GHOST

Ground-based Hardware for Optical Space Tracking

Project Manager: Jack Toland

Hardware: Lucas Calvert, Duncan McGough, Seth Hill, Jake Vendl

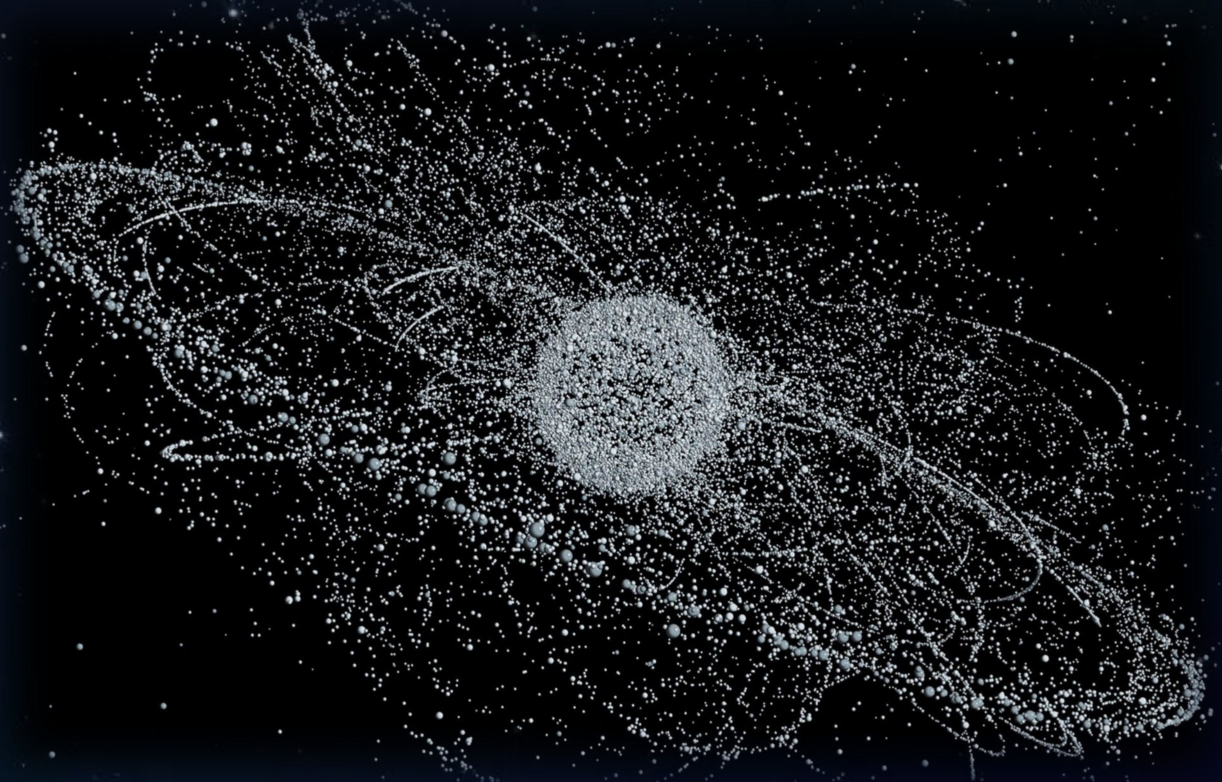
Software: Kira Altman, Ginger Beerman, Connie Childs, Keith Covington, Rachel Mamich, Connor Ott

Sponsor: The Aerospace Corporation

Advisor: Marcus Holzinger

The Problem

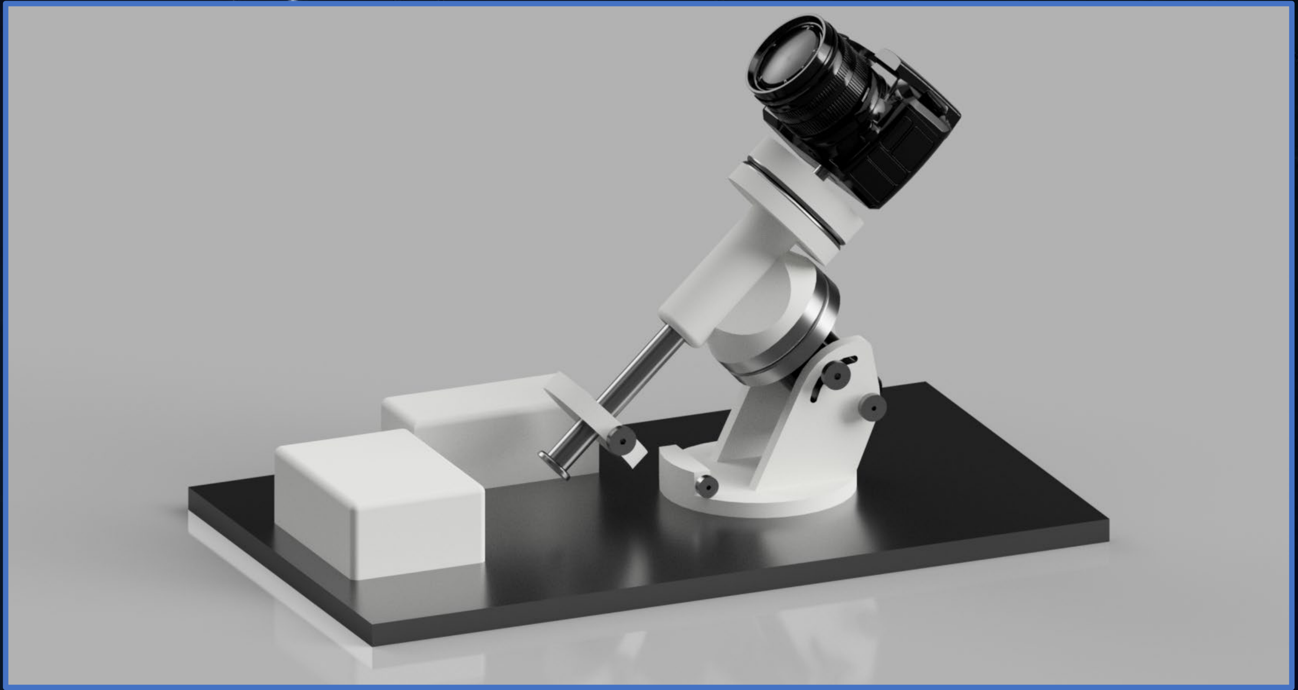
- Increasing number of space objects
  - CubeSats
  - Mega Constellations
  - Debris
- International dependence on space
  - Communication
  - Weather
  - National Security



The Solution GHOST

Optical space object tracking system

- Low-cost
- Small
- Easy to setup
- Built using COTS hardware



World-wide deployment possible for increased observation frequency

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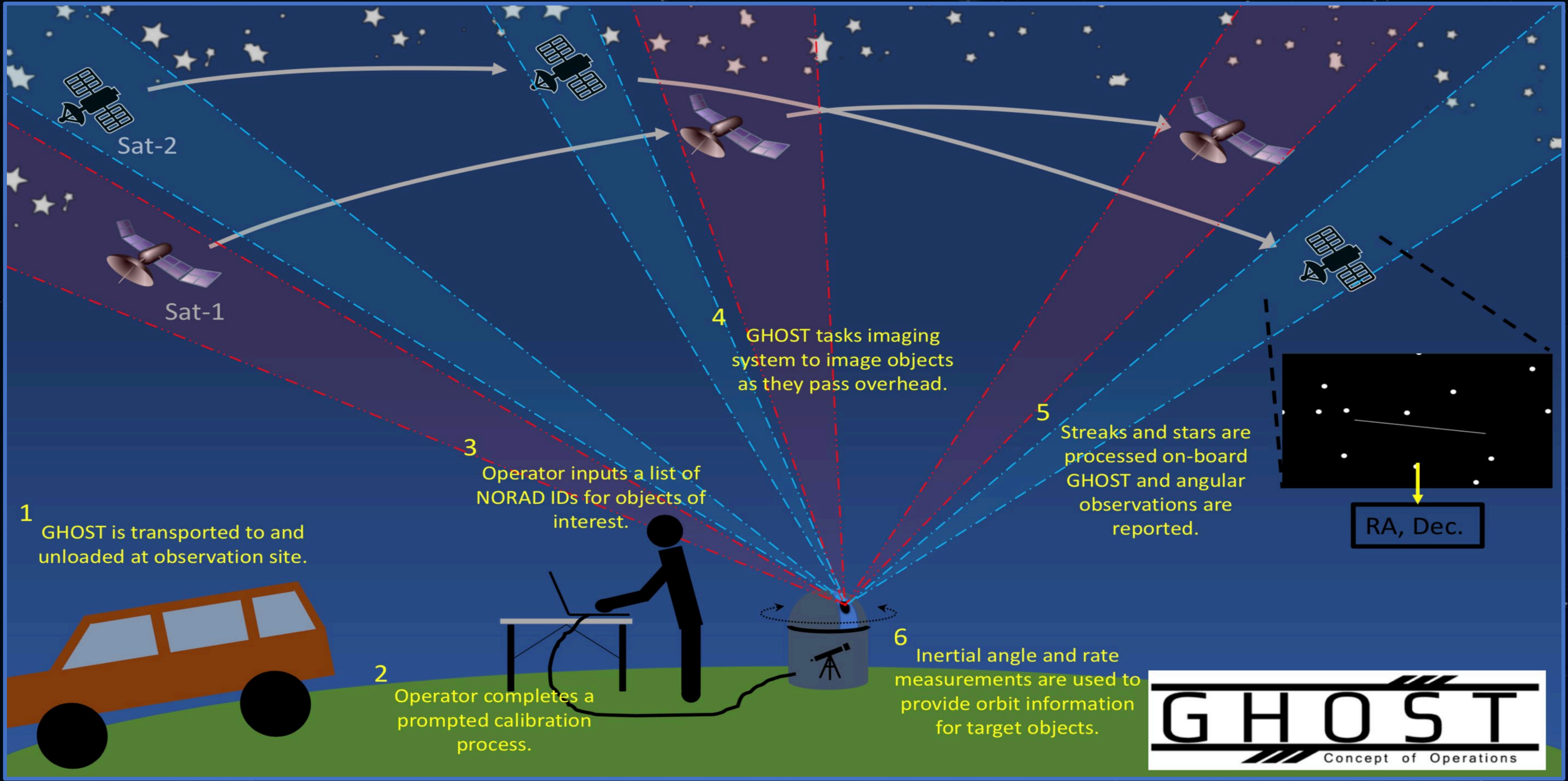
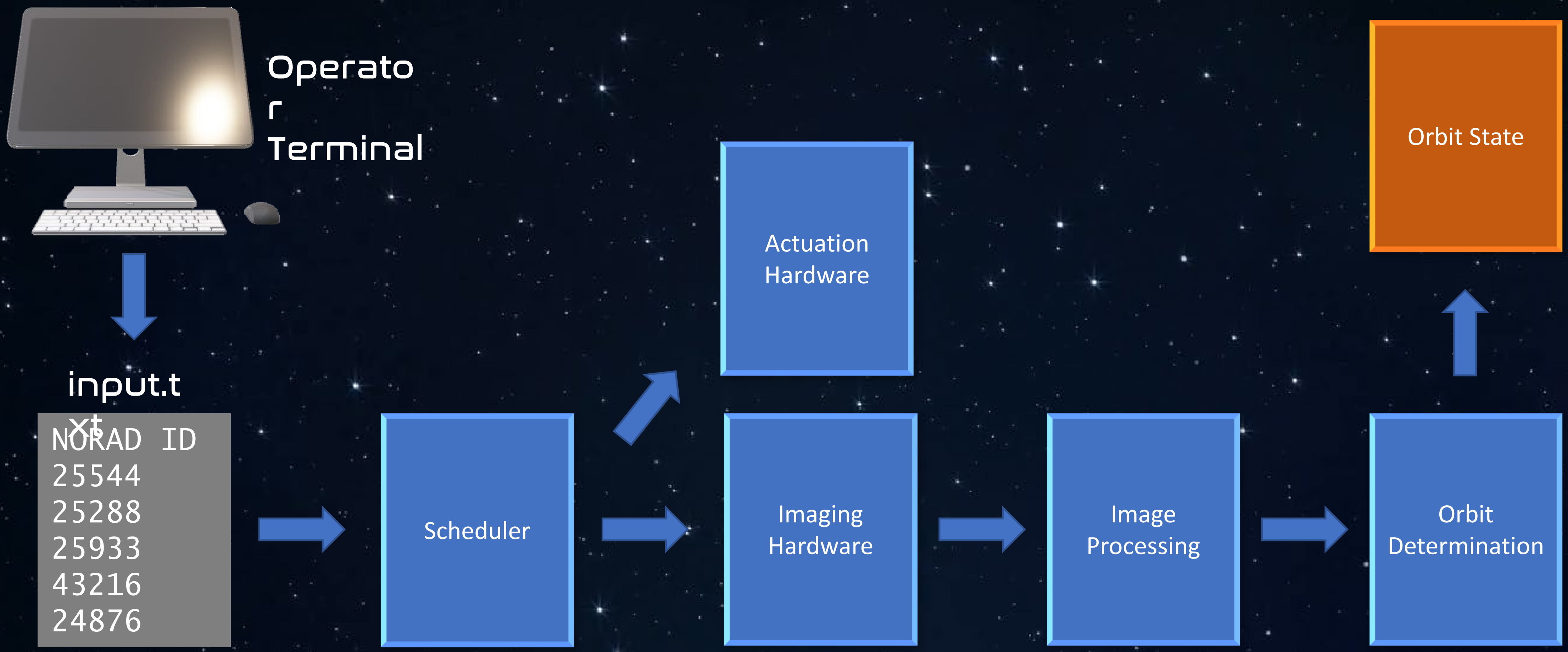
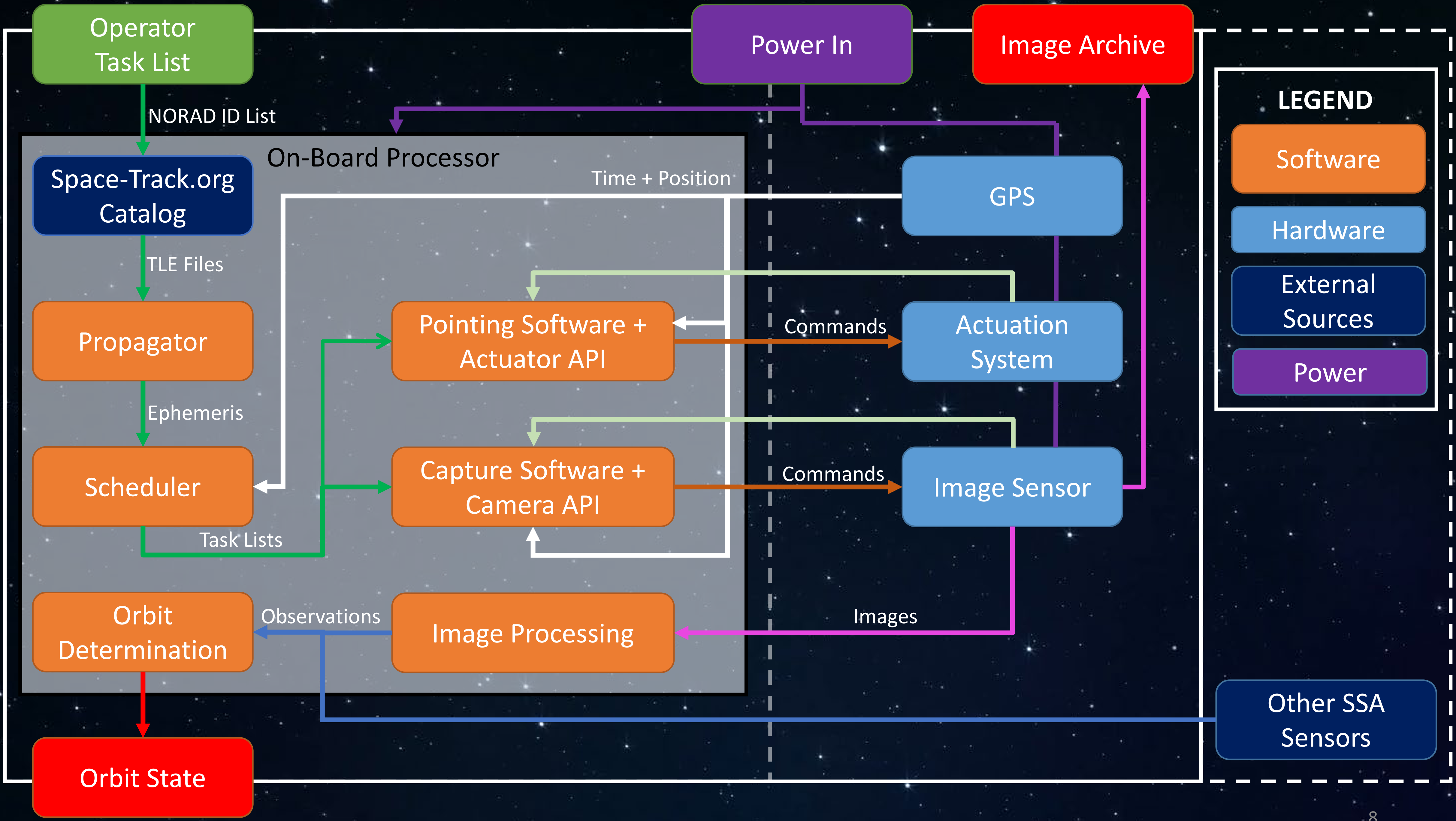
Concept of Operations



GHOST Pipeline





Operator Task List
NORAD ID List
Power In
Image Archive
LEGEND
Software
Hardware
External Sources
Power
On-Board Processor
Space-Track.org Catalog
Time + Position
GPS
TLE Files
Propagator
Pointing Software + Actuator API
Commands
Actuation System
Ephemeris
Scheduler
Capture Software + Camera API
Commands
Image Sensor
Task Lists
Orbit Determination
Observations
Image Processing
Images
Other SSA Sensors
Orbit State

Critical Project Elements

CPE	Description	Slide
Scheduler Software	The scheduler will task the system based on visibility of space objects and associated priority. The system cannot operate without accurate tasking as the space object will not be in the field of view.	14
Actuation Hardware	The actuation hardware will point the imaging hardware as tasked by the scheduler software. Accurate pointing is required in order to capture the space object entirely within the field of view.	20
Imaging Hardware	The imaging hardware will capture the light signature of a space object. The hardware must be selected and adjusted such that objects of varying brightness can be captured with manual adjustment.	26
Image Processing	The image processing will analyze an image and provide data points containing right ascension, declination, and time for the start and end of each space object capture streak.	35
Orbit Determination	The orbit determination will provide the final output of the system. This element is required to ultimately provide a valid result.	41

Baseline Design

Hardware

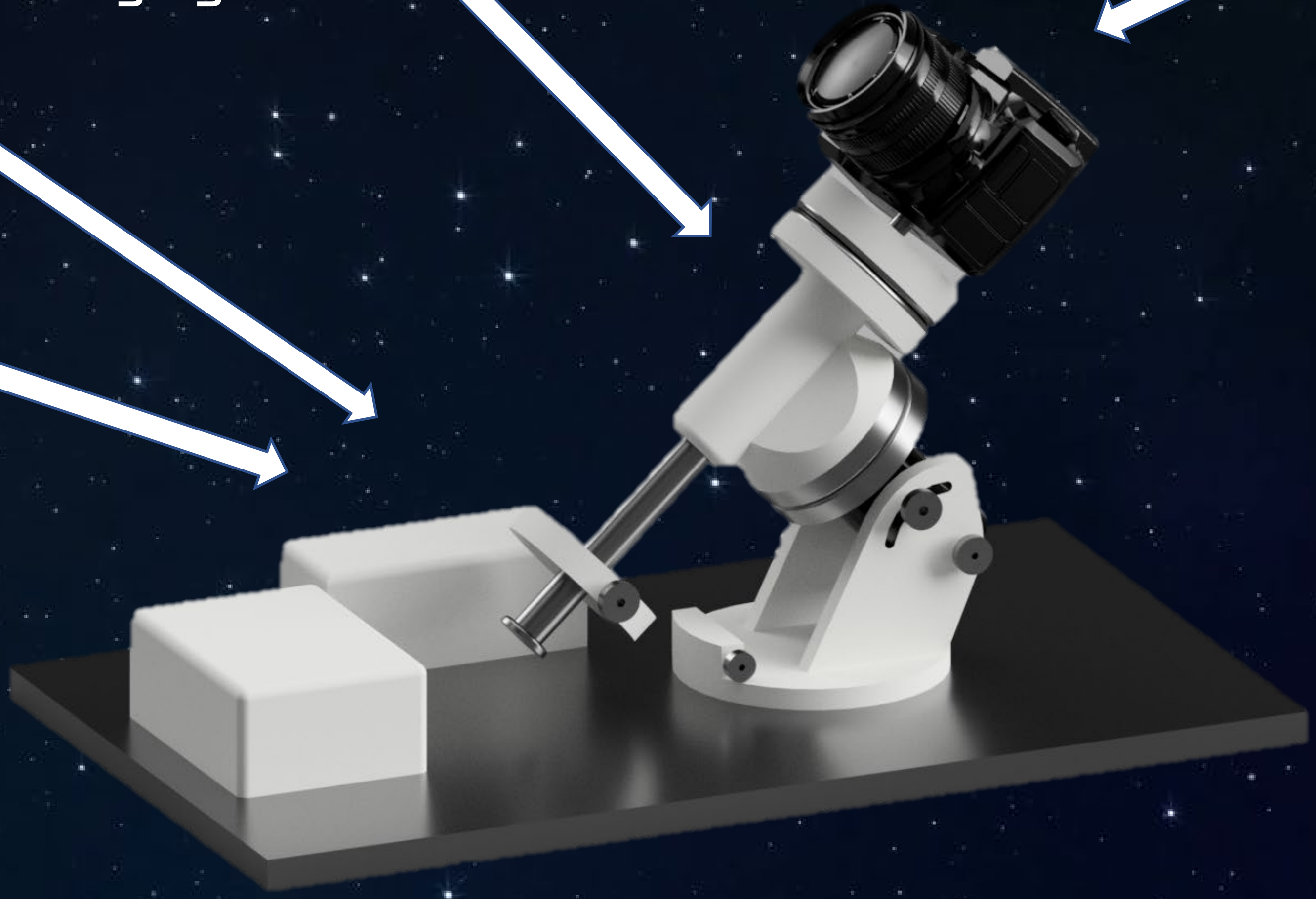
Precise Point Positioning (PPP) GPS Receiver
- GPS unit simplifies timing and calibration
- PPP units have comparatively high positional accuracy
- Easily integrated with software packages
- Units can be bought with specifications suited to project

General Purpose Computing Board
Satisfies DR 3.2, DR 4.4, DR 4.5
- Easy to use
- Capable of running Linux OS

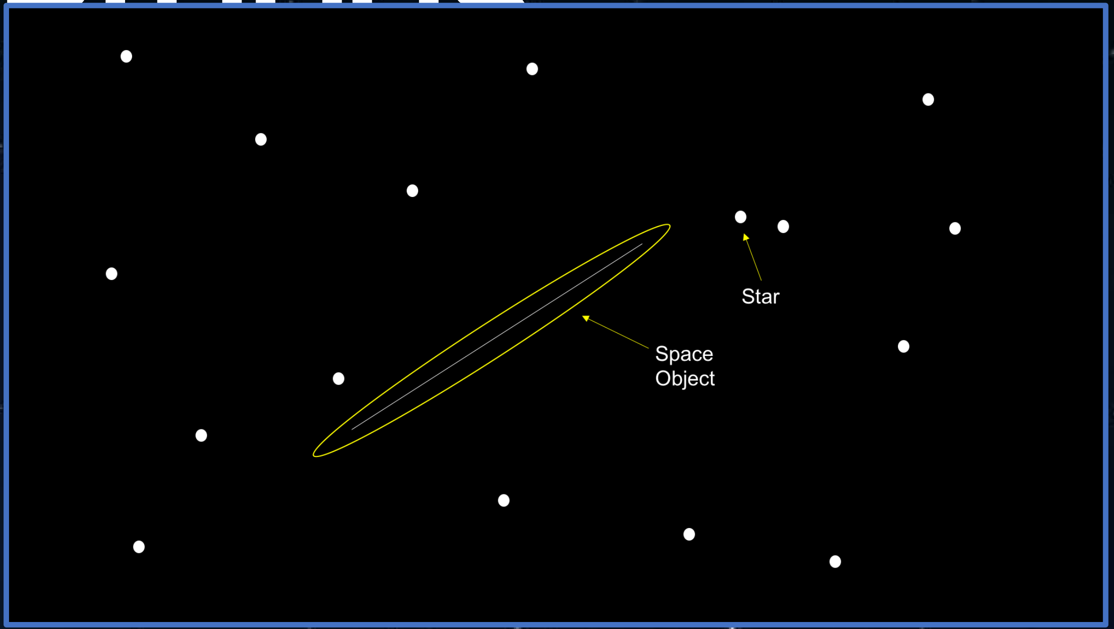
Power Distribution
- 120V Source Power
- Onboard distribution to subsystems

COTS Sidereal Stationary Moun
- Low risk
- Capabilities documented and known
- Compatible with chosen imaging method

DSLR and Camera Lens
- Readily available
- Large pixel size
- APIs available for most br

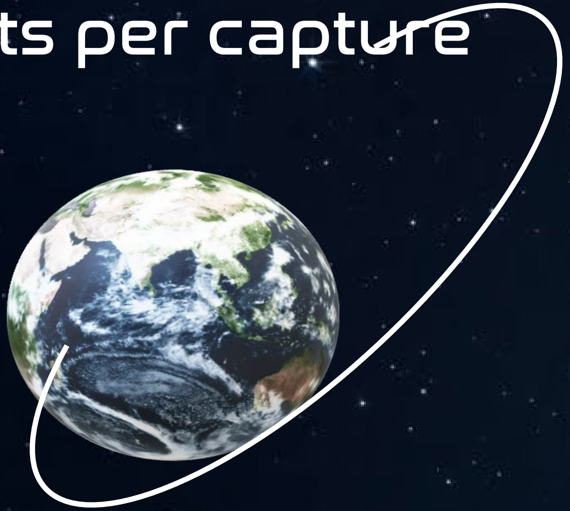


Software and Methods



Sidereal-Stationary Image Capture

- Stars will be stationary for easy registration with Tycho2 catalog
- Space objects will appear as streaks providing up to 2 data points per capture



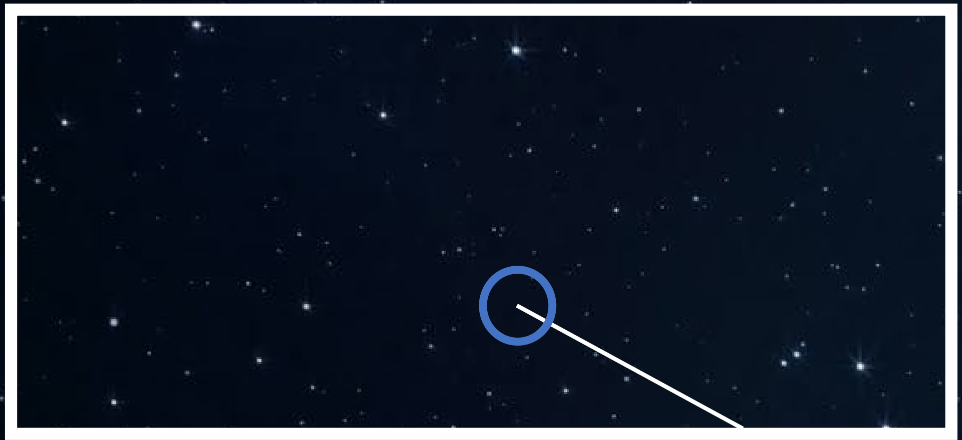
Non-Linear Batch Least Squares Filter for OD

- High accuracy
- Legacy method with prior SSA implementations
- Requires 6 discrete angular measurements

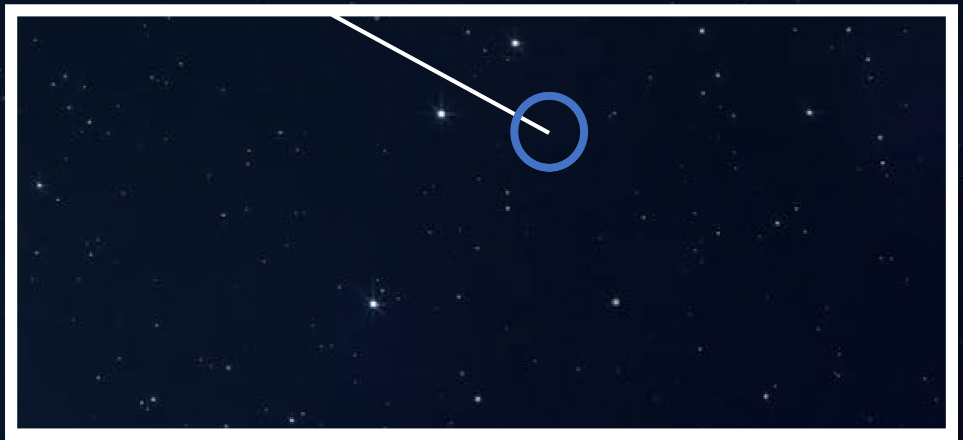
Possible Image Cases

Case 1 – Full Streak (2 points)

Case 2 – Missed Entire Streak



Case 3 – Missed Beginning of Streak (1 point)



Case 4 – Missed End of Streak (1 point)

Evidence of Feasibility: Scheduler

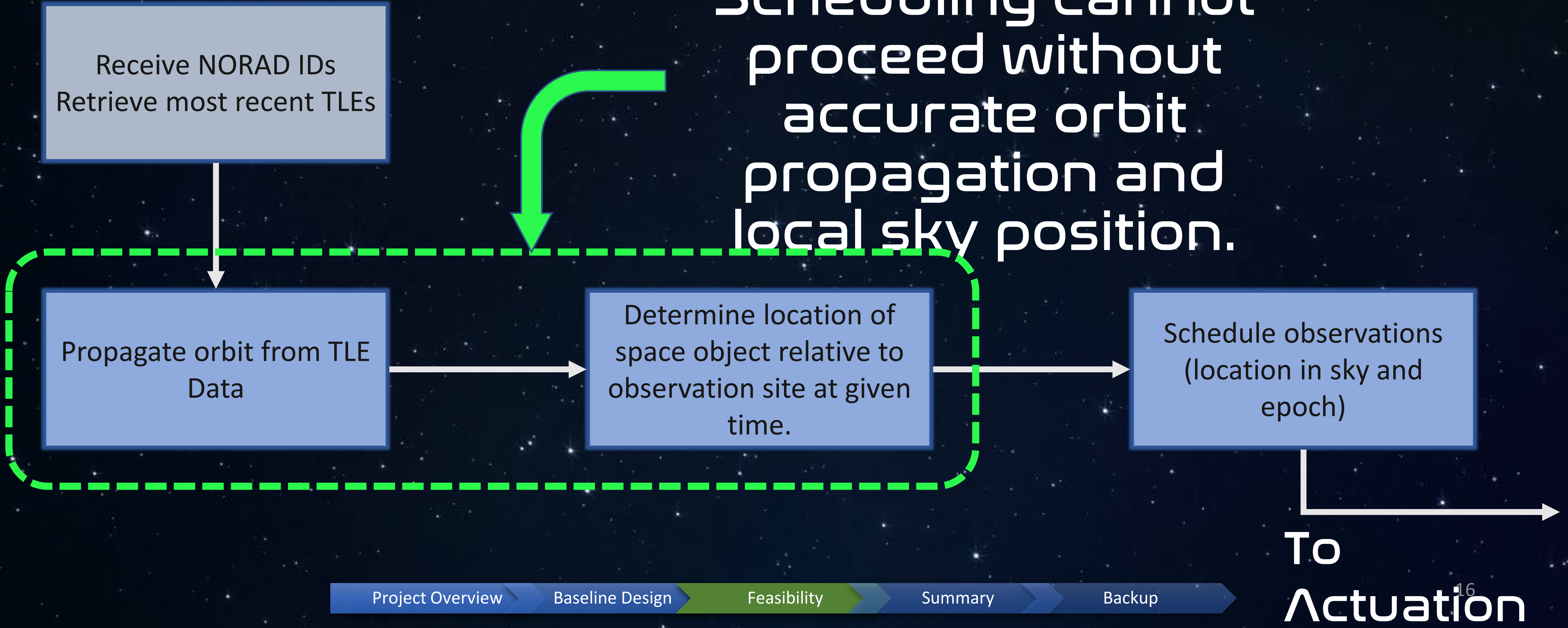
Scheduler Requirements

Requirement		Slide
DR 4.1	The system scheduling software shall be able to schedule imaging tasks given a list of NORAD IDs.	17
DR 4.1.1	The system shall be able to download TLE files from Space-Track.org	17
DR 4.1.3	The system shall propagate a space object’s orbit from a TLE.	18

Scheduler Motivation

Condensed version of Scheduler pipeline:

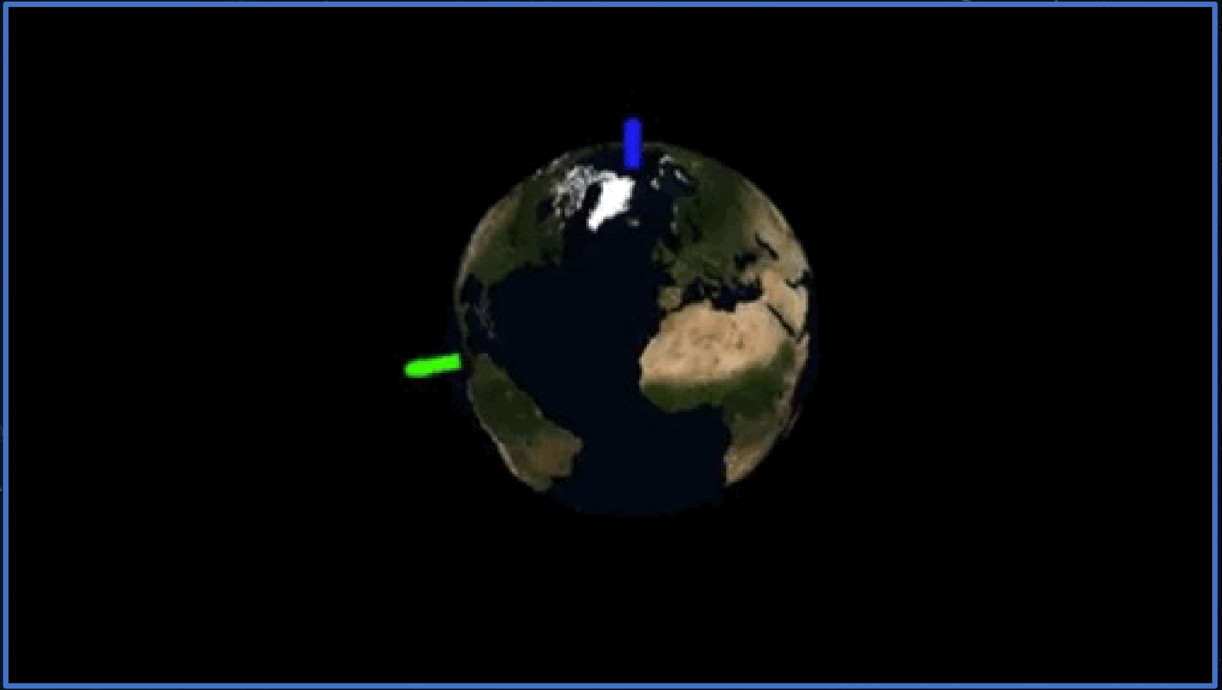
Scheduling cannot proceed without accurate orbit propagation and local sky position.



Scheduler Evidence

Orbit Propagation

- MATLAB ode113 vs GMAT 2BP w/ J2 Perturbation
  - 0.21960 deg error in Azimuth
  - 0.09160 deg error in Elevation

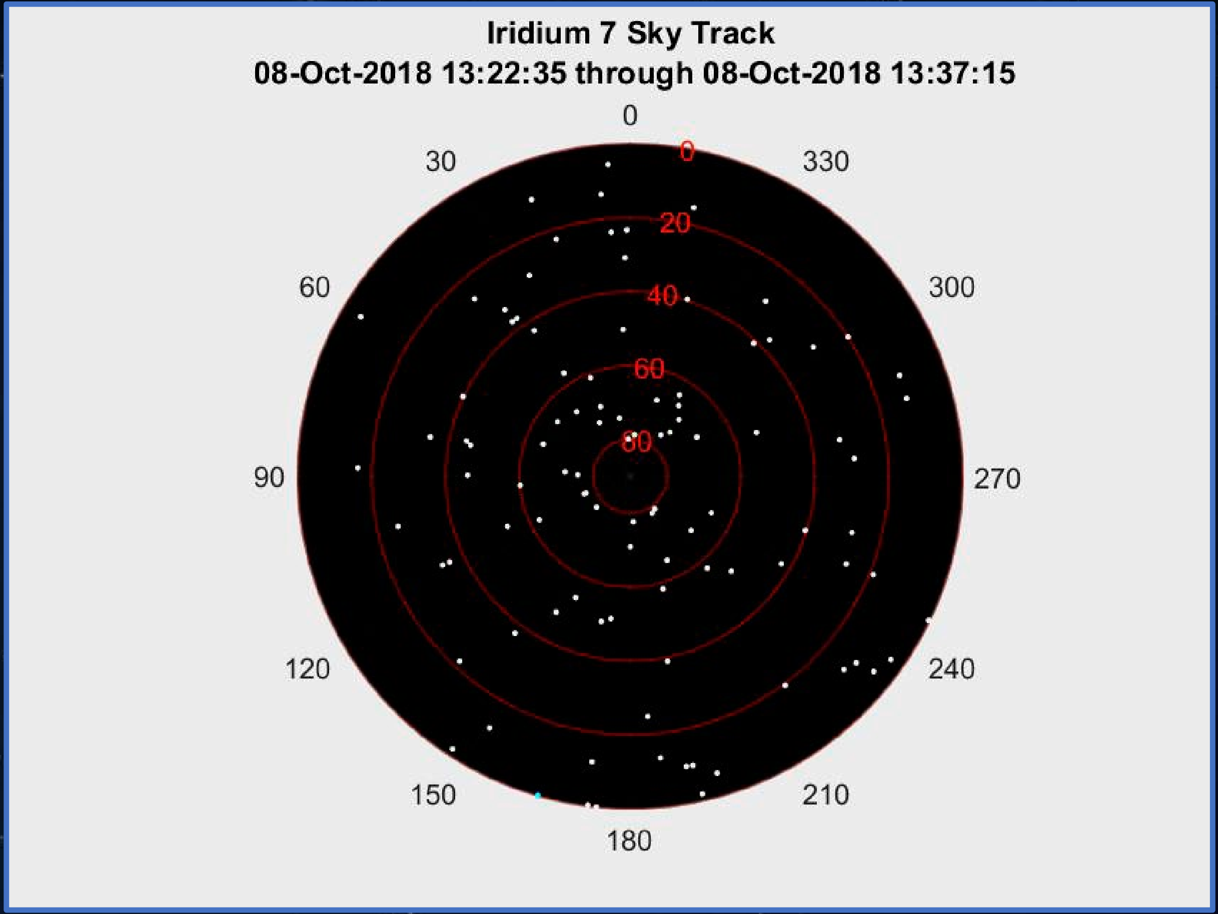


Future Plans

- Explore SGP4

Scheduler Evidence

- Az/El Plot – Evidence that ECI position data can be converted to Azimuth and Elevation.
- These Az/El predictions allow schedule generation.



Scheduler Proof of Feasibility

TLE

↓

ode133

↓

XYZ --> RA/DEC

↓

RA/Dec --> Az/El

DR 4.1: Provide Azimuth, Elevation, and Time predictions for scheduling

YES

DR 4.1.3: Propagate a TLE

YES

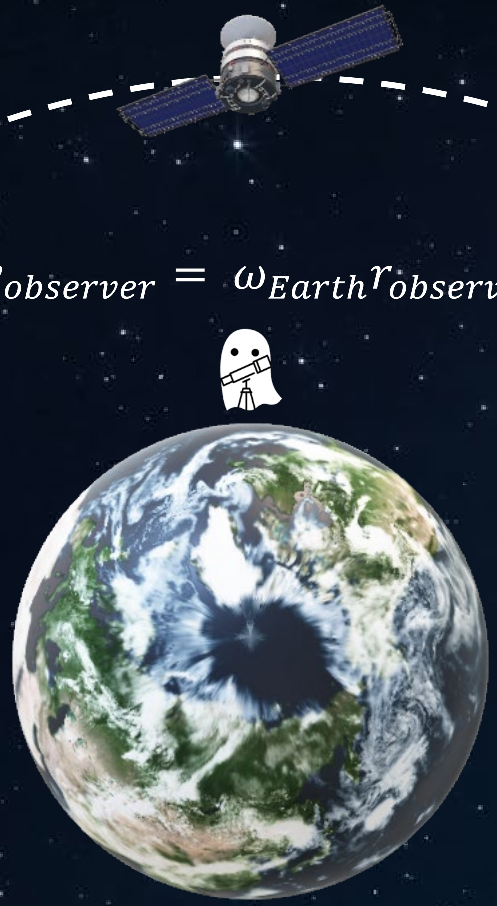
Evidence of Feasibility: Actuation Hardware

Actuation Hardware Requirements

Requirement		Slide
FR 2	The actuation system shall be capable of imaging space objects in GEO, MEO, and LEO orbits.	22
DR 2.1	The mounting subsystem shall be capable of slewing at >= 2 deg/s	23
DR 2.2	The mounting subsystem shall mechanically interface with the imaging subsystem hardware.	24
DR 4.2	The system shall autonomously slew between scheduled pointing locations	24
FR 5	The system shall use commercial-off-the-shelf (COTS) imaging hardware.	24

Actuation Hardware Motivation

$$v_{object} = \sqrt{\frac{\mu_{Earth}}{r_{object}}}$$



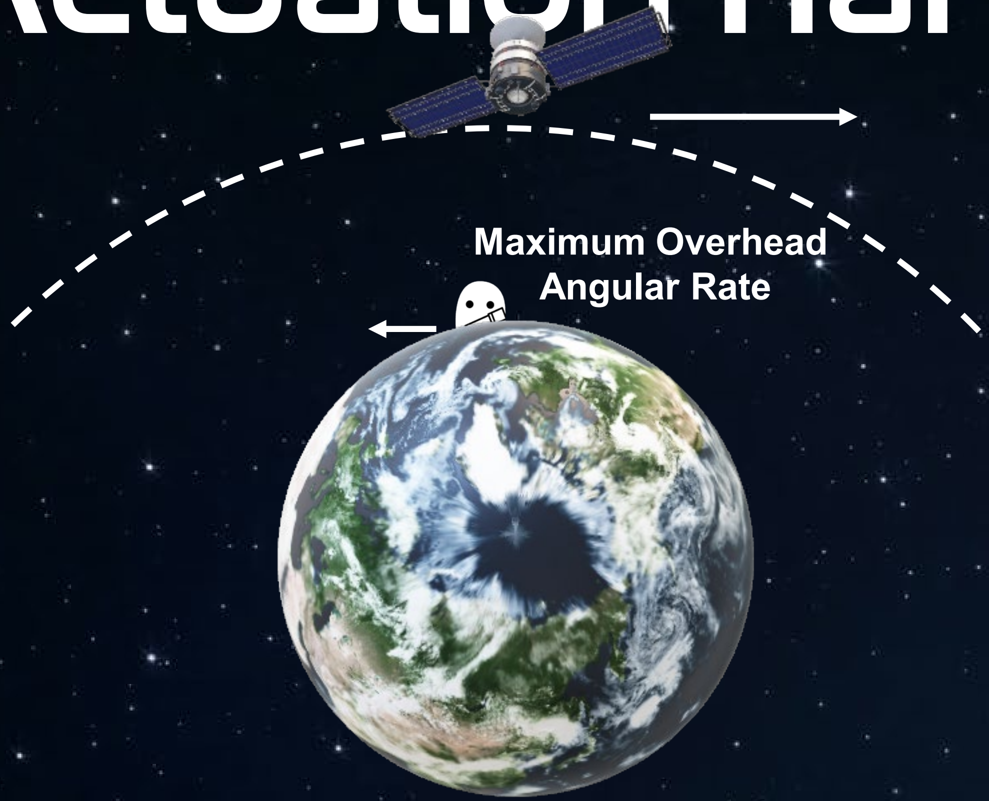
$$v_{observer} = \omega_{Earth} r_{observer}$$

Using the relative velocities:

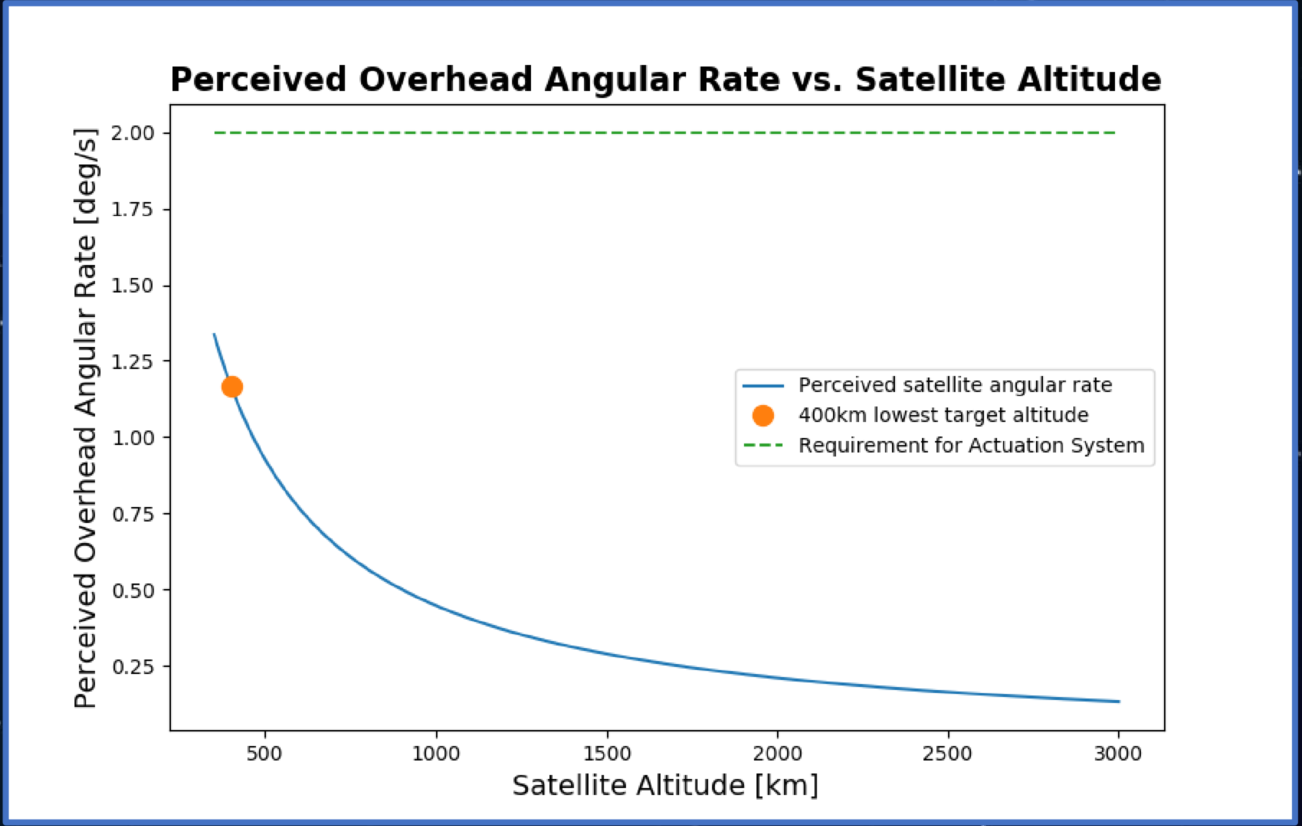
$$\underbrace{v_{apparent}} = v_{object} + v_{observer}$$

$$\boxed{\omega_{apparent} = \frac{v_{apparent}}{h_{object}}}$$

Actuation Hardware Evidence



$$\omega_{apparent} = \frac{v_{apparent}}{h_{object}}$$



Actuation Hardware Evidence

Performance Measure	SkyWatcher EQM-35	iOptron iEQ45
Max Slew Rate	3.4	5.8
Pointing Precision	7 arcseconds	0.09 arcseconds
Hardware Mount	Vixen-Style Saddle	Dual Dovetail Saddle
Data Protocol	ASCOM	ASCOM
Price	$750	$1700

iOptron

SkyWatcher

Actuation Hardware Proof of Feasibility

Requirements met:

FR2 – Track LEO, MEO, GEO objects **YES**

DR2.1 - slew rate >= 2 deg/s **YES**
DR2.2 - dovetail to screw mount adapter . **YES**

DR4.2 - ASCOM communication protocol **YES**

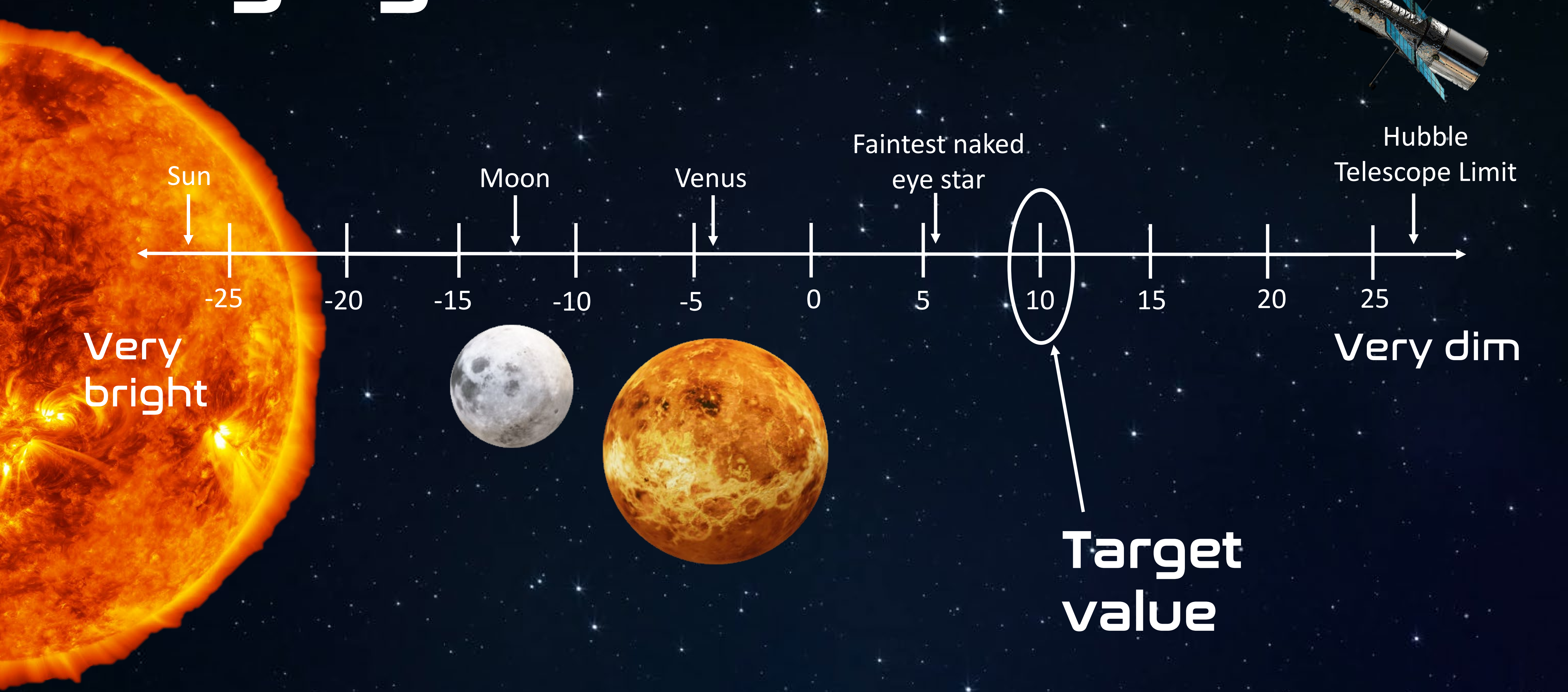
FR5 - all tracking components are COTS **YES**

Evidence of Feasibility: Imaging Hardware

Imaging Hardware
Requirements

Requirement		Slide
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.	32
DR 1.1	The optical system shall have a field of view (FOV) of at least 6 degrees diagonally.	34
DR 1.2	The camera sensor selected shall have a pixel size greater than or equal to 2µm	34
FR 5	The system shall use commercial-off-the-shelf (COTS) imaging hardware	34
DR 5.1	The lens and sensor shall be available within 4 weeks from a U.S. retailer.	34

Imaging Hardware Motivation



Imaging Hardware Motivation

Limiting Stellar Magnitude (LSM)

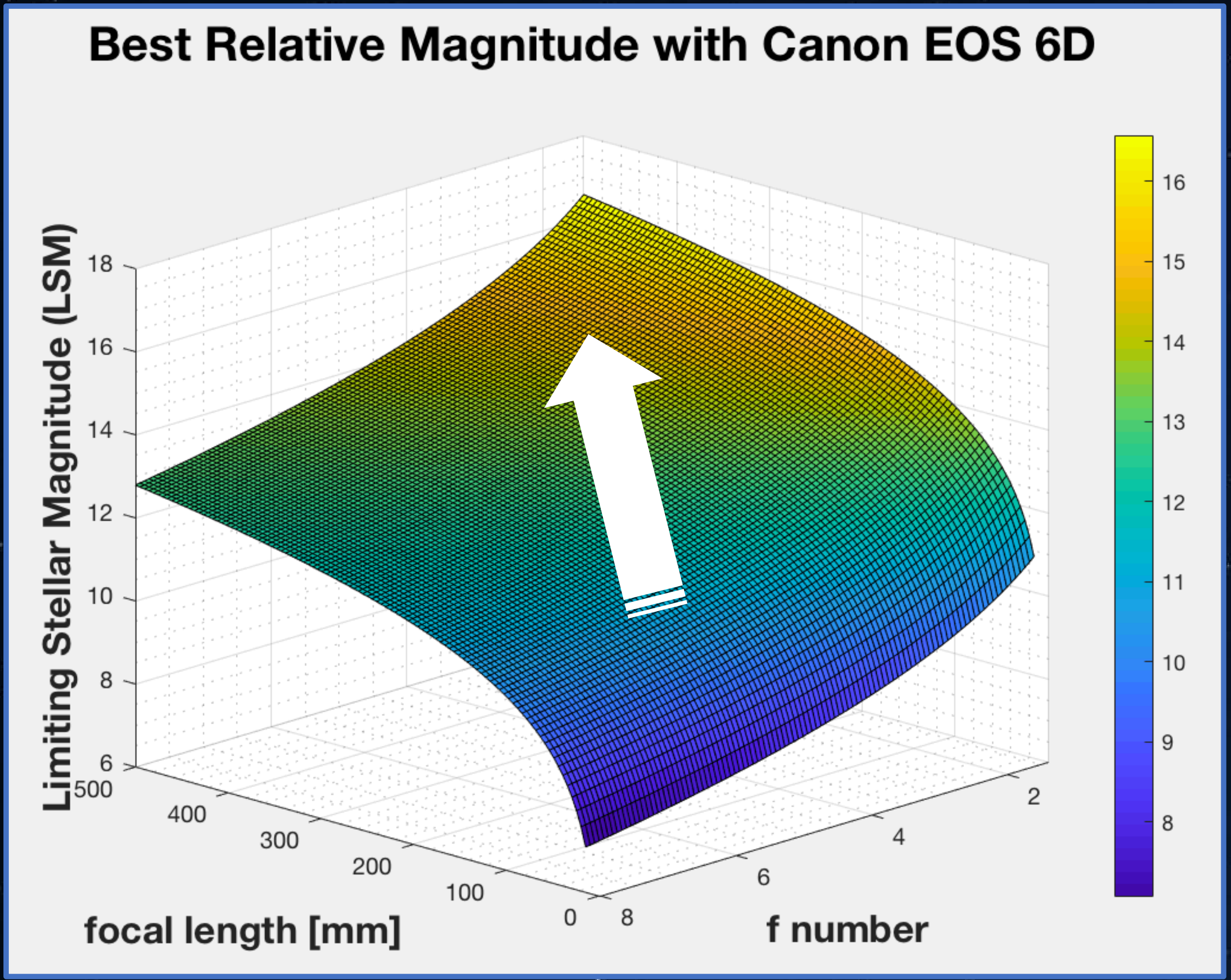
Physics-based model says system can be designed based on 3 parameters

- 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)

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

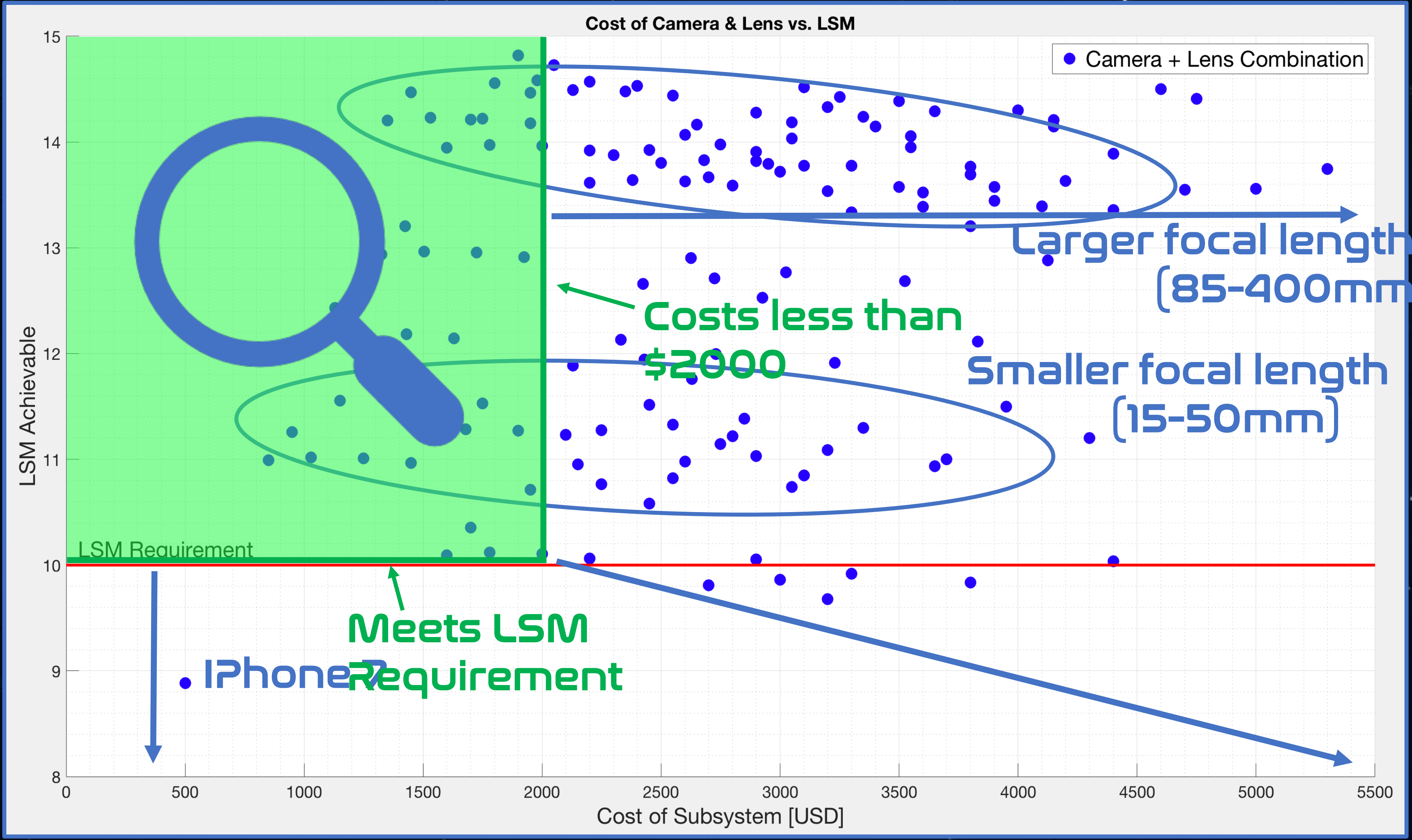
Imaging Hardware Motivation



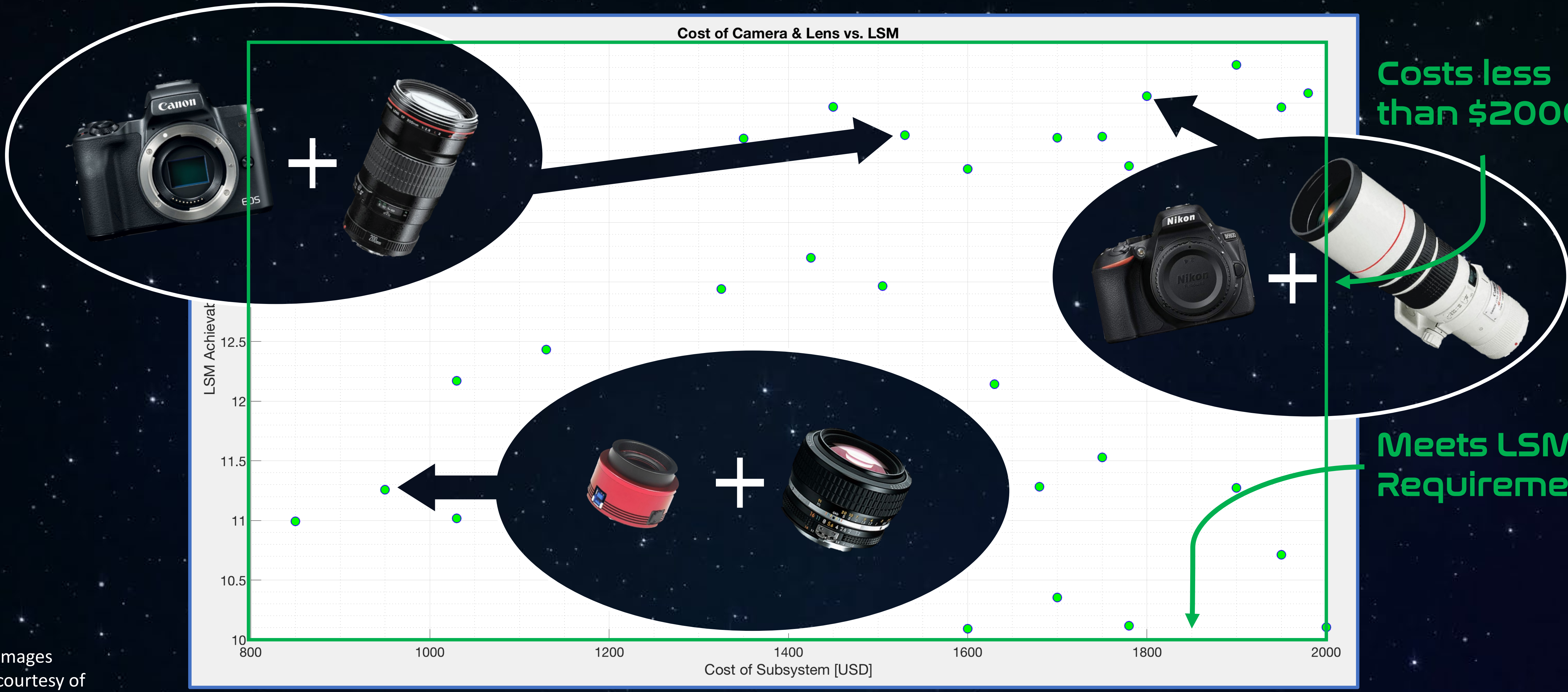
Physics-based model show 2 relevant trends for increasing LSM :

1) Decreasing f-number
2) Increasing focal length

Imaging Hardware Evidence



Imaging Hardware Evidence



Costs less than $200(

Meets LSM Requireme

Images courtesy of Nikon, Canon, Rokinon, and Zwo

Imaging Hardware
Evidence

LSM

Example: Canon EOS M50 and Canon EF 200mm f/2.8

Cost: $1530

Example: Nikon D5600 and Canon EF 400mm f/5.6

Cost: $1800

Example: Zwo Asi183MM and NIKKOR 50mm f/1.2

Cost: $1425

Imaging Hardware Proof of Feasibility

Example: Canon EOS M50 and Canon EF 200mm f/2.8

Limiting Stellar Magnitude, under ideal conditions	14.2	FR 2
Field of View	12°	DR 1.1
Pixel Size	3.7μm	DR 2.2
COTS?	Available Today	DR 5.1 & FR 5

Requirements met:

FR 1, $m_v \geq 10$ **YES**

DR 1.1, FOV≥6° **YES**

DR 1.2, p≥2μm **YES**

FR 5, COTS **YES**

DR 5.1, Avail. within 4 weeks **YES**

Evidence of Feasibility: Image Processing

Image Processing Requirements

Requirement		Slide
DR 3.1	The system shall provide ≥ 6 angular measurements from a single orbit pass.	38
DR 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.	39
DR 3.3.1	The system shall be capable of identifying and rejecting images that cannot be processed for boresight or space object inertial position.	39
DR 4.3	The GHOST module will perform image processing on-board and without operator input.	40

Image Processing Motivation

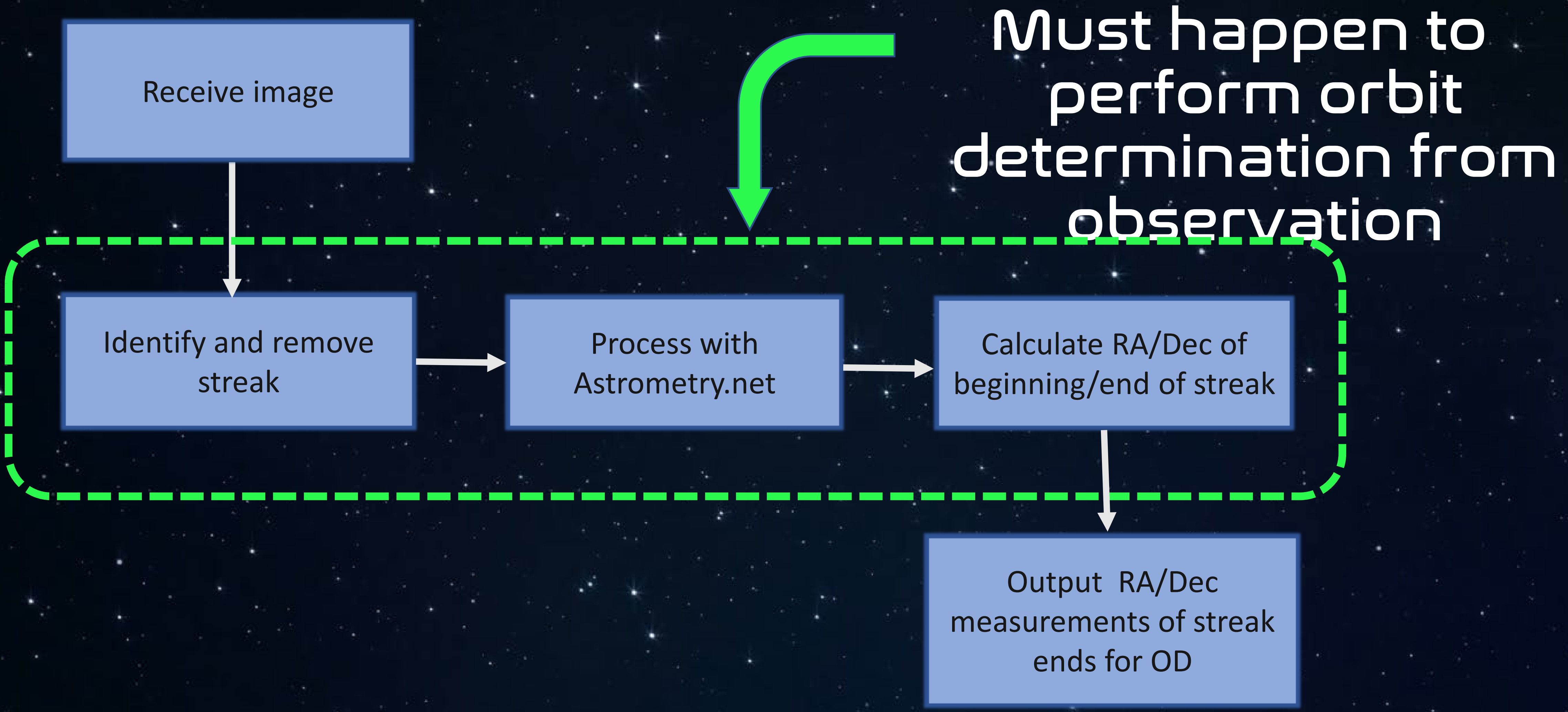


Image Processing Evidence

1. Streak Identification:

- ASTRiDE python package license for commercial and private use posted on GitHub
- "Boundary Tracing"
- Handles long, short, and curved streaks
- "Circularity" parameter can be adjusted

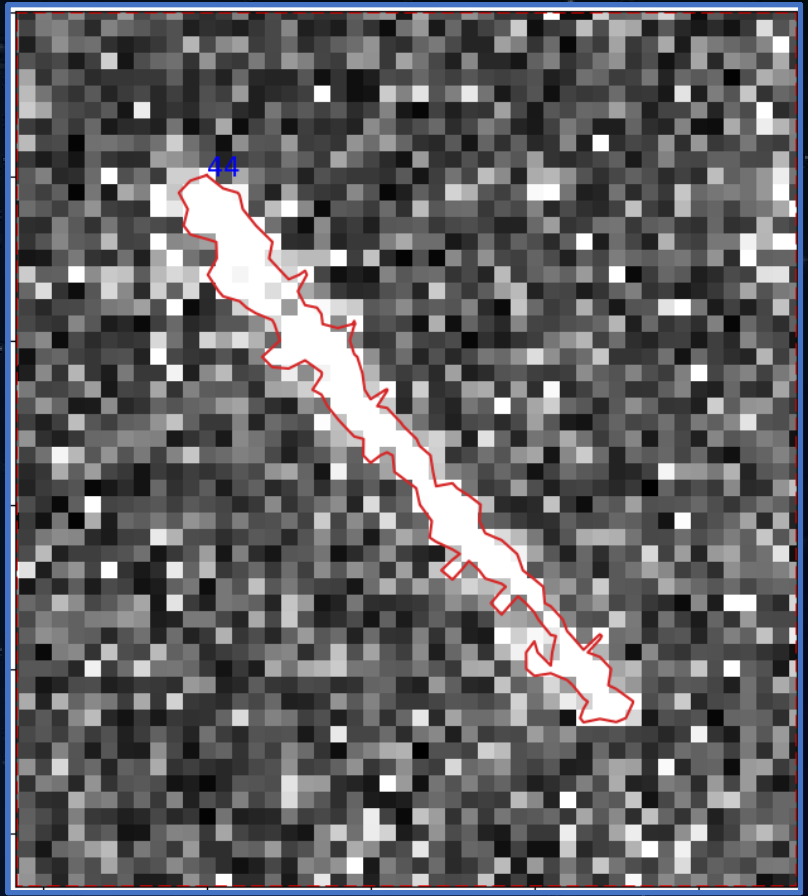
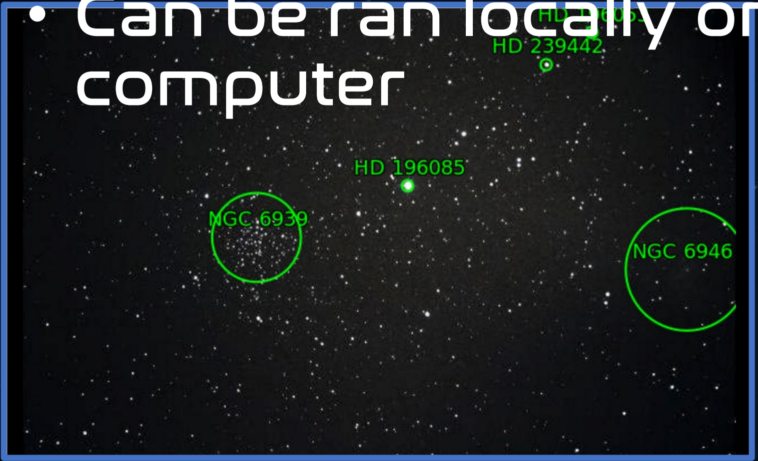


Image from Dr. Holzinger's PhD students. Processed using ASTRiDE

Image Processing Evidence

2. Astrometry.net

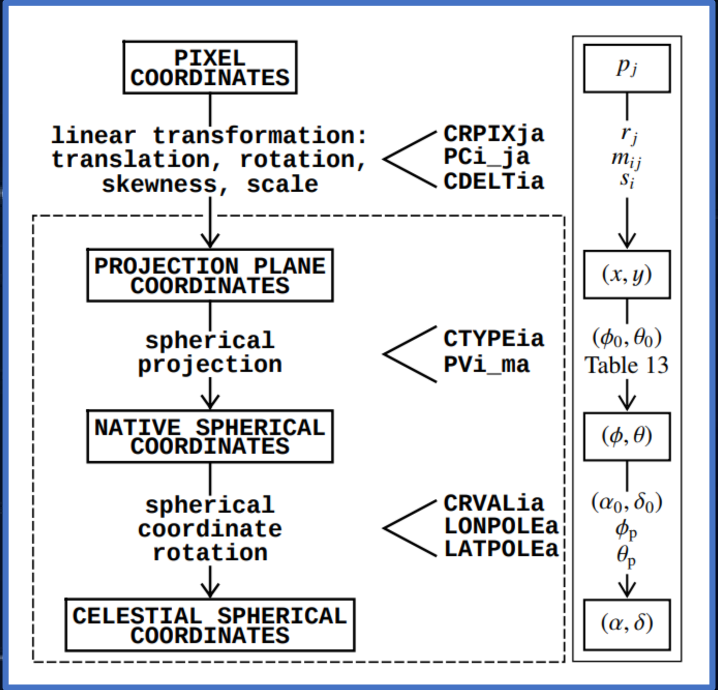
- Compares images to a catalogue of stars using a registration algorithm
- Robust means of identifying RA/Dec of image center
- Can be ran locally on computer



Calibration

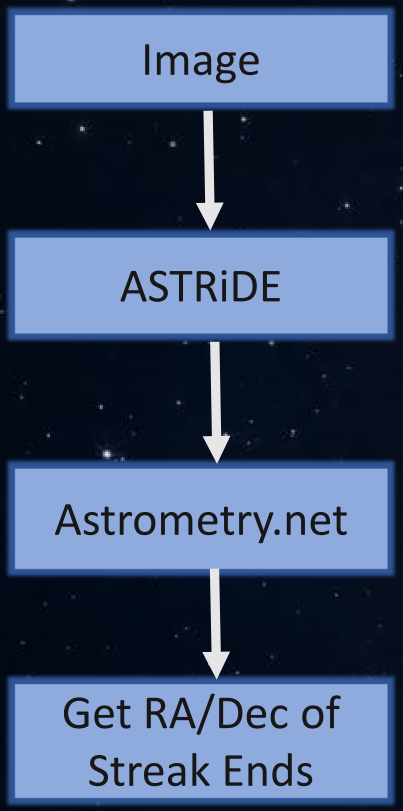
Center (RA, Dec):	(308.110, 60.507)
Center (RA, hms):	$20^h\,32^m\,26.374^s$
Center (Dec, dms):	+60° 30' 26.277"
Size:	64.3 x 42.9 arcmin
Radius:	0.644 deg
Pixel scale:	0.74 arcsec/pixel
Orientation:	Up is 125 degrees E of N

3. Algorithm for converting x,y pixel coordinates to RA/Dec



Algorithm from Calabretta and Greisen [1]

Image Processing Proof of Feasibility



Requirements Met:

DR 3.1, ≥ 6 angular measurements **YES**

DR 3.3, process streak with visual magnitude of ≤ 10 **YES**

DR 3.3.1, reject unfit images **YES**

DR 4.3, run autonomously on-board **YES**

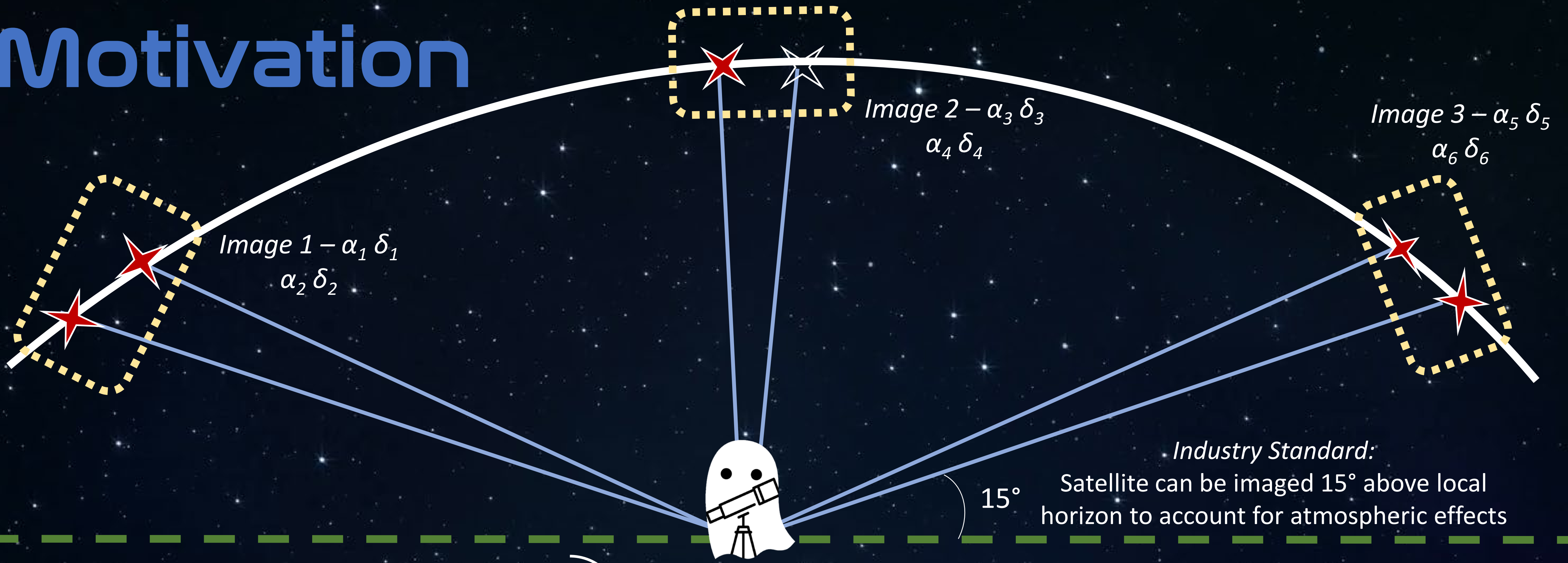
Evidence of Feasibility: Orbit Determination

Orbit Determination Requirements

Requirement		Slide
FR 3	The system shall provide an orbit estimate if there are sufficient observations available	47

Orbit Determination

Motivation



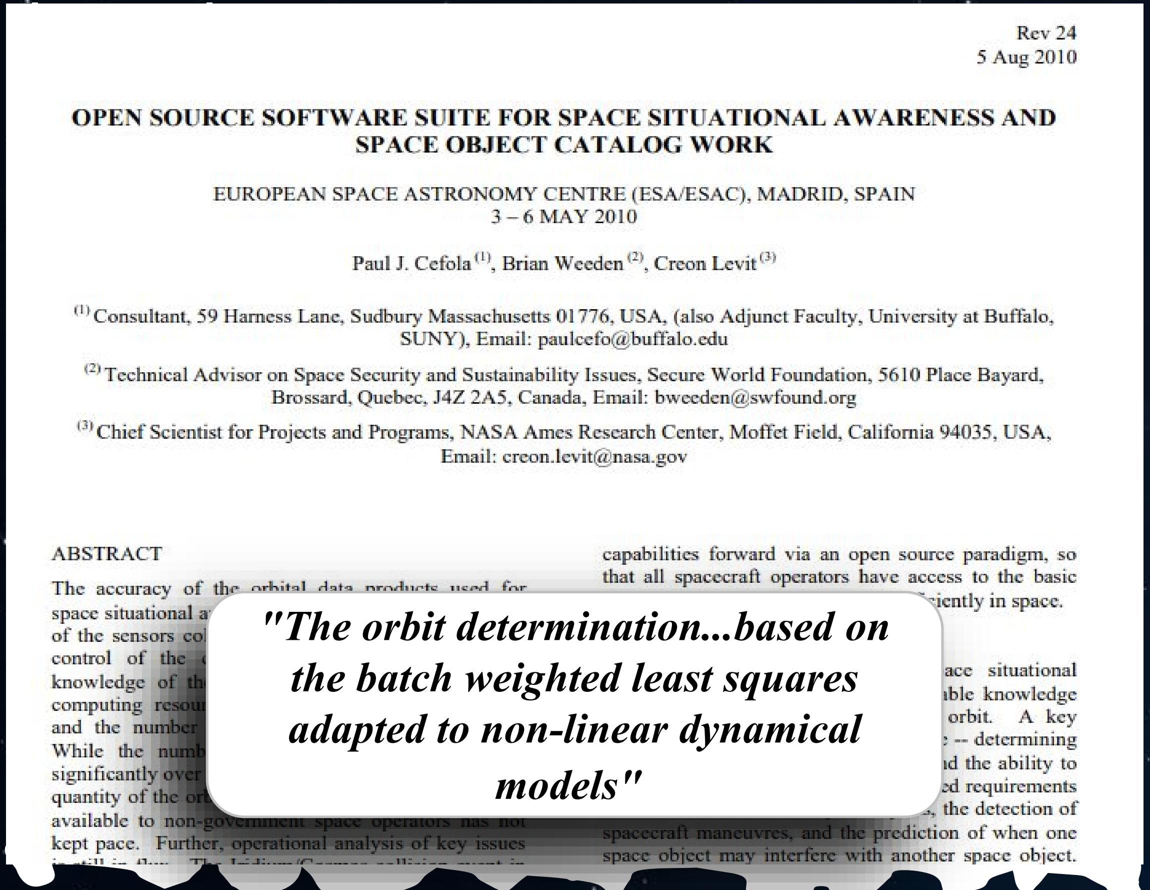
Assuming ideal conditions:
3 Images Captured for each satellite

$\alpha_1\ \delta_1$
$\alpha_2\ \delta_2$
$\alpha_3\ \delta_3$
$\alpha_4\ \delta_4$
$\alpha_5\ \delta_5$
$\alpha_6\ \delta_6$

Observation data to be used:
Minimum of 6 observations needed to fully determine an orbital state

Orbit Determination Evidence

Examples in industry pertaining to optical data processed with non-



Rev 24
5 Aug 2010

OPEN SOURCE SOFTWARE SUITE FOR SPACE SITUATIONAL AWARENESS AND SPACE OBJECT CATALOG WORK

EUROPEAN SPACE ASTRONOMY CENTRE (ESA/ESAC), MADRID, SPAIN
3 – 6 MAY 2010

Paul J. Cefola [1], Brian Weeden [2], Creon Levit [3]

[1] Consultant, 59 Harness Lane, Sudbury Massachusetts 01776, USA, (also Adjunct Faculty, University at Buffalo, SUNY), Email: paulcefo@buffalo.edu

[2] Technical Advisor on Space Security and Sustainability Issues, Secure World Foundation, 5610 Place Bayard, Brossard, Quebec, J4Z 2A5, Canada, Email: bweeden@swfound.org

[3] Chief Scientist for Projects and Programs, NASA Ames Research Center, Moffet Field, California 94035, USA, Email: creon.levit@nasa.gov

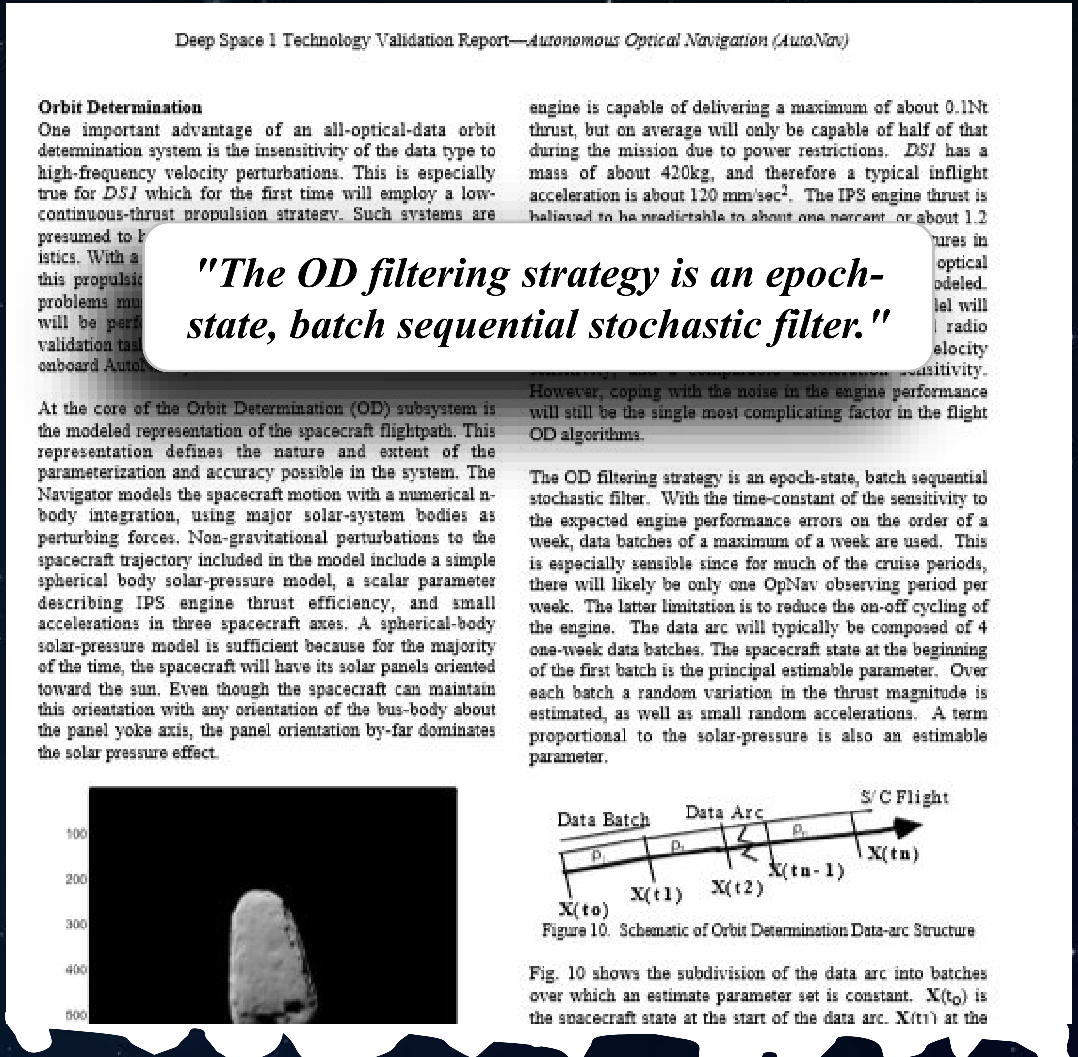
ABSTRACT

The accuracy of the orbital data products used for space situational a... of the sensors col... control of the ... knowledge of th... computing resou... and the number ... While the numb... significantly over... quantity of the or... available to non-government space operators has not kept pace. Further, operational analysis of key issues

capabilities forward via an open source paradigm, so that all spacecraft operators have access to the basic ...iently in space.

...ace situational ...able knowledge ... orbit. A key ... -- determining ...d the ability to ...ed requirements ..., the detection of spacecraft maneuvres, and the prediction of when one space object may interfere with another space object.

"The orbit determination...based on the batch weighted least squares adapted to non-linear dynamical models"



Deep Space 1 Technology Validation Report—*Autonomous Optical Navigation (AutoNav)*

Orbit Determination

One important advantage of an all-optical-data orbit determination system is the insensitivity of the data type to high-frequency velocity perturbations. This is especially true for *DS1* which for the first time will employ a low-continuous-thrust propulsion strategy. Such systems are presumed to b... istics. With a ... this propulsio... problems mu... will be perf... validation tas... onboard Auto...

At the core of the Orbit Determination (OD) subsystem is the modeled representation of the spacecraft flightpath. This representation defines the nature and extent of the parameterization and accuracy possible in the system. The Navigator models the spacecraft motion with a numerical n-body integration, using major solar-system bodies as perturbing forces. Non-gravitational perturbations to the spacecraft trajectory included in the model include a simple spherical body solar-pressure model, a scalar parameter describing IPS engine thrust efficiency, and small accelerations in three spacecraft axes. A spherical-body solar-pressure model is sufficient because for the majority of the time, the spacecraft will have its solar panels oriented toward the sun. Even though the spacecraft can maintain this orientation with any orientation of the bus-body about the panel yoke axis, the panel orientation by-far dominates the solar pressure effect.

engine is capable of delivering a maximum of about 0.1Nt thrust, but on average will only be capable of half of that during the mission due to power restrictions. *DS1* has a mass of about 420kg, and therefore a typical inflight acceleration is about 120 mm/sec^2. The IPS engine thrust is believed to be predictable to about one percent, or about 1.2 ...ures in ... optical ...odeled. ...lel will ... radio ...elocity ...sitivity. However, coping with the noise in the engine performance will still be the single most complicating factor in the flight OD algorithms.

The OD filtering strategy is an epoch-state, batch sequential stochastic filter. With the time-constant of the sensitivity to the expected engine performance errors on the order of a week, data batches of a maximum of a week are used. This is especially sensible since for much of the cruise periods, there will likely be only one OpNav observing period per week. The latter limitation is to reduce the on-off cycling of the engine. The data arc will typically be composed of 4 one-week data batches. The spacecraft state at the beginning of the first batch is the principal estimable parameter. Over each batch a random variation in the thrust magnitude is estimated, as well as small random accelerations. A term proportional to the solar-pressure is also an estimable parameter.

Data Batch, Data Arc, S/C Flight, X(to), X(t1), X(t2), X(tn-1), X(tn)

Figure 10. Schematic of Orbit Determination Data-arc Structure

Fig. 10 shows the subdivision of the data arc into batches over which an estimate parameter set is constant. $X(t_0)$ is the spacecraft state at the start of the data arc. $X(t_1)$ at the

"The OD filtering strategy is an epoch-state, batch sequential stochastic filter."

Paper courtesy of the ESA

Paper courtesy of JPL

Orbit Determination Evidence

NON-LINEAR BATCH FILTERING:

Non-Linear: dynamical model of an orbit:

$$\ddot{\vec{r}} = -\frac{\mu}{r^3}\vec{r}$$

- ***LINEARIZE*** model through a Taylor series
  - TLE's provide initial guess
  - Minimize difference between TLE initial guess and known observations
- ***ITERATE*** until a threshold is met

WEIGHTED MEASUREMENTS:

- ***WEIGH*** more confident measurements
- ***SOLVE*** for *weighted solution state:*

$$\hat{X} = PA^T Wb$$

Orbit Determination Evidence

A fully defined orbit requires **6** variables:

Keplerian elements:

a	e
i	Ω
ω	θ^*

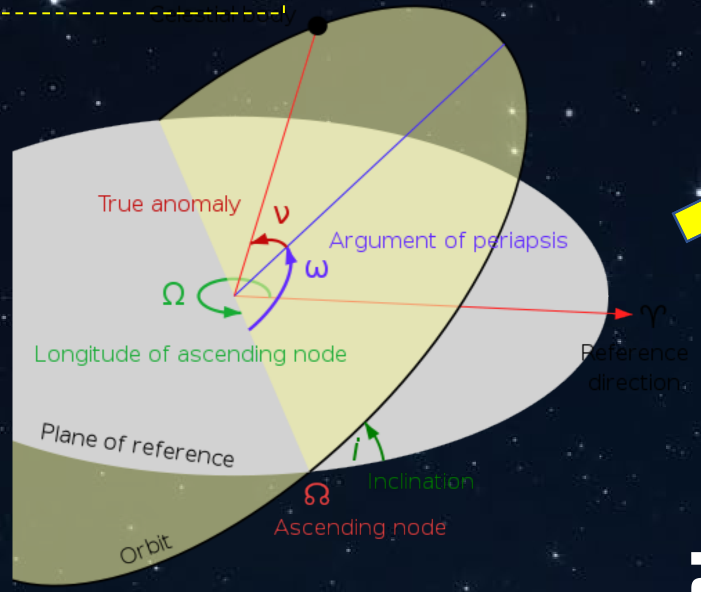
Cartesian elements:

r_x	v_x
r_y	v_y
r_z	v_z

Either/Or

Orbit Determination Proof of Feasibility

Orbital State



Non-linear batch filtering on observations

Output to GHOST Global Network and Traffic Management

Requirements met:

FR 3, return orbit state: YES

Summary of Feasibility

Feasibility Summary

◊ Scheduler **FEASIBLE**
- ◊ Orbit propagation of a TLE can lead to an Az/El of the space object in observer's local sky as a function of time.
- ◊ Scheduler will prioritize where imaging hardware points based on which space object appears first in observer's local sky chronologically.

◊ Actuation Hardware **FEASIBLE**
- ◊ Available COTS options within the given budget have the required slew rate and pointing accuracy
- ◊ Mechanical interfacing can be done with an adapter and data transmission is standardized with the ASCOM protocol

◊ Imaging Hardware **FEASIBLE**
- ◊ Available options meeting FR1 fall within budget constraints
- ◊ All options considered are COTS and available from U.S. retailers in 4 weeks.

◊ Image Processing **FEASIBLE**
- ◊ Available software for detecting streaks and calculating RA/Dec
- ◊ Known algorithms for converting pixel locations to RA/Dec

◊ Orbit Determination **FEASIBLE**
- ◊ The non-linear batch algorithm is understood by the GHOST team.

Project Logistics: Power & Budget

Power

Power Consuming Devices:

- Camera
- Actuation Mount
- Computer
- Lighting

100 W 42000 mAh

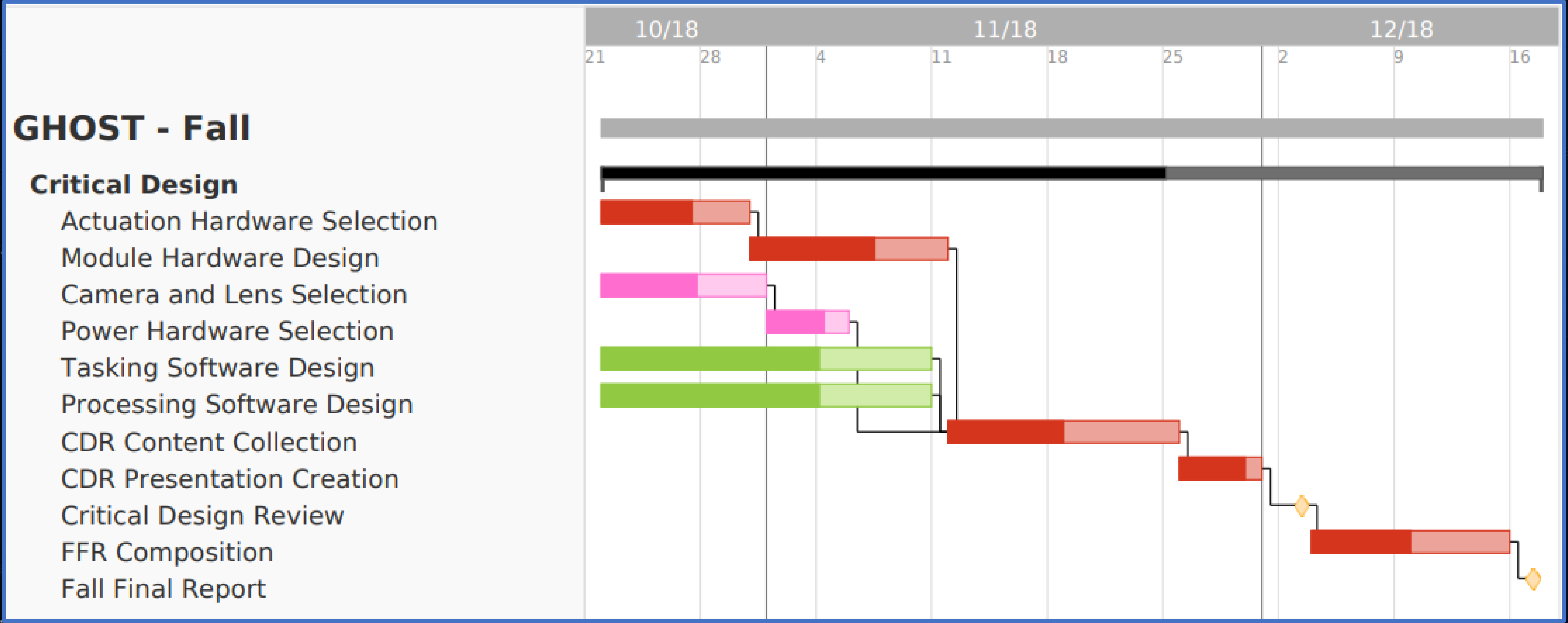
Satisfies power requirement FR 6

Budget

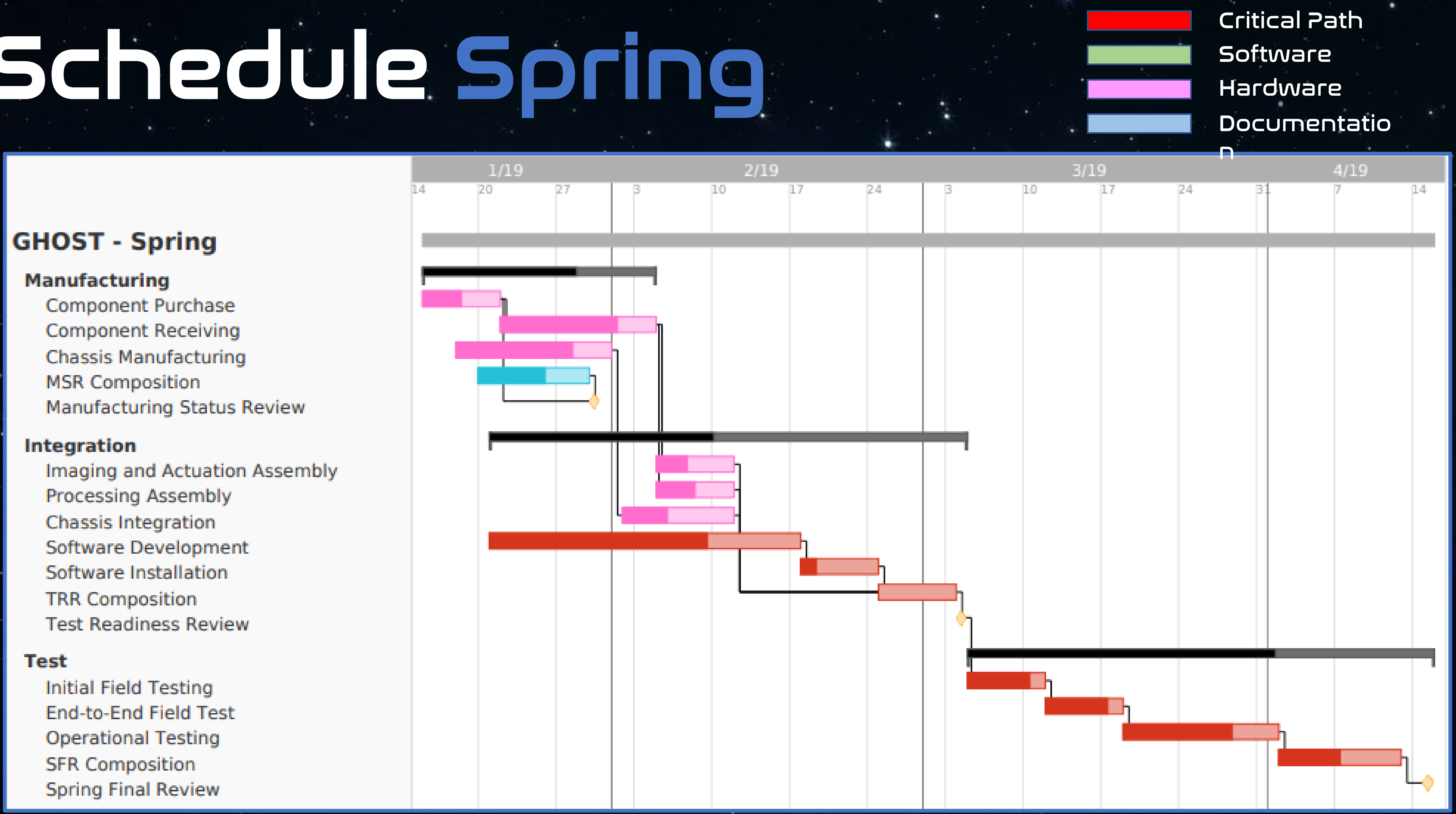
Subsystem	Example Minimum Capable	Cost	Budget	Margin
Camera and Lens	Nikon D5600 Rokinon 35mm f/1.4	$1050	$2000	$950 (48%)
Actuation System	Sky-Watcher EQM-35	$725	$1500	$775 (52%)
Chassis and Mounting Hardware	Actuation system incl. tripod	$100	$500	$400 (80%)
Processing System	ODROID-XU4	$75	$300	$225 (75%)
Power and Distribution Network	120v Portable Power Pack Basic Wiring	$150	$200	$50 (25%)
GPS	SIM868 GMR GPRS GPS Module	$200	$500	$300 (60%)
Total		**$2300**	**$5000**	**$2700 (54%)**

Schedule Fall

Critical Path
Software
Hardware
Documentation



Schedule Spring



Acknowledgements

GHOST would like to thank the following for assistance and contributions…

- Dr Holzinger
- Dr Jackson
- Project Advisory Board
- Ian Cooke
- Sam Fedeler
- Shez Virani
- Stefano Bonasera
- HEPCATS Team
- RAPTR Team

Questions?

Sources

- Slide Background Links:
  - https://www.reddit.com/r/dankmemes/comments/9gn4qq/picture_is_irrelevant_bring_back_the_stefan_karl/
  - http://audiosoundclips.com/wp-content/uploads/2015/03/Stars-Space-Effect-Background-HD.mp4

Acronyms

Acronym	Definition
Az & El	Azimuth and Elevation
CONOPS	Concepts of Operations
COTS	Commercial Off The Shelf
DR	Derived Requirement
DSLR	Digital Single Lens Reflex
EKF	Extended Kalman Filter
FBD	Functional Block Diagram
FOV	Field of View
FR	Functional Requirement
GEO	Geosynchronous Orbit

Acronym	Definition
GHOST	Ground Hardware for Optical Space Tracking
GPS	Global Positioning System
IOD	Initial Orbit Determination
LEO	Low Earth Orbit
LKF	Linearized Kalman Filter
MEO	Middle Earth Orbit
NTP	Network Time Protocol
OD	Orbit Determination
PPP	Precise Point Positioning

Acronym	Definition
RTK	Real-Time Kinematics
SSA	Space Situational Awareness
STK	Systems Tool Kit
STM	Space Traffic Management
TBD	To Be Determined
TLE	Two-line Element
RA	Right Ascension
RSO	Resident Space Object
RTK	Real-Time Kinematic
UTC	Coordinated Universal Time

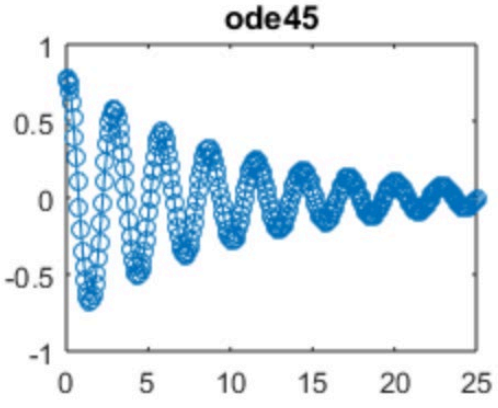
Retrieving TLEs

- Remotely accessing space-track.org TLE catalog
- Interfacing with space-track.org API
- Request most recent, or possibly the 5 most recent, TLEs for each space object

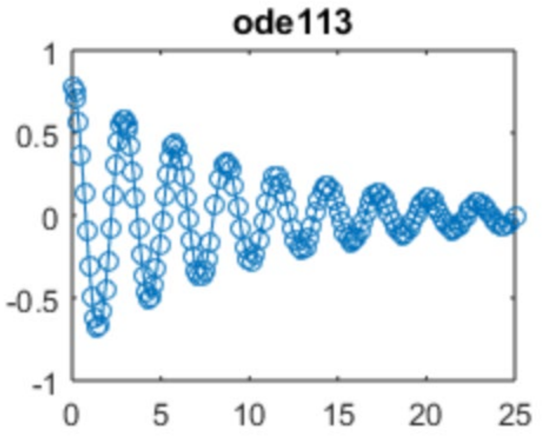
Orbit Propagation

- "ode113 is a multi-step solver and is preferred over ode45 if the function is expensive to evaluate, or for smooth problems where high precision is required. For example, ode113 excels with orbital dynamics and celestial mechanics problems." –mathworks.com

```
Stats for ode45:
75 successful steps
0 failed attempts
451 function evaluations
Elapsed time is 0.011970 seconds.
```




```
Stats for ode113:
159 successful steps
3 failed attempts
322 function evaluations
Elapsed time is 0.018056 seconds.
```



J2 Perturbation Implementation

- 2-Body Equation of Motion:

$$\ddot{\vec{r}} = \frac{-\mu}{|\vec{r}|^3}\vec{r}$$

- 2-Body w/ J2 Equation of Motion:

$$\ddot{\vec{r}} = \frac{-\mu}{|\vec{r}|^3}\vec{r} + \frac{J_2}{|\vec{r}|^7}\begin{bmatrix} r_1\left(6{r_3}^2 - \frac{3}{2}\left({r_1}^2 + {r_2}^2\right)\right) \\ r_2\left(6{r_3}^2 - \frac{3}{2}\left({r_1}^2 + {r_2}^2\right)\right) \\ r_3\left(3{r_3}^2 - \frac{9}{2}\left({r_1}^2 + {r_2}^2\right)\right) \end{bmatrix}$$

SGP4 Dynamics Model

Simplified General Perturbations Model

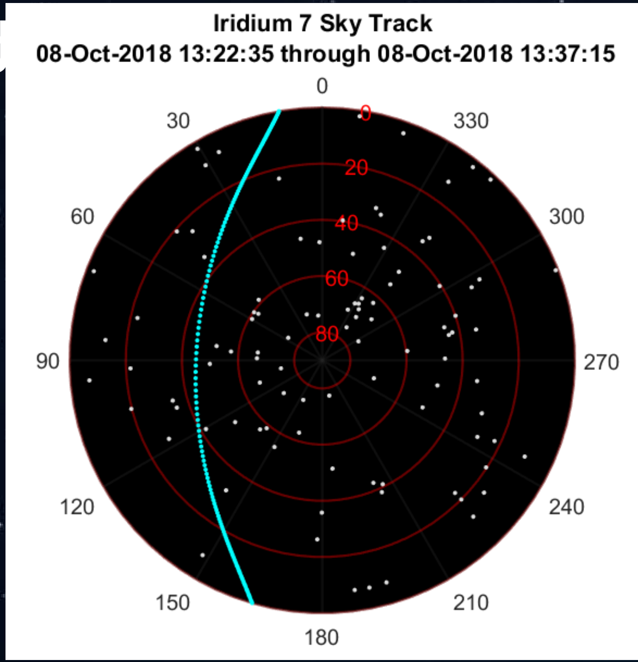
- Incorporates resonances, third-body forces, atmospheric drag, and other perturbations.

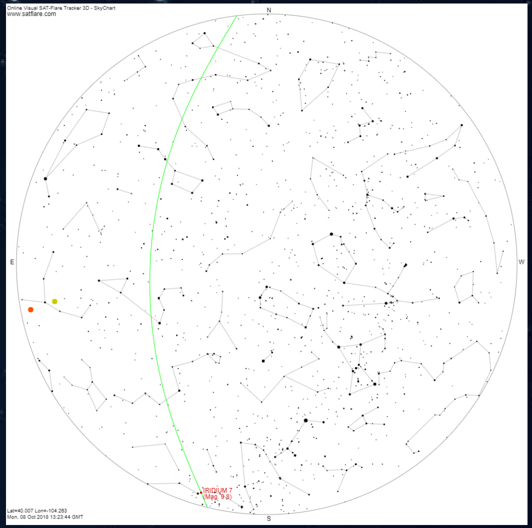
Legacy

- Developed by the Air Force initially
- Widely used by amateurs satellite trackers and researchers alike
- Most common practice for propagating TLEs
- Open source!

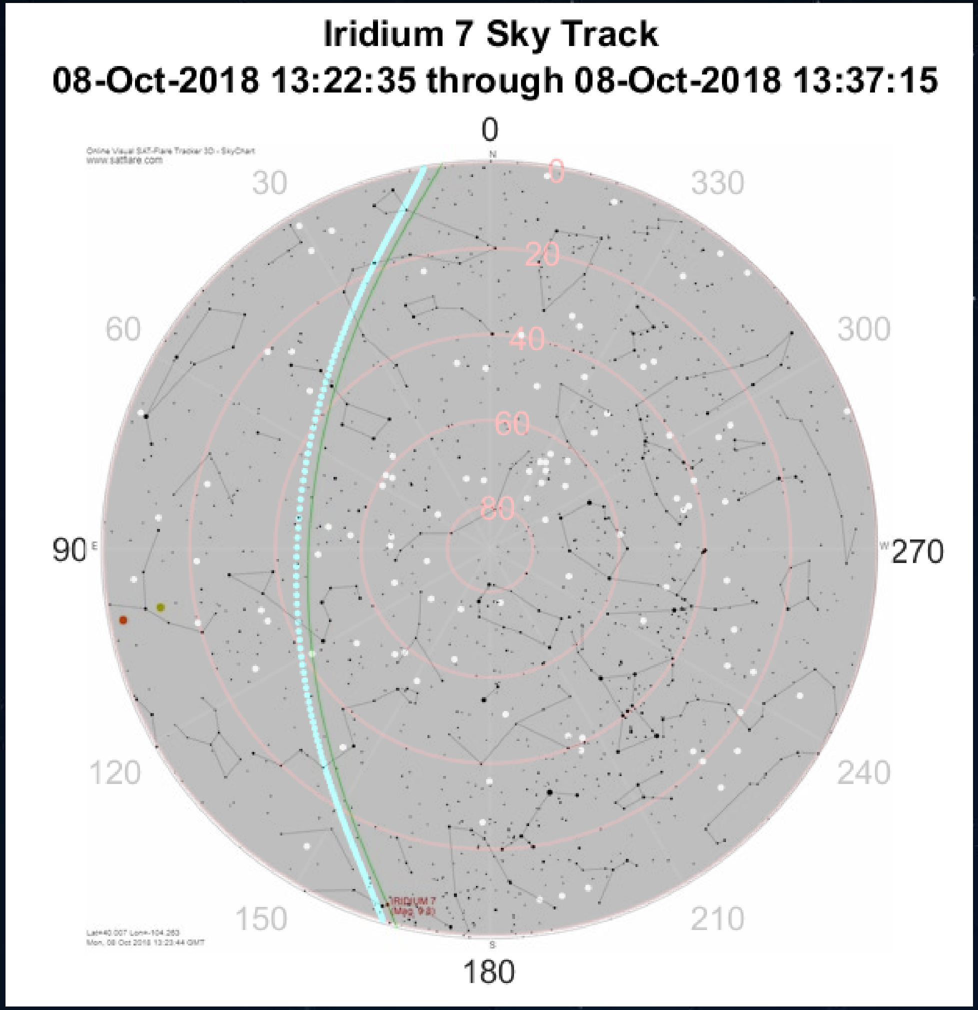
Az/El Tentative Validation

- When compared to data from www.satflare.com, Azimuth and Elevation predictions hold up reasonably well.
- It's not clear how satflare collects data, and does not provide data files for comparison
- Side by sid dicate at least correct shape and timing





Az/El Tentative Validation



Site Position

Topocentric RA/Dec calculations require $\boldsymbol{r}_{siteECI}$, the position of the observation site in ECI coordinates. $\left(\lambda, \phi, JD0, alt \Rightarrow \boldsymbol{r}_{siteECI}\right)$

$$T_0 = (JD0 - 2451545)/36525$$

$$\theta_{GMST} = 100.4606148° + 36000.77004T_0^2 + 0.000387933T_0^3 - 2.8 \times 10^{-8}\mathrm{T}_0^3$$

$$LST = \theta_{GMST} + \lambda$$

$$\vec{r}_{siteECI} = (R_E + alt)\begin{pmatrix} cos\phi \cos LST \\ cos\phi \sin LST \\ sin\phi \end{pmatrix}$$

Topocentric RA/Dec

- Calculating Az/El requires Topocentric RA/Dec. Using Modified Algorithm 26, Vallado 4th Ed. $(\vec{r}_{ECI}, \vec{r}_{siteECI} \Rightarrow \alpha_t, \delta_t)$

$$\vec{\rho}_{ECI} = \vec{r}_{ECI} - \vec{r}_{siteECI}$$

$$\sin \delta_t = \frac{\rho_k}{\rho_{ECI}}$$

$$\tan \alpha_t = \frac{\rho_J}{\rho_I}$$

Converting Topocentric RA/Dec to Az/El

- From an example on p267 of Vallado 4th Ed. $(\theta_{LST}, \alpha_t, \delta_t, \phi \Rightarrow \beta, el)$, using RaDec2AzEl.m by Darin C. Koblick (FileExchange)

$$LHA = \theta_{LST} - \alpha_t$$

(Local Hour Angle)

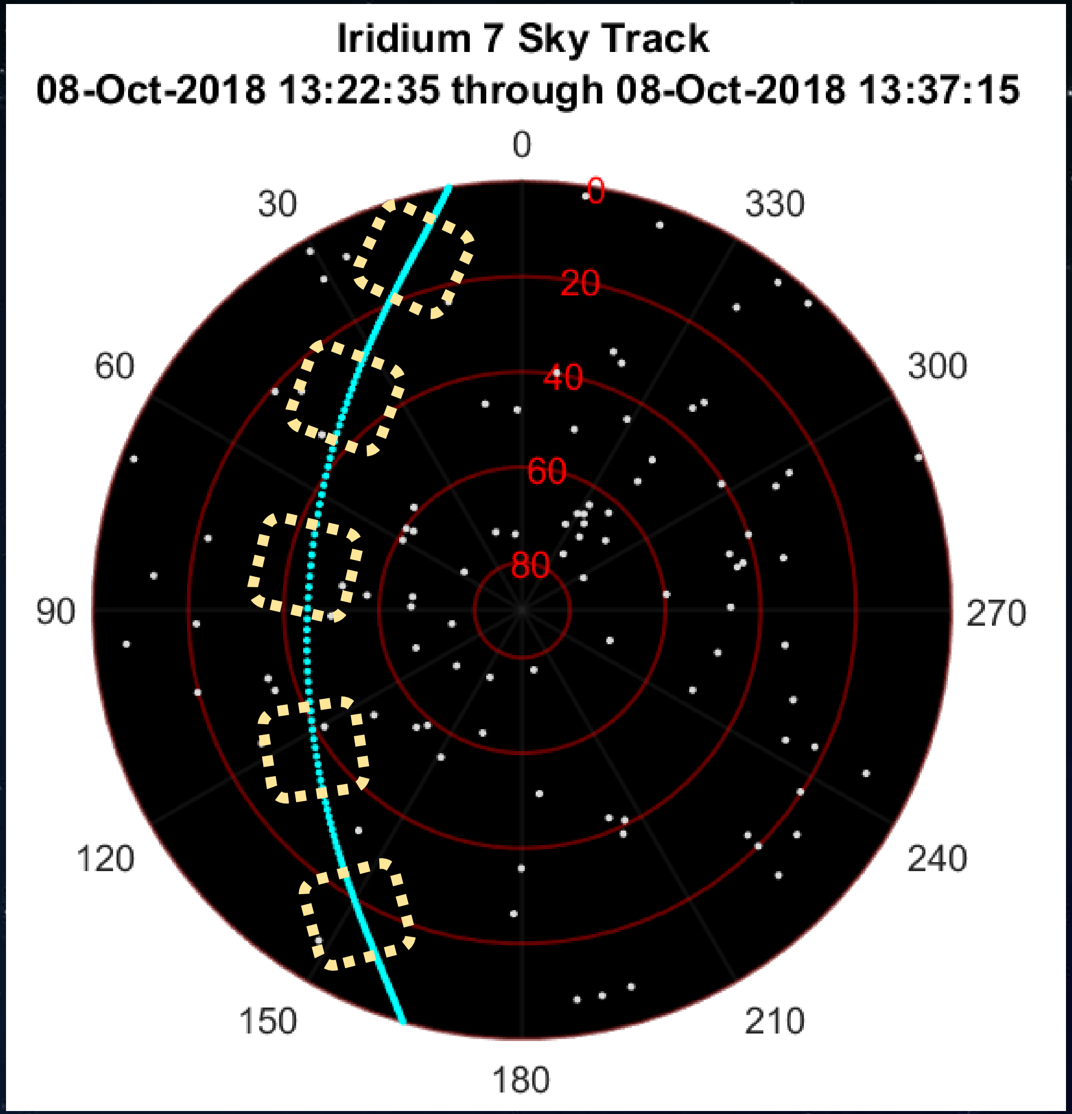
$$\sin el = \sin\phi \sin\delta_t + \cos\phi \cos\delta_t \cos LHA$$

$$\tan\beta = \frac{\dfrac{-\sin LHA \cos\delta_t}{\cos el}}{\dfrac{\sin\delta_t - \sin el \sin\phi}{\cos el \cos\phi}}$$

Scheduling Plan

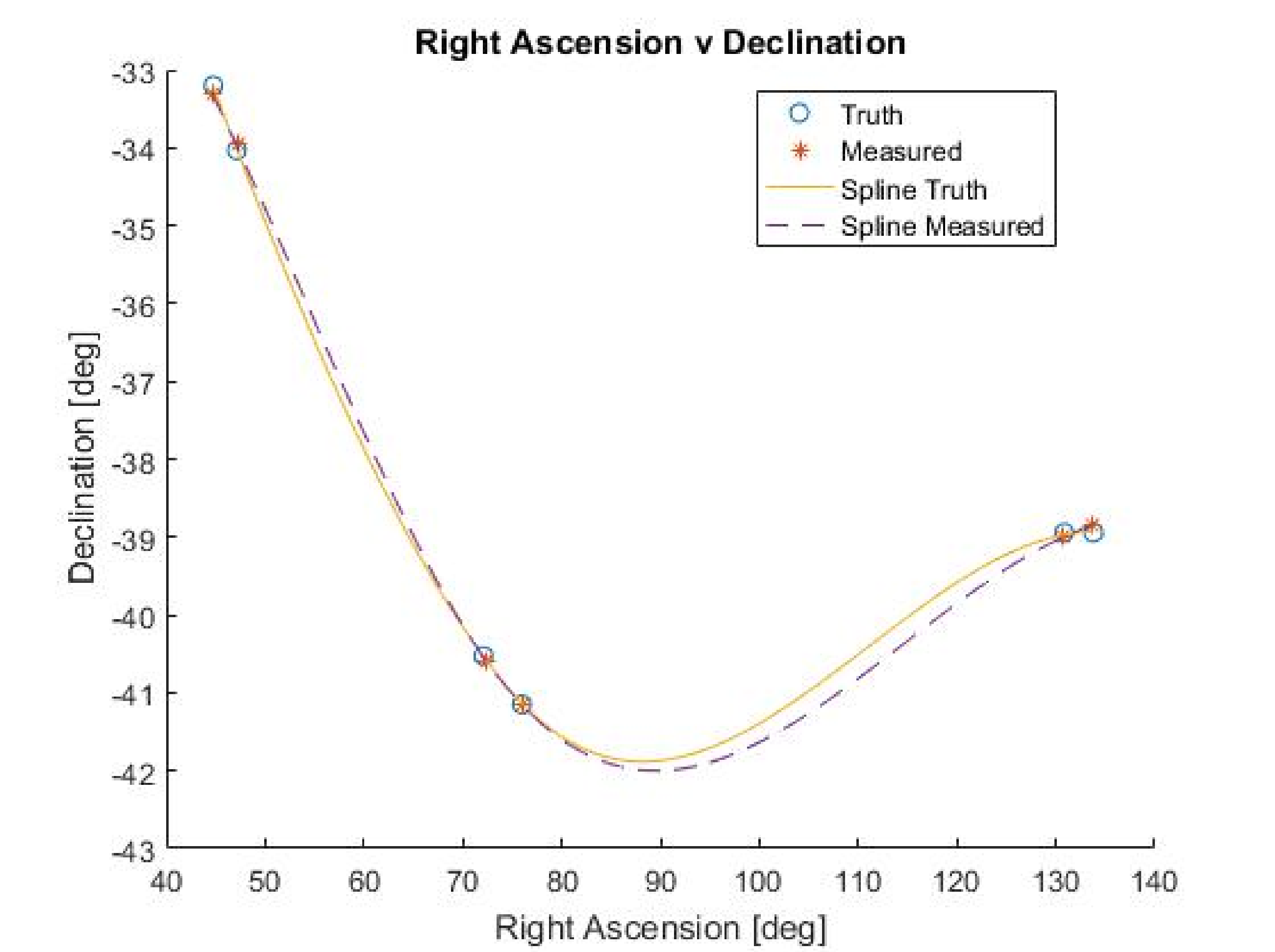
Fore each requested object:

- Propagate orbit from TLE
- Determine times and locations of possible observations
  - Is it in the Az/El plot?
- Plan observations to encourage many unique measurements (driven by OD)
- Resolve conflicts as they occur
  - Cancel observations



Orbit Determination

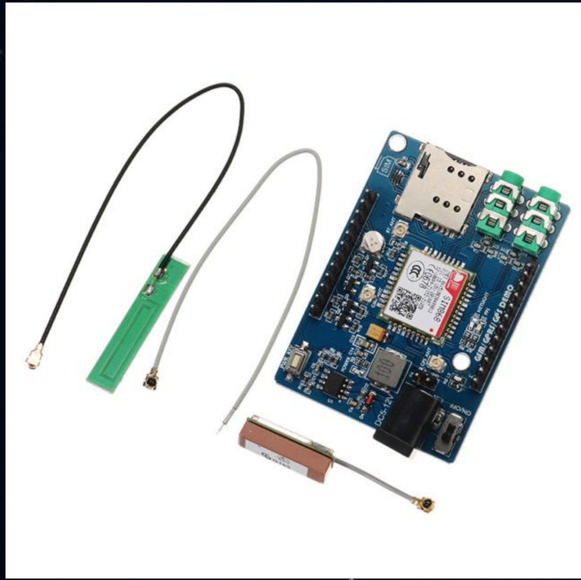
- Non-Linear Batch filtering in this context is an estimation method that uses the probability distributions of the different sources of error to estimate the state of the space object being observed.
- As an initial study, spline curve fitting was used to approximate how results vary with different RA/Dec



Position and Timing

- PPP GPS Receiver

Requireme nt	Description	Met
DR 3.2	The system shall provide timing with a precision of 5 milliseconds	YES
DR 4.5	The system shall know its own geodetic latitude, longitude, and altitude (wrt WGS84 ellipsoid) to an accuracy of 10 meters	YES



SIM868 GSM GPRS GPS
Receiver
$36.99

Electron flux computation (from Shell)

Assume background apparent magnitude Mb = 20

$$L_b = 5.6 \times 10^{-0.4Mb} \cdot \left(\frac{180}{\pi}\right)^2 \cdot 3600^2 \;\; [ph/sec/m^2/sr] \; = \; 2.3825e13$$

Background photon incident rate on a pixel of leg length x

$$P_N = \frac{\tau \cdot \pi \cdot L_b}{\left[1 + 4\left({}^{f}/_{d}\right)^2\right]} \cdot x^2 \;\; [ph/sec]$$

And $P_N = \; q_{p,sky}$

Limiting Stellar Magnitude

Making assumptions and choosing values:

$$m_i \sim 50 \text{ pixels}$$

$$q_{p,sky} \sim 120 \ \frac{\mathrm{e^-}}{\mathrm{s/pixel}}$$

$$q_{p,dark} \sim 0.2 \ \frac{\mathrm{e^-}}{\mathrm{s/pixel}}$$

$$\mathrm{SNR}_{alg} = 6$$

$$\tau_{atm} = 0.69$$

$$\tau_{opt} = 0.90$$

$$QE = 0.5$$

$$\omega = 7.27 \text{ x } 10^{-5} \mathrm{rad/s}$$

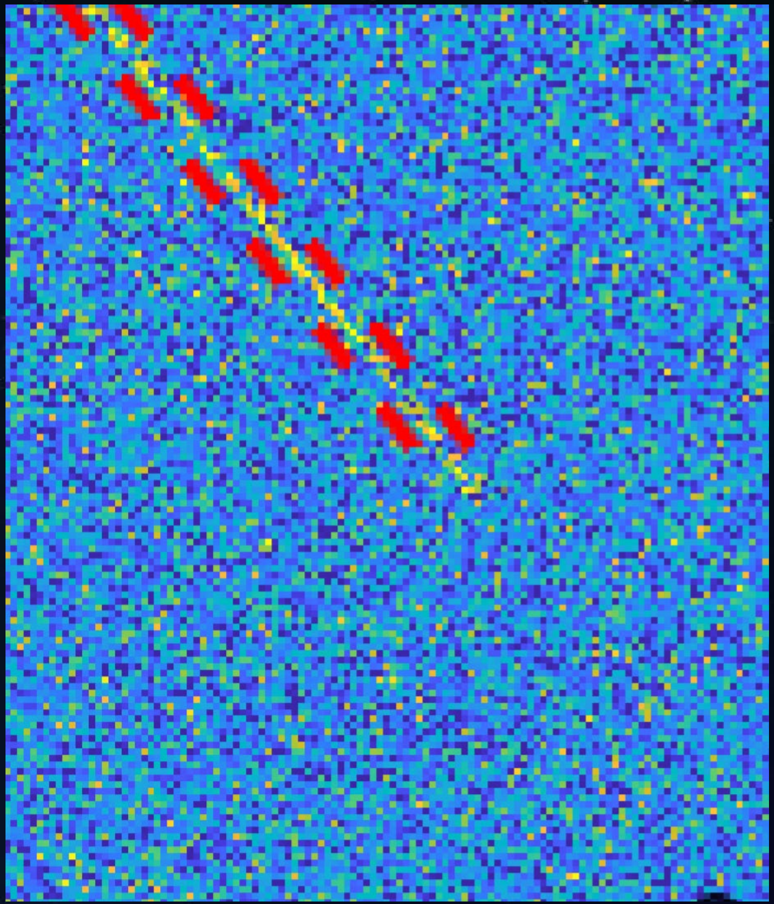
$$\Phi_0 = 5.6 \text{ x } 10^{10} \ \frac{\mathrm{photons}}{\mathrm{s/m^2}}$$

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

Image Processing

Streak Identification:

- Fast Radon Transform (FRT)
- Robust
    - Handles low intensity streaks
- Efficient



Example streak recognition by FRT program

Linearization

- Understand *dynamical nature* of an orbit to create mathematical model
- Fit measurements to model

$$\hat{X} = (A^T A)^{-1} A^T b$$

Estimation of State, X

Solve matrix:

- Goal is to make "best guess"
- Find minimal error between observations and expected measurements
- Solve the dynamic equations using the initial guess from TLEs

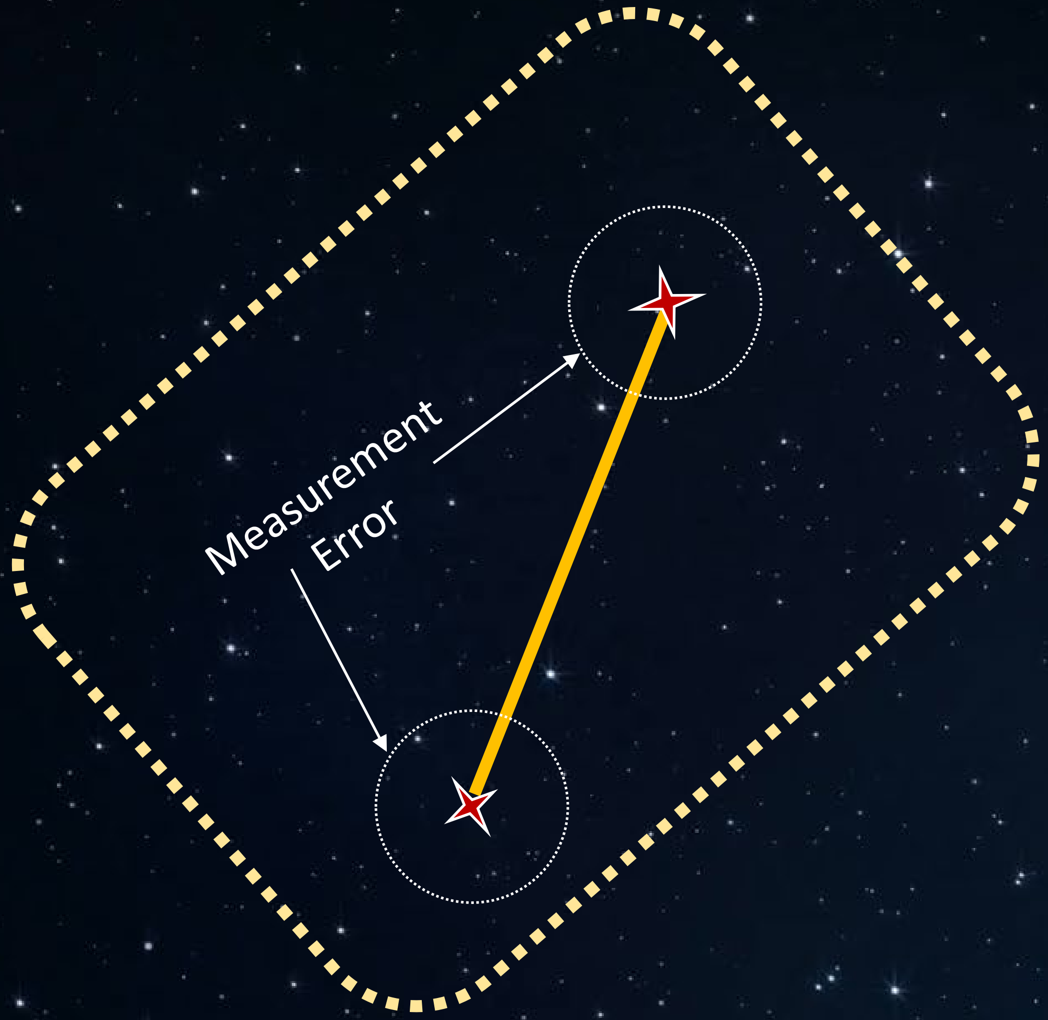
$$A = \begin{bmatrix} 1 & \partial\alpha_1 \\ 1 & \partial\delta_1 \\ \vdots & \vdots \end{bmatrix}$$

Partial-derivative matrix minimizing difference between dynamic model and observations

$$b = [\mathit{Initial\ orbital\ state\ guess}]$$

Initial guess from TLEs

Non-Linear Dynamics



Known dynamical orbital model:

$$\ddot{\vec{r}} = -\frac{\mu}{r^3}\vec{r}$$

- To use least squares, must linearize model using a Taylor series
- ***ITERATE*** through multiple solutions to meet an error threshold

Taylor Series used for Derivatives:

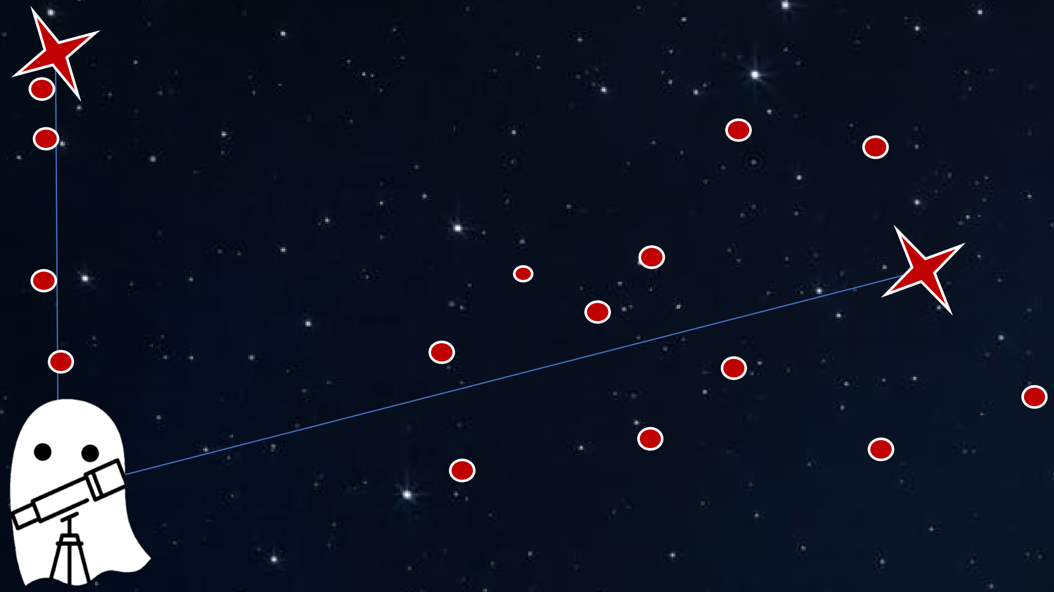
$$y_{n_i} = y_{n_i} + \Delta\alpha \frac{\partial y_{n_i}}{\partial \alpha} + \Delta\beta \frac{\partial y_{n_i}}{\partial \beta}$$

When ignoring second order terms (and higher):

$$\Delta\alpha = \alpha - \alpha_n$$
$$\Delta\beta = \beta - \beta_n$$

Covariance

Differences in Measurement Accuracy



Observations near zenith weighted *more heavily* than observations near horizon (more chance of atmospheric distortion)

Weighted Least Squares:
Expecting different residuals at different observations

Create Covariance matrix to apply weights on all six observations:

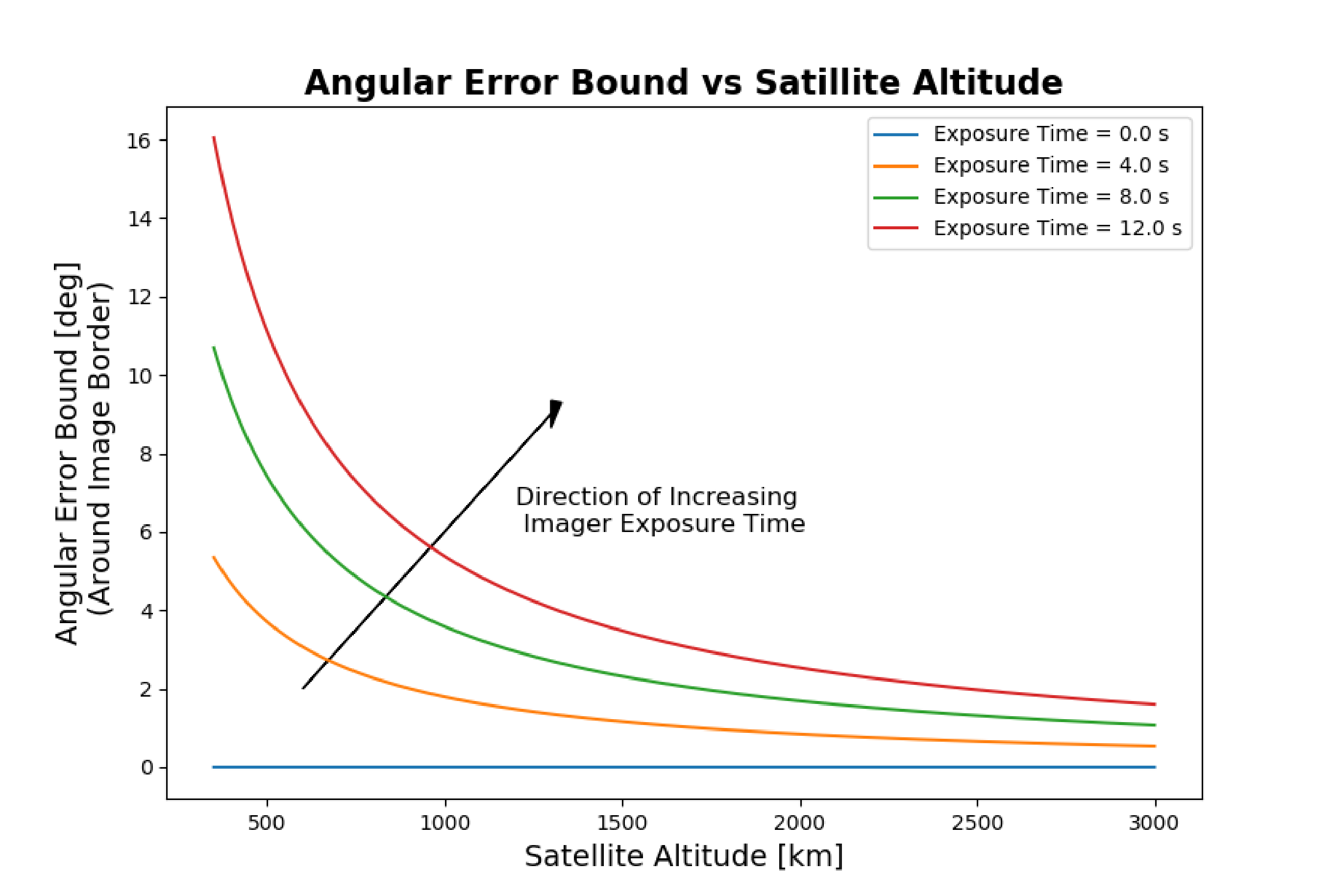
covariance matrix P:

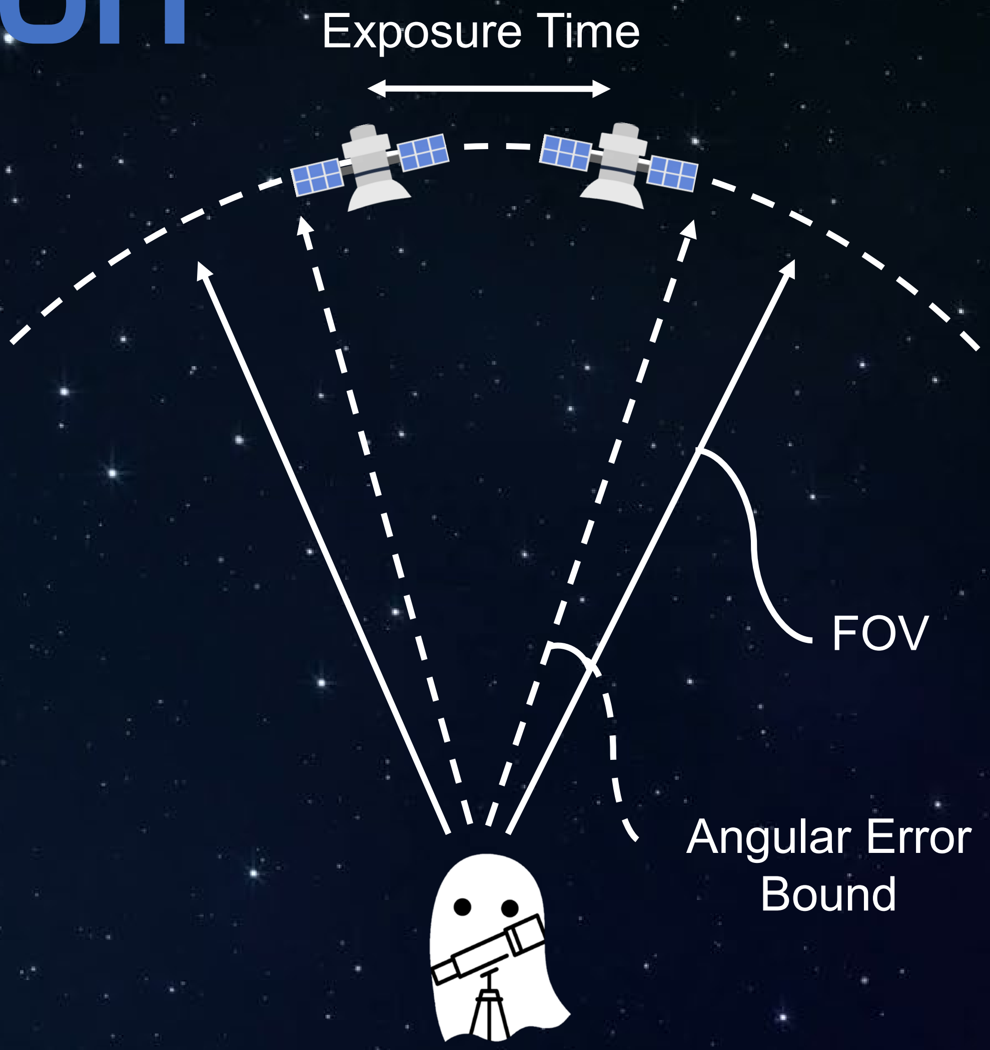
$$P = (A^T W A)^{-1}$$

Weighted Solution State:

$$\hat{X} = P A^T W b$$

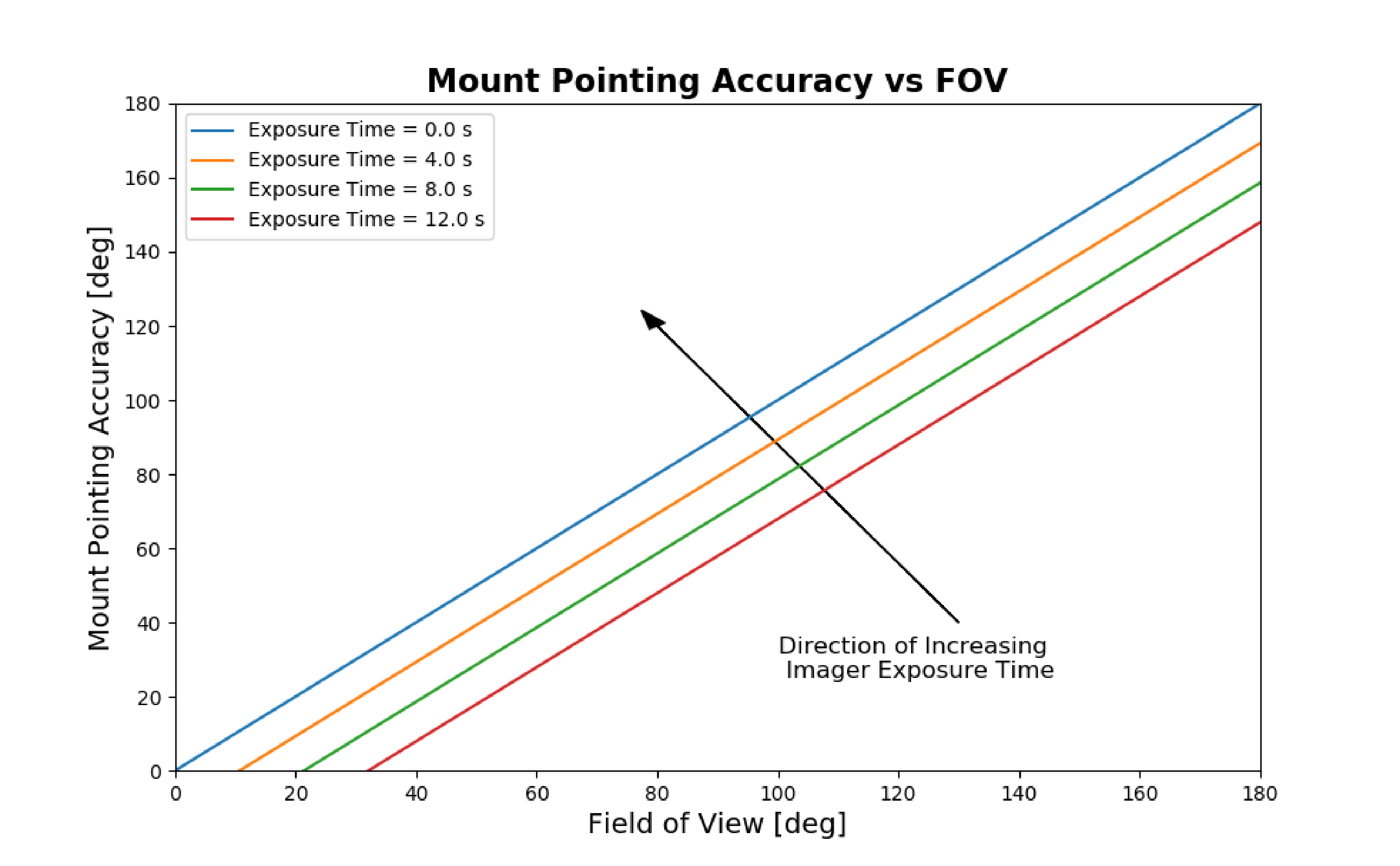
Actuation Hardware Motivation





Requirement FR2

Actuation Hardware Motivation



Requirement FR2

Actuation Hardware Option 1

iOptron iEQ45 Pro

Type: German Equatorial Mount

Max Slew Rate: 5.8°/s

Pointing Precision: 0.09 arcseconds

Hardware Mount: Dual Dovetail Saddle

Data Interface: RJ9/RS232

Data Protocol: ASCOM

Price: $1700

Actuation Hardware Option 2

Sky-Watcher EQM-35

Type: German Equatorial Mount

Max Slew Rate: 3.4°/s

Pointing Precision: 7 arcseconds

Hardware Mount: Vixen-Style Saddle

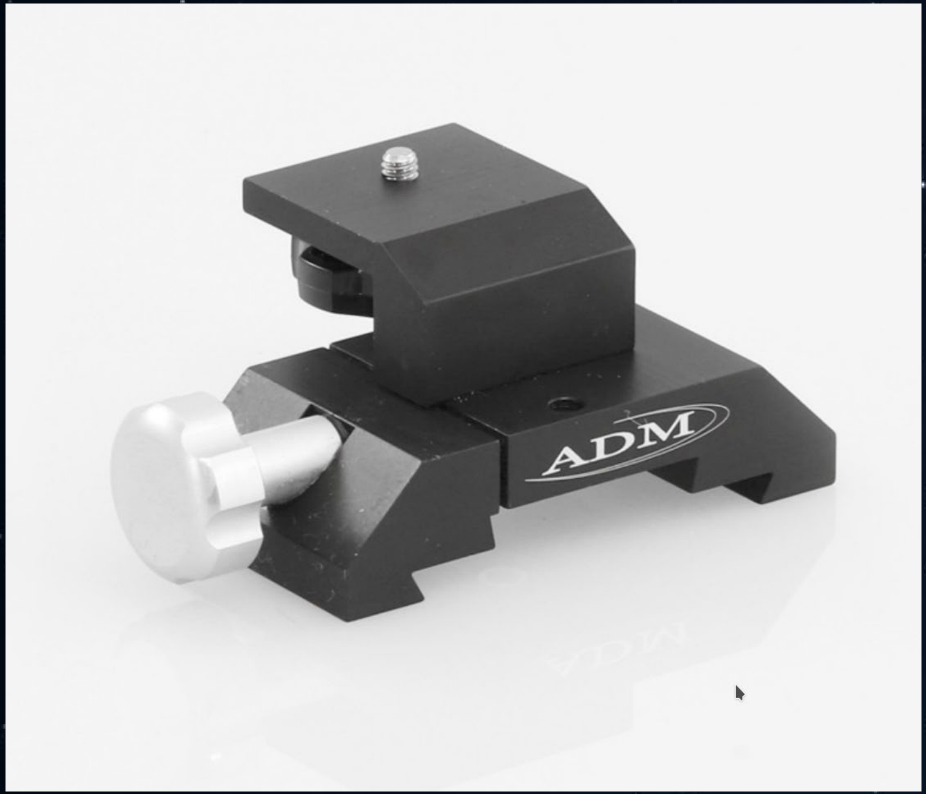
Data Interface: RS232/RJ9

Data Protocol: ASCOM

Price: $725

Actuation Hardware Evidence

Mechanical Interfacing (Tracker to Camera):



Dovetail to ¼" UNC Screw Mount Adapter needed

https://www.highpointscientific.com/

Actuation Hardware Evidence

Data/Software Interfacing:

- ASCOM protocol
  - AStronomy Common Object Model
  - Collection of properties and methods that allow for user control of the actuation system
- Standard USB and US232/RJ9 data connections

https://www.highpointscientific.com/

References

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