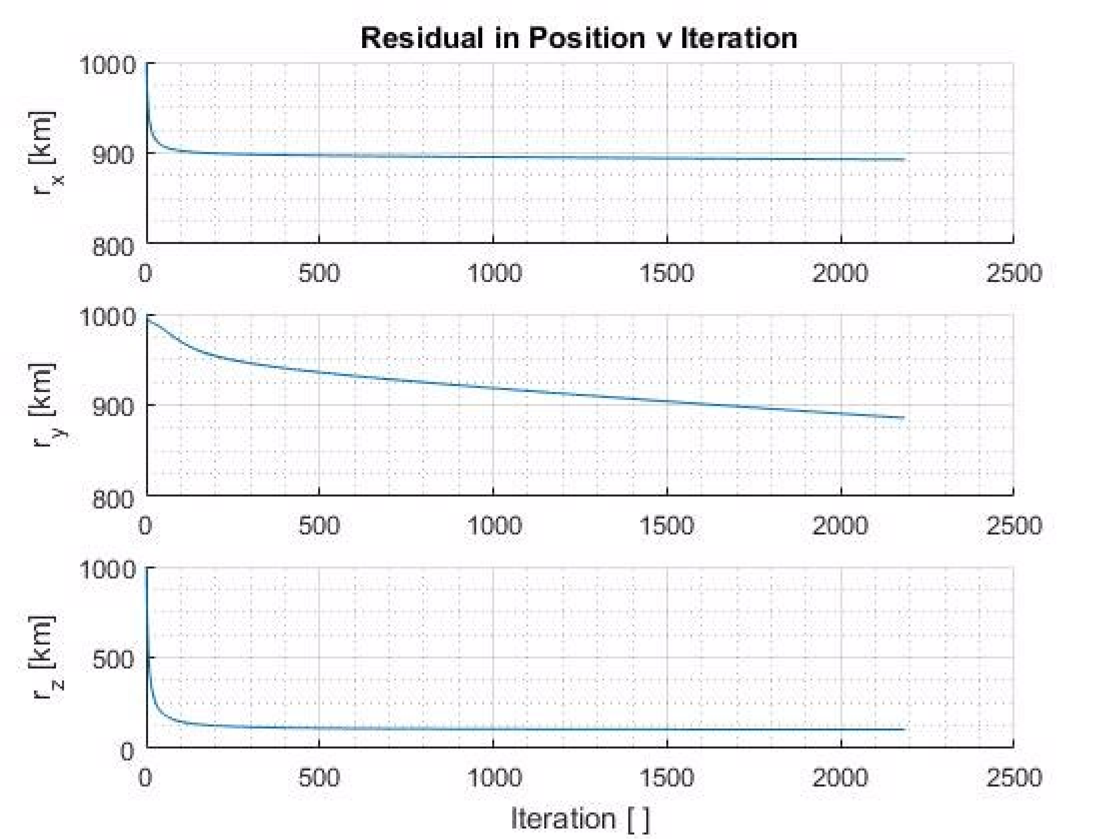
- Two body Problem with J2 Perturbations

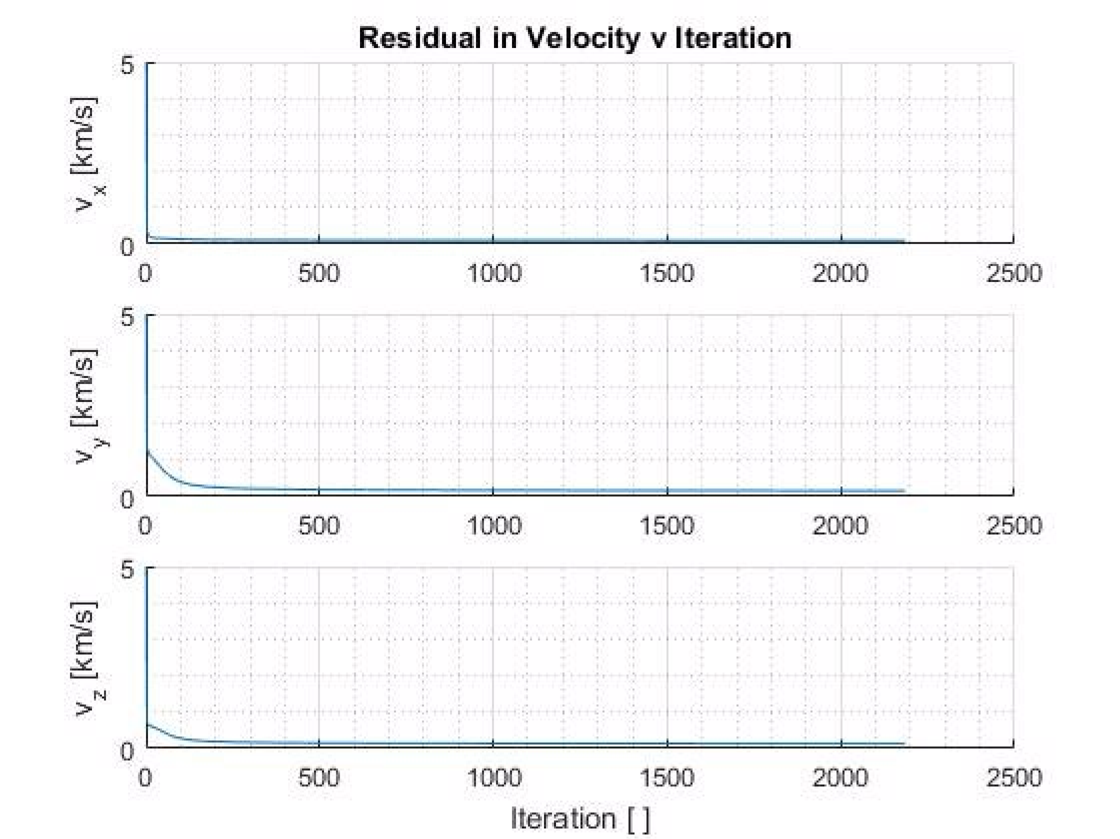
$$a_x = -\frac{\mu}{r^3} r_x - \frac{3}{2} J_2 \left(\frac{\mu}{r^2}\right) \left(\frac{r_{eq}}{r}\right)^2 \left(\left(1 - 5 \left(\frac{r_z}{r}\right)^2 \right) \frac{r_x}{r} \right)$$

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

$$a_z = \underbrace{-\frac{\mu}{r^3} r_z}_{\text{Two Body Effects}} \underbrace{- \frac{3}{2} J_2 \left(\frac{\mu}{r^2}\right) \left(\frac{r_{eq}}{r}\right)^2 \left(\left(3 - 5 \left(\frac{r_z}{r}\right)^2 \right) \frac{r_z}{r} \right)}_{J_2 \text{ Effects}}$$

Textbook Example Residuals





Batch Process

The filter is initialized with $\boldsymbol{X} = \boldsymbol{X_0}$, $\Phi = I_{6x6}$, $\Lambda = 0$, and $N = 0$

A measurement is read in at $t_i, \boldsymbol{Y_i}, R_i$

ODE 45 is used to propagate $\vec{X}$ and Φ 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.

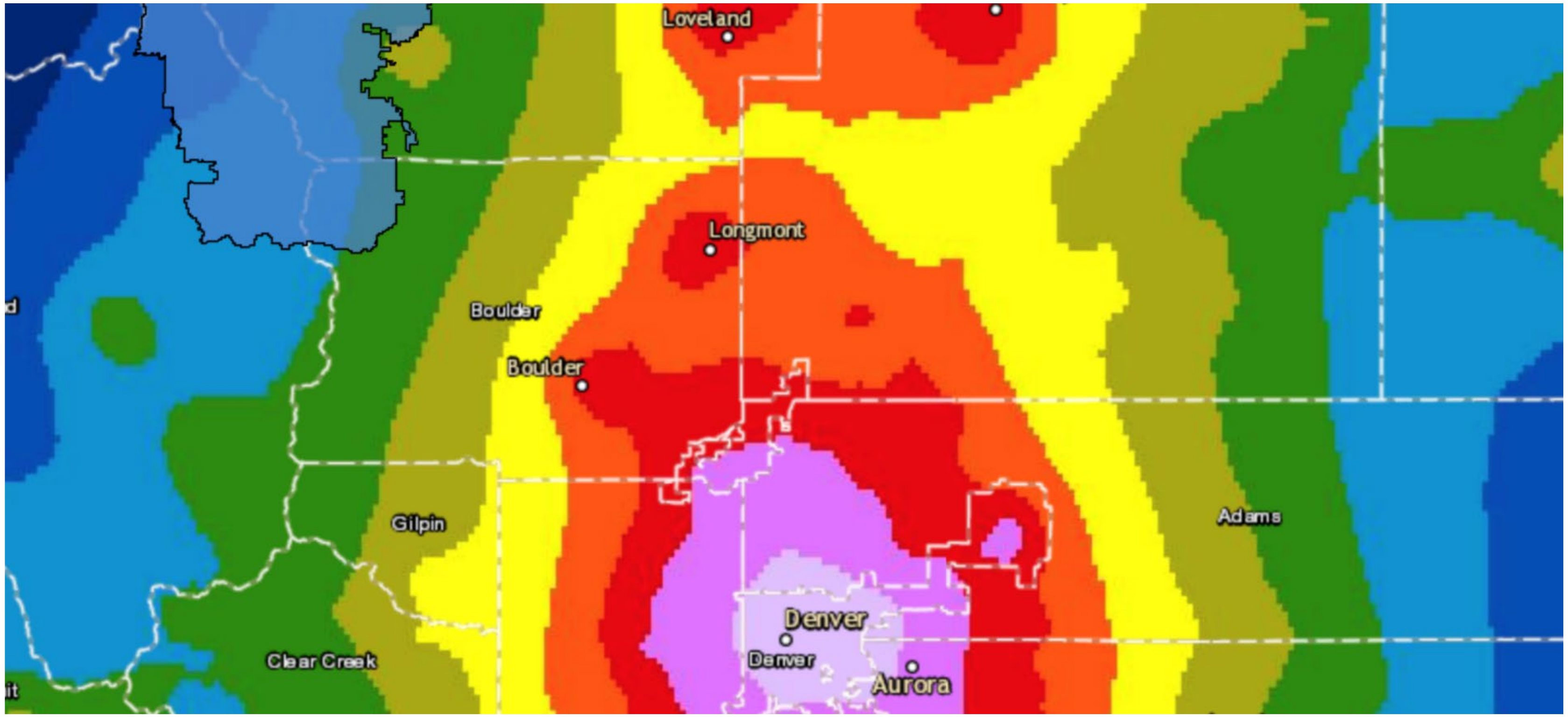
If $t_i > t_{final}$, the normal equations are solved

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 Light Pollution



Source: NOAA

Color	Dark blue	Light blue	Green	Olive	Yellow	Orange	Red	Violet
Max LSM	12.6	12.2	11.9	11.5	11.1	10.7	10.4	10.0

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)