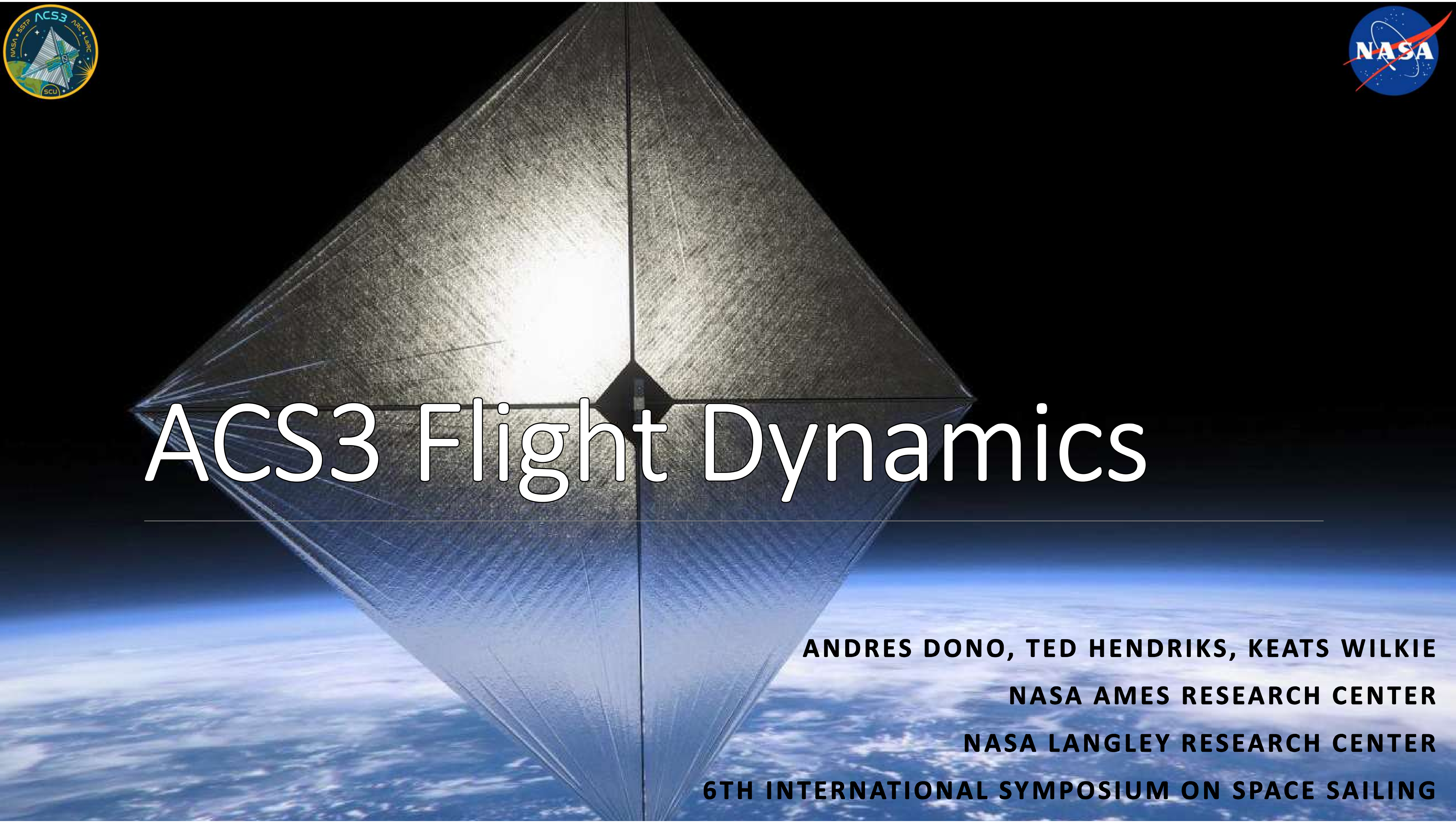

ACS3 Flight Dynamics

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6TH INTERNATIONAL SYMPOSIUM ON SPACE SAILING

Outline

ACS3 Mission Overview

Flight Dynamics Architecture

Solar Sail Simulation

Orbit Determination

Conclusions

ACS3 Overview

- ACS3 is a 12U spacecraft that will deploy an 81 m^2 solar sail in low Earth orbit.
- Launch: October-December 2023 (TBD)
- Orbit: 715 km - 1000 km (TBD)
- Midnight-Noon Sun Synchronous
- Objectives:
  - Primary: On-orbit deployment and characterization of a smallsat-class composite solar sail.
  - Secondary: Demonstrate controlled solar sailing flight (e.g., SMA-raising/lowering) in LEO. Characterize deployed structural dynamics.

https://www.nasa.gov/sites/default/files/thumbnails/image/acs3-animation-5seconds-nocaptions_0.gif

Video Credit: NASA Ames

ACS3 Flight Subsystems

Image credit: NASA Langley

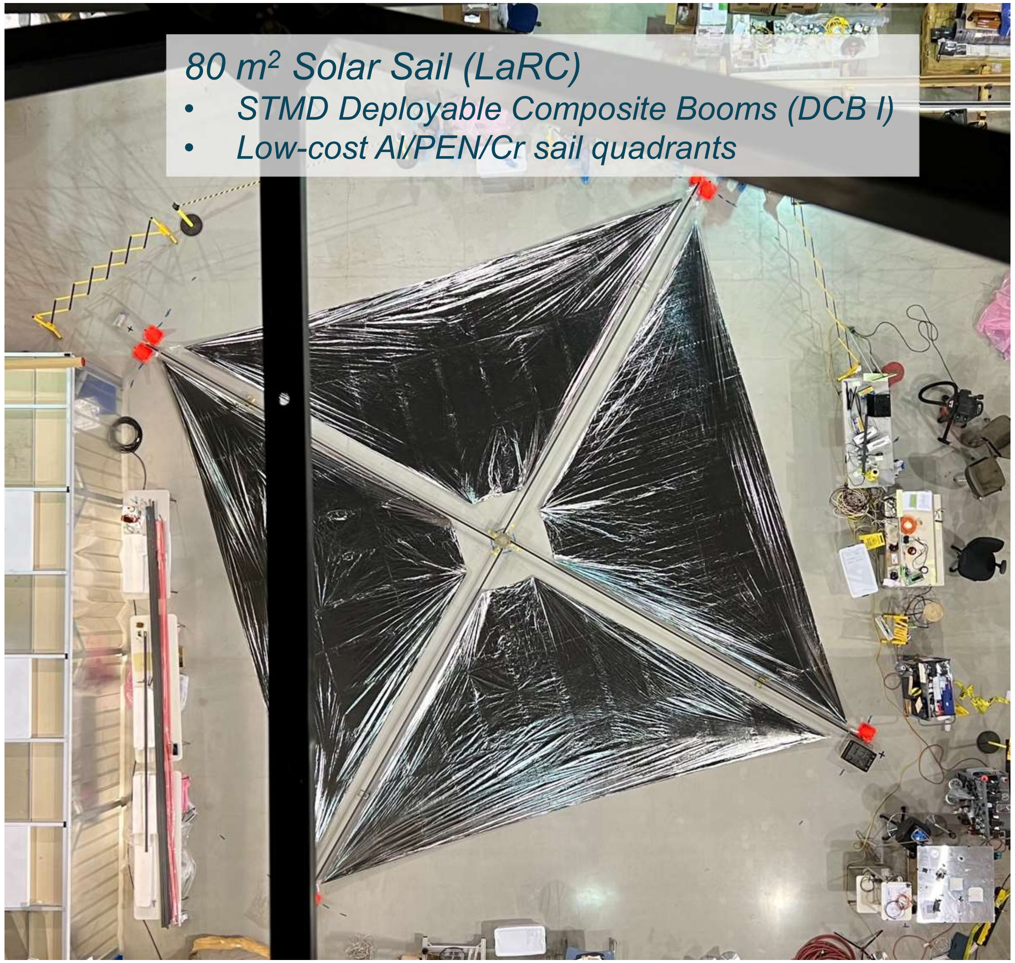
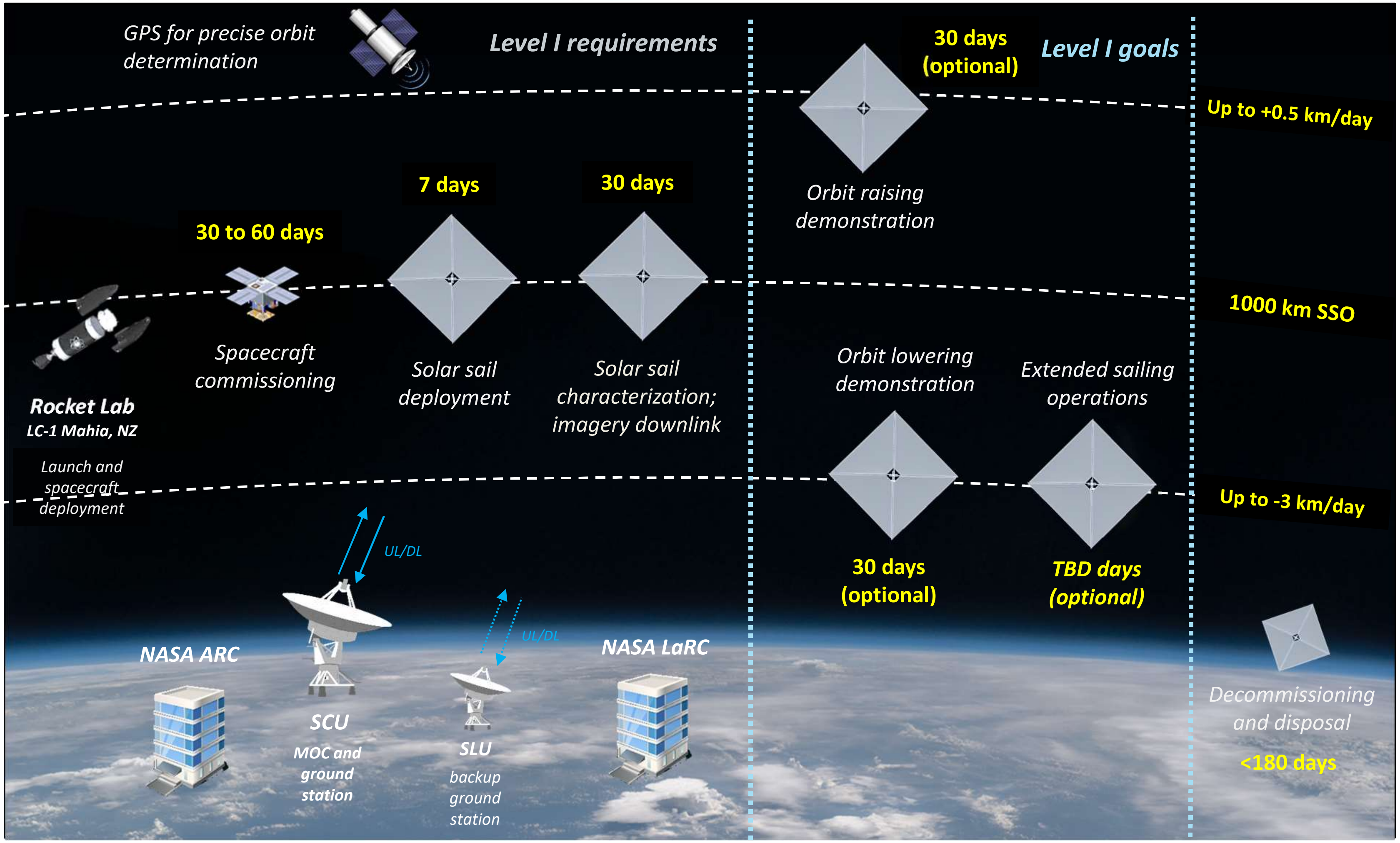
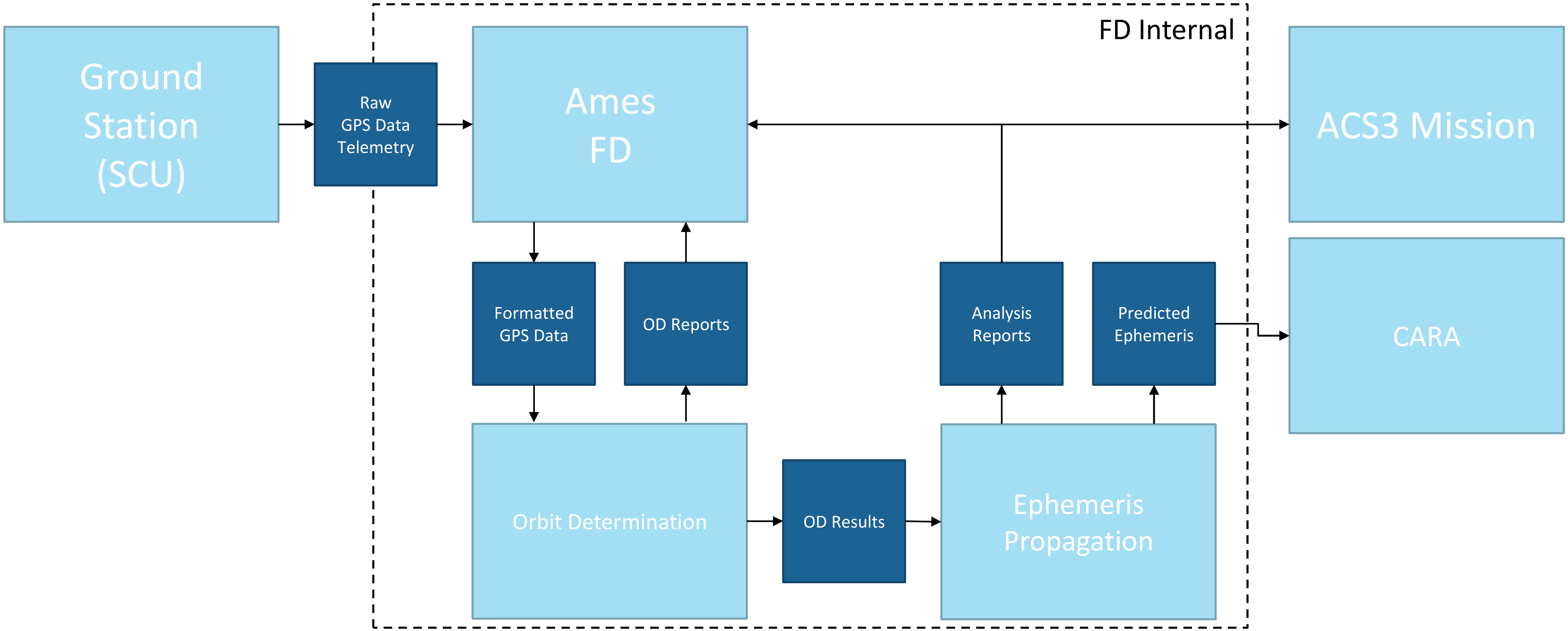


Image credit: NASA Langley

ACS3 CONOPS

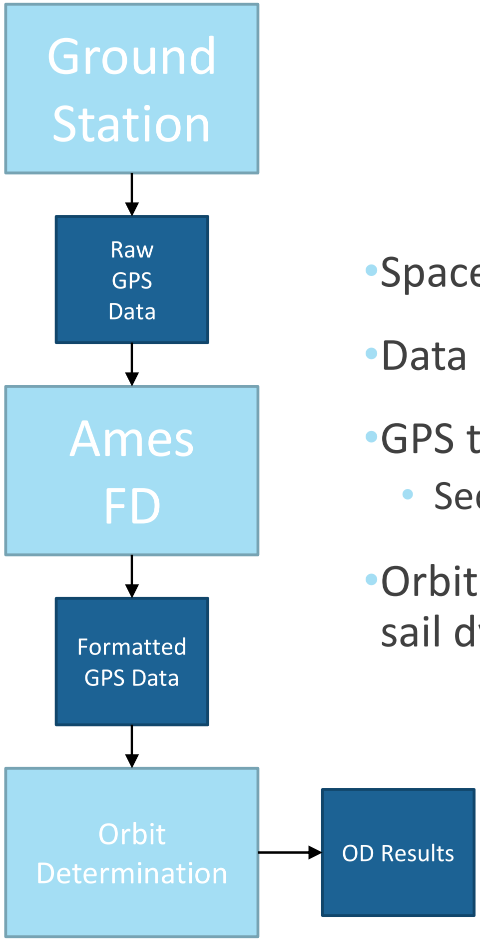

GPS for precise orbit determination
Level I requirements
30 days (optional)
Level I goals
Up to +0.5 km/day
Orbit raising demonstration
7 days
30 days
30 to 60 days
1000 km SSO
Spacecraft commissioning
Solar sail deployment
Solar sail characterization; imagery downlink
Orbit lowering demonstration
Extended sailing operations
Rocket Lab
LC-1 Mahia, NZ
Launch and spacecraft deployment
Up to -3 km/day
UL/DL
30 days (optional)
TBD days (optional)
UL/DL
NASA ARC
NASA LaRC
SCU
MOC and ground station
SLU
backup ground station
Decommissioning and disposal
<180 days

Flight Dynamics Architecture



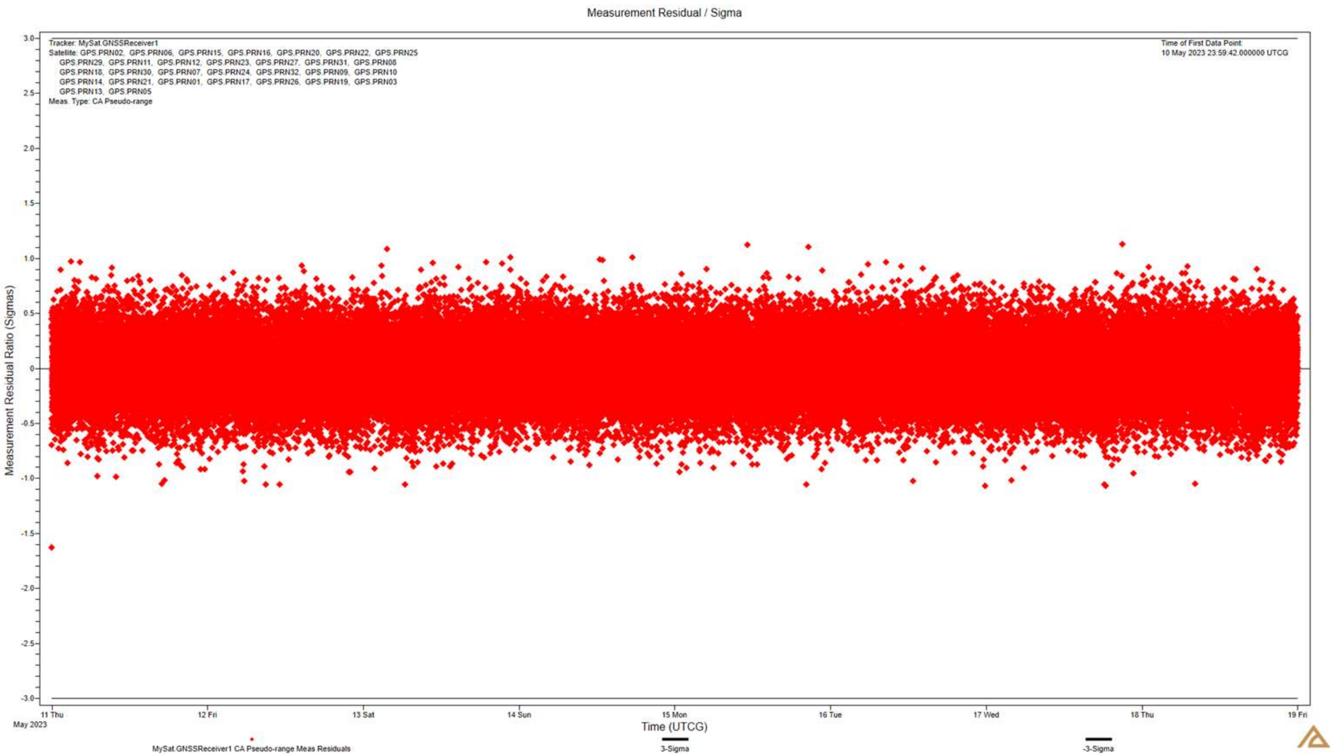
Orbit Determination

Orbit Determination Process



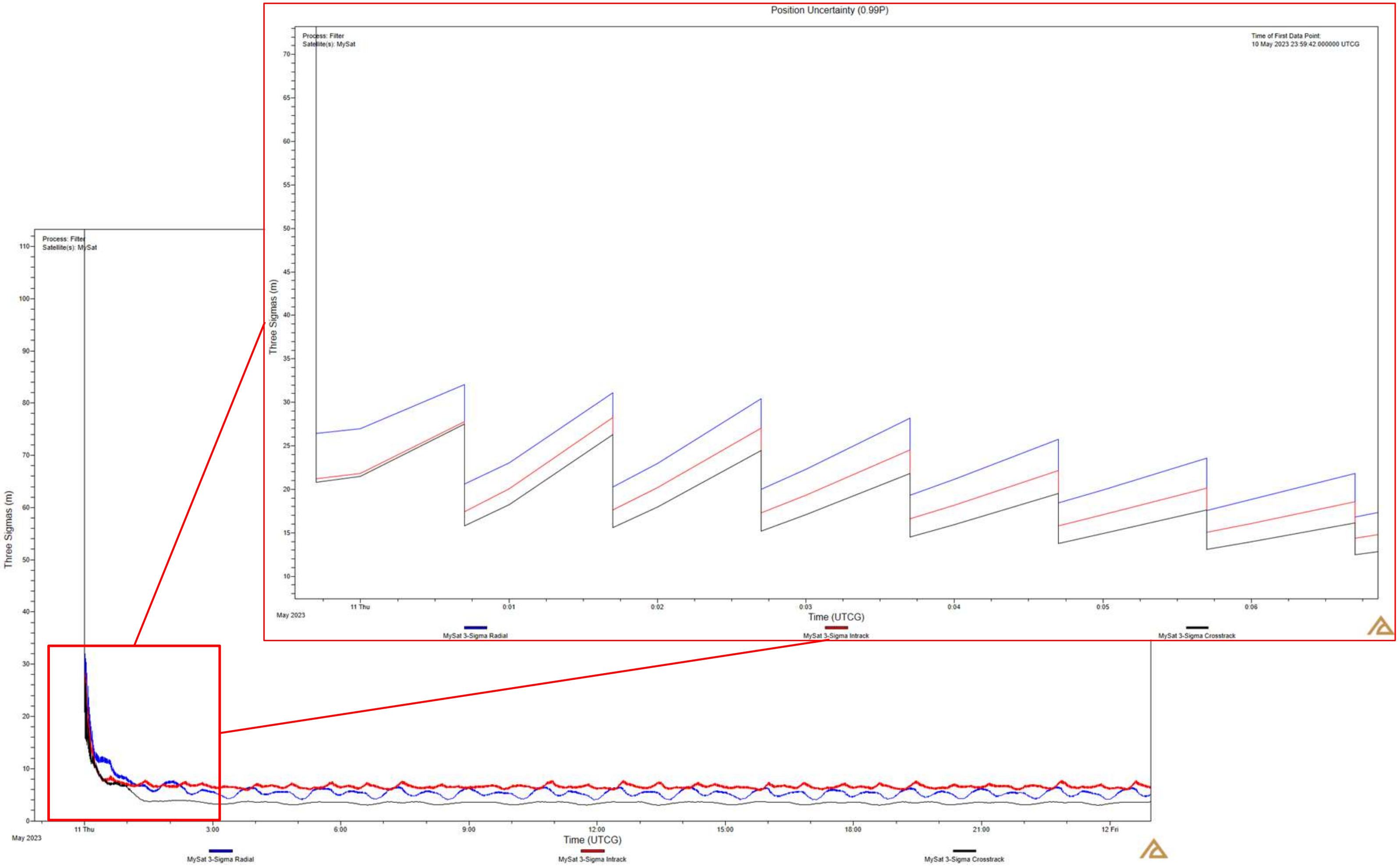
- Spacecraft records one GPS measurement per minute
- Data is downlinked at each ground pass (~12 hours between passes)
- GPS telemetry data is processed by Ames Flight Dynamics team
  - Sequential filter is used to obtain ephemeris solution based on GPS tracking data
- Orbit determination results are then used to generate predictive ephemeris with solar sail dynamics model

Simulated Tracking Data: Residual Ratios



- To prepare for the mission we are running operation readiness tests (ORT)
- Test simulates one week of GPS tracking data
- Initial position uncertainty (3-σ) of 3 km
- Initial velocity uncertainty (3-σ) of 0.3 m/s
- Sequential filter and smoother were used to produce an OD solution
- Measurement (pseudo-range) residual ratios are portrayed on the left

Simulated Tracking Data: Position Uncertainty

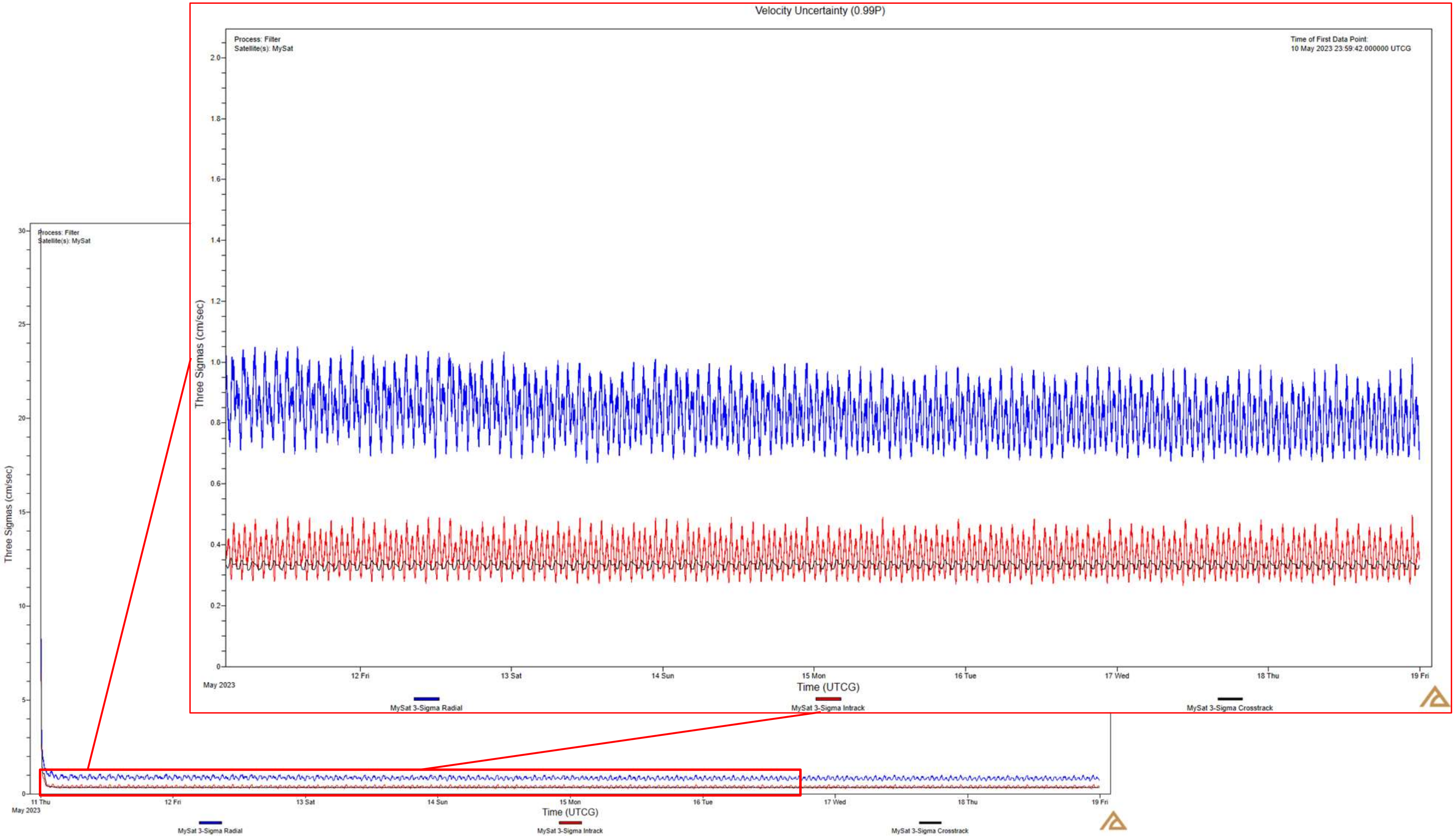


After first measurement position uncertainty drops rapidly

Uncertainty grows between measurement points

Long term uncertainty is controlled at this measurement cadence

Simulated Tracking Data: Velocity Uncertainty

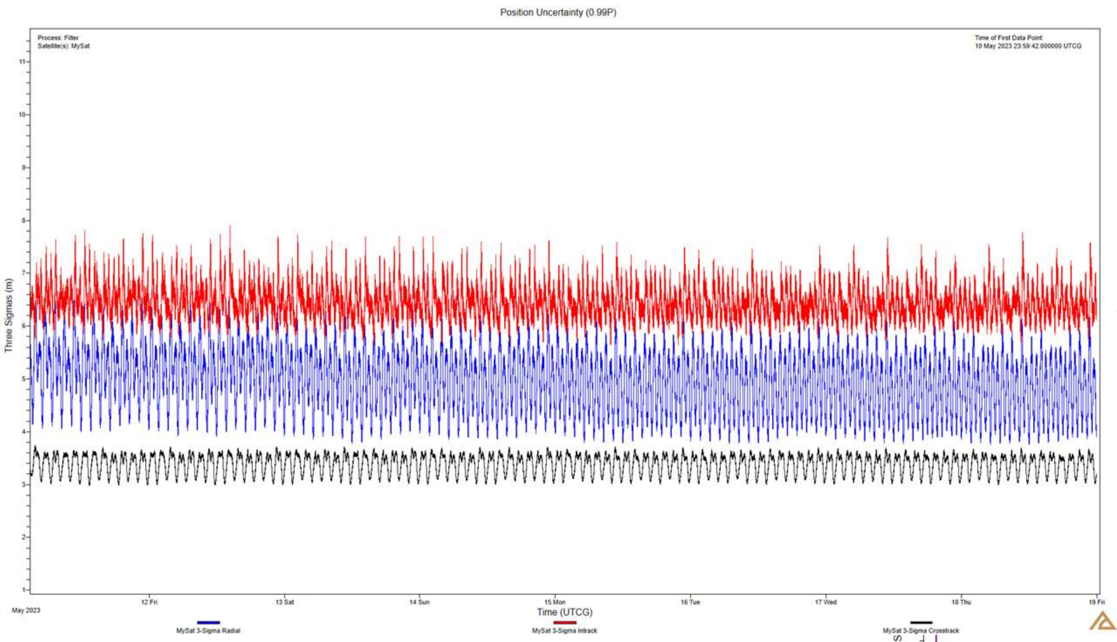


As with position, after the first measurement velocity uncertainty drops rapidly

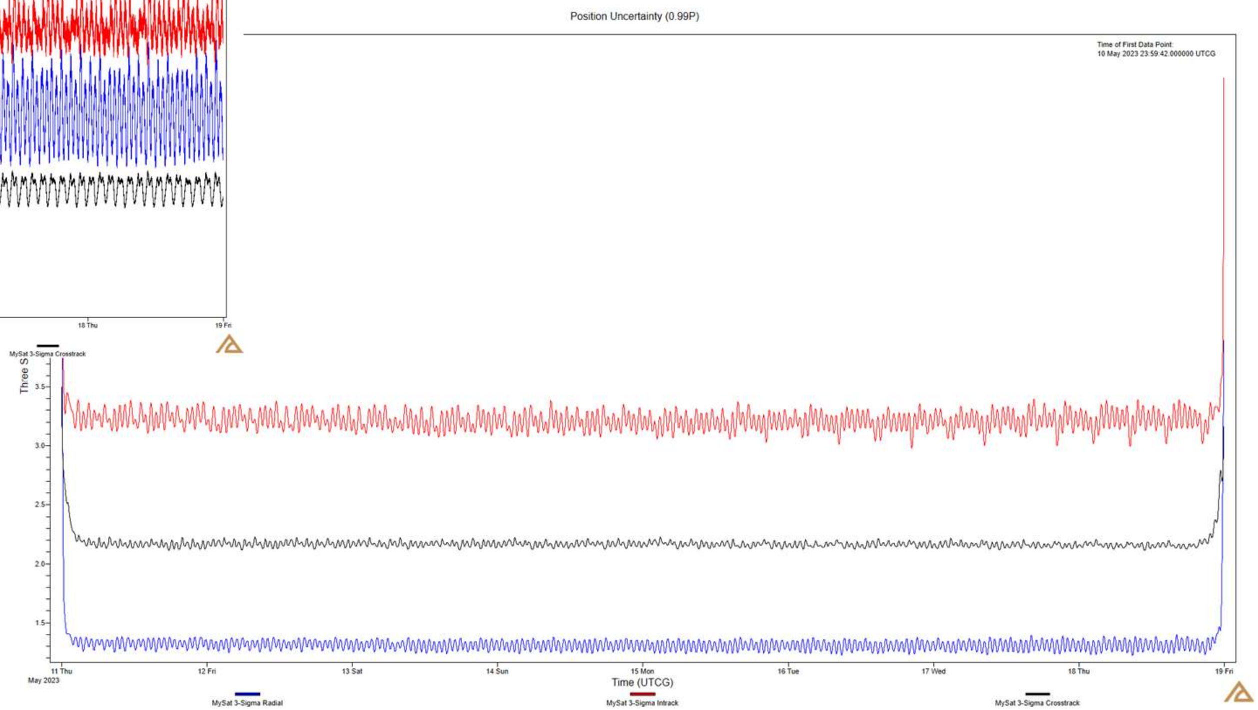
Uncertainty grows between measurement points

Long term uncertainty is controlled at this measurement cadence

Simulated Tracking Data: Filter vs. Smoother



Filter position uncertainties
In-track: 7-8 m
Radial: 4-6 m
Cross-track: 3-4 m

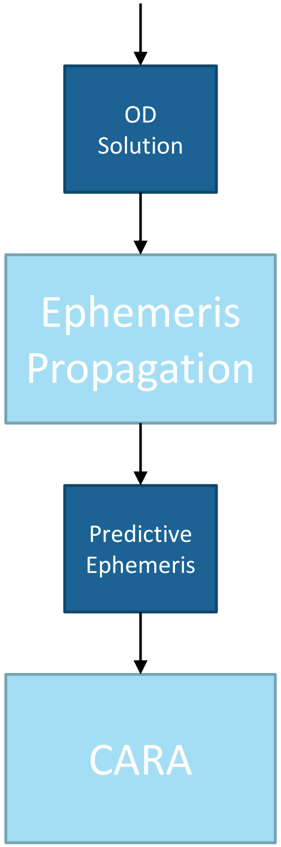


Smoother position uncertainties
In-track: 3-3.5 m
Radial: 1-1.5 m
Cross-track: 2-2.5 m

Solar Sail Simulation

VEHICLE MODELING AND PROPAGATION

Propagation



Need one week of predictive ephemeris for collision avoidance screenings

Predicted ephemeris, including covariance matrix, is provided to the NASA Conjunction Assessment Risk Analysis (CARA) team to comply with requirements

Ephemeris is produced utilizing a high-fidelity propagator with a full atmospheric density model, and updated solar radiation pressure

Propagator Components	
Integrator	RKF7(8)
Gravity Model	EGM08 24x24
Atmosphere Model	NRLMSISE-00
Third Bodies	Sun, Moon
Solar Radiation Pressure	N-Plate Model, spherical
Solar Weather	Daily F10.7

Vehicle Modeling

SPHERICAL SOLAR RADIATION PRESSURE (SRP)

Vehicle is a sphere with a constant cross-sectional area.

Attitude of vehicle does not affect apparent cross-sectional area

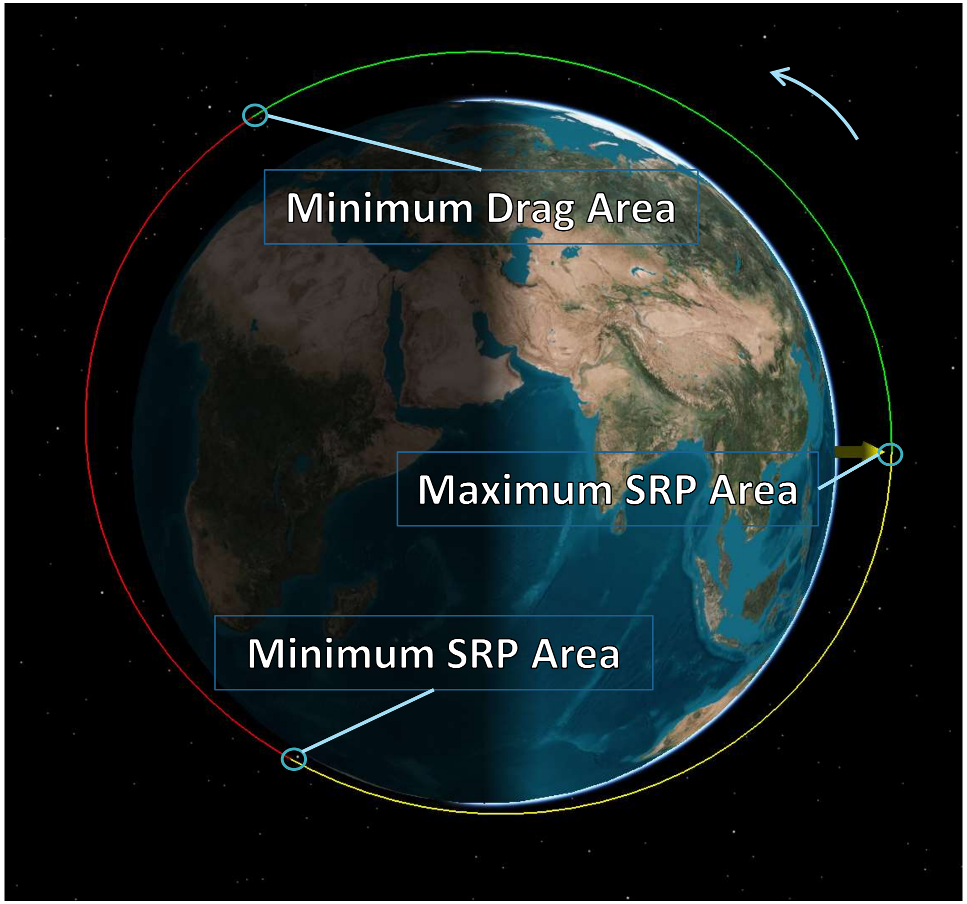
We update the cross sectional area accordingly in this model to simulate desired attitude.

N-PLATE

Vehicle is a collection of flat plates with orientations defined in the body fixed axes

Drag and SRP area are dependent on the attitude, position, and velocity of the spacecraft

Orbit Raising with Spherical Model



Drag area and SRP area are linked

Update drag and SRP area at certain points in the orbit to maximize SMA change

During eclipse, drag area is minimized

When sun would reduce SMA, minimize SRP area

SRP area is maximized when crossing the ecliptic

Spherical SRP Simulation

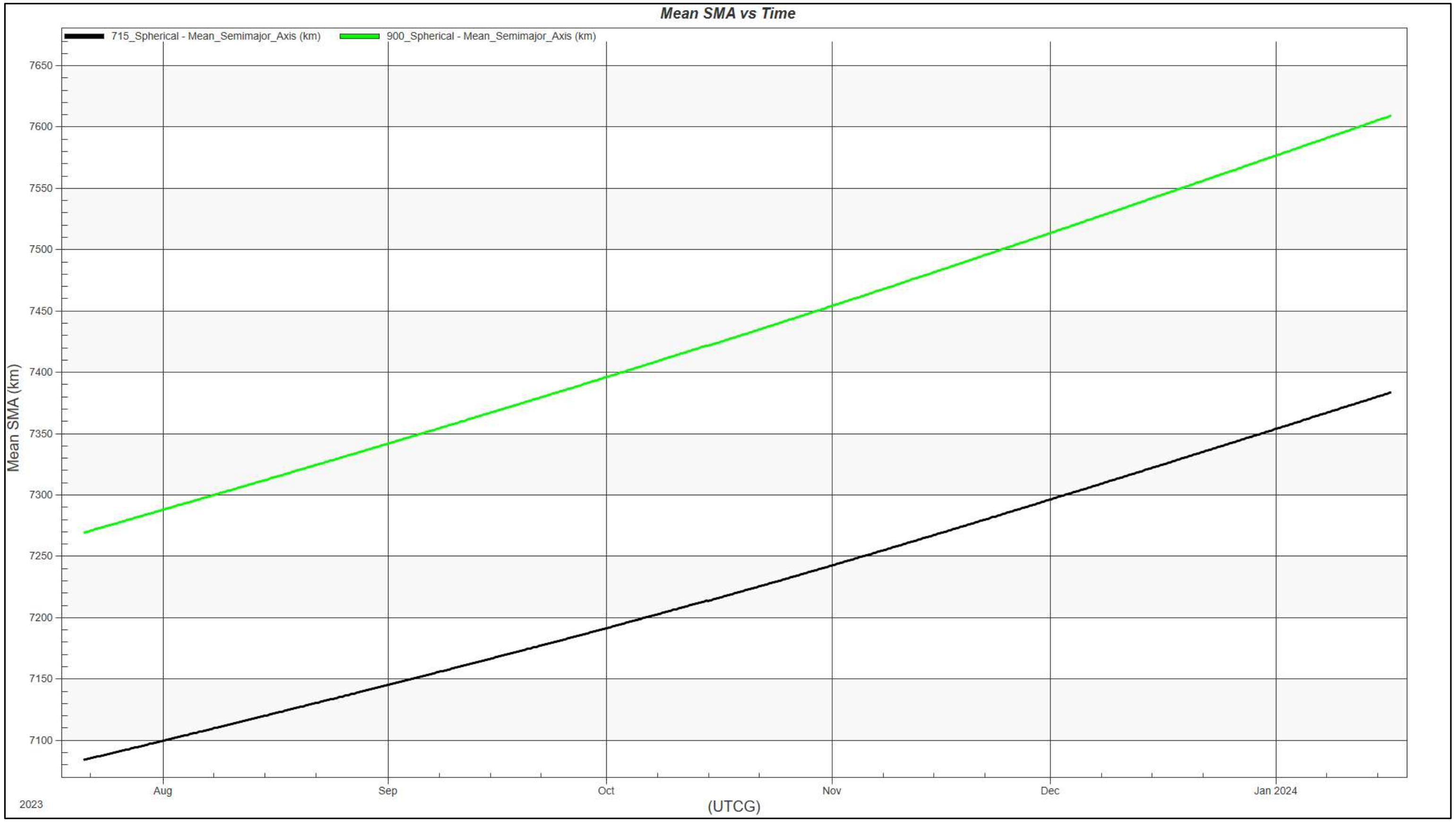
Two cases based on potential operational altitudes

Goal was to raise the semi-major axis of each orbit

Simulated each case for **180 days** and tracked the mean semi-major axis

	715 km	900 km
Initial Epoch	21 Jul 2023 00:00:00.000	
Propagation Time	180 Days	
Semi Major Axis	7093.137 km	7278.137 km
Eccentricity	0.00	
Local Time of Asc. Node	00:00 (Midnight)	
Inclination	99.370°	99.154°
Max Drag/SRP Area	81 m^2	
Min Drag/SRP Area	0.06 m^2	
Mass	16 kg	

Results: Spherical SRP model



Both cases saw an increase in semi major axis in 6 months

900 km

- Initial – 7269 km
- Final – 7609 km
- **SMA increase – 340 km**

715 km

- Initial – 7084 km
- Final – 7383 km
- **SMA increase – 301 km**

SMA Raising/Lowering Steering Profile [ref: McInnes, 1999]

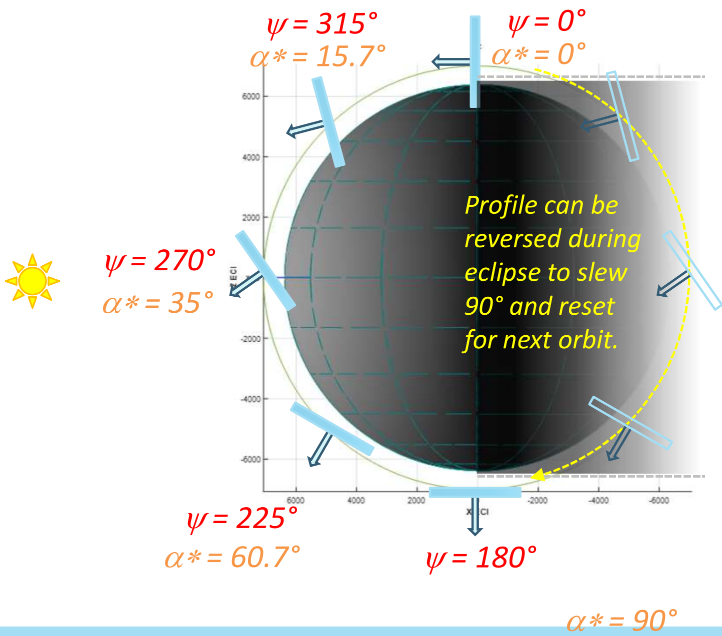
Locally optimal steering law for maximum energy gain/loss each orbit.

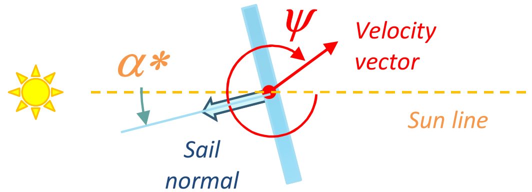
- Sail oriented to maximize solar radiation thrust component in direction of flight.
- For lowering, thrust component opposite direction of flight is maximized.

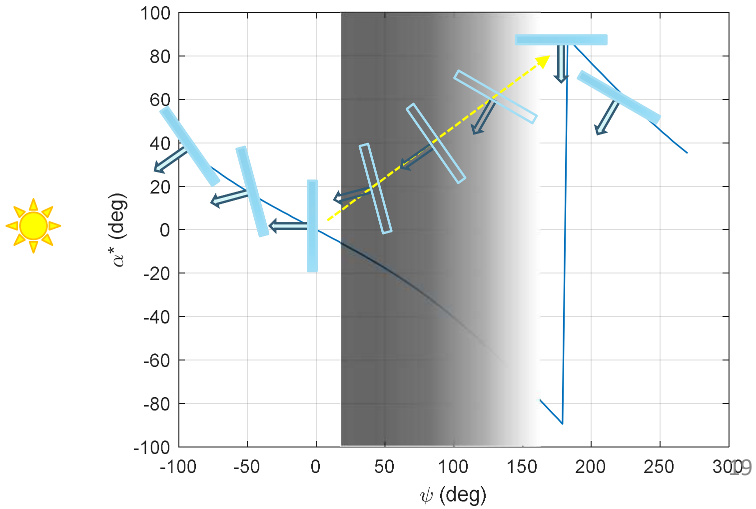
$$\alpha^* = \frac{1}{2}\left[\psi - \sin^{-1}\left(\frac{\sin\psi}{3}\right)\right]$$

Locally optimal sail pitch angle.

Angle of velocity vector with respect to sun line.







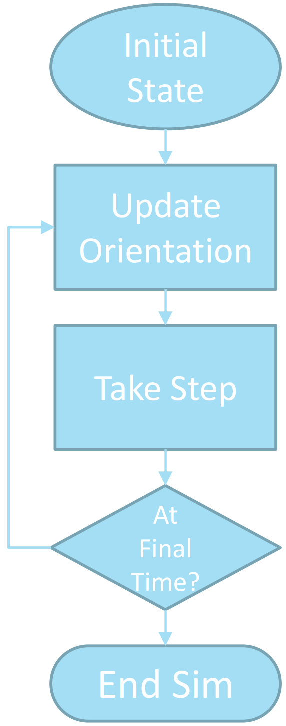
- Noon-midnight SSO example shown. -

Propagation of N-Plate Model

N-Plate model requires an accurate model for spacecraft attitude

Current approach is to propagate the spacecraft for 180 days, record needed values, compute attitude for all time points, and then re-run simulation with new attitude values

More accurate model can be achieved by updating vehicle attitude at each time step



Conclusions

- Our simulations show that the mission can achieve the mission goals
- The ACS3 solar sail dynamics model can be utilized to complete the navigation process and can be used to produce updated predictive ephemeris for the spacecraft orbit transfer
- We have built a custom flight dynamics system to support the ACS3 mission according to NASA CARA and project management requirements
- Initial ORT has shown that the spacecraft can be tracked, and position and velocity uncertainty can be contained within expectations
- NASA Ames Flight Dynamic team will collaborate with NASA Langley and SCU to track the spacecraft and meet requirements.