James Webb Space Telescope
Navigation Optimization Challenges

James Logan[1], Ashok Verma[1], Sarah Cavanaugh[1], and Andrew Yu[2]

[1]Flight Dynamics Facility, NASA-GSFC, Omitron Inc.
[2]Flight Dynamics Facility, NASA-GSFC, Pearl River Technologies LLC

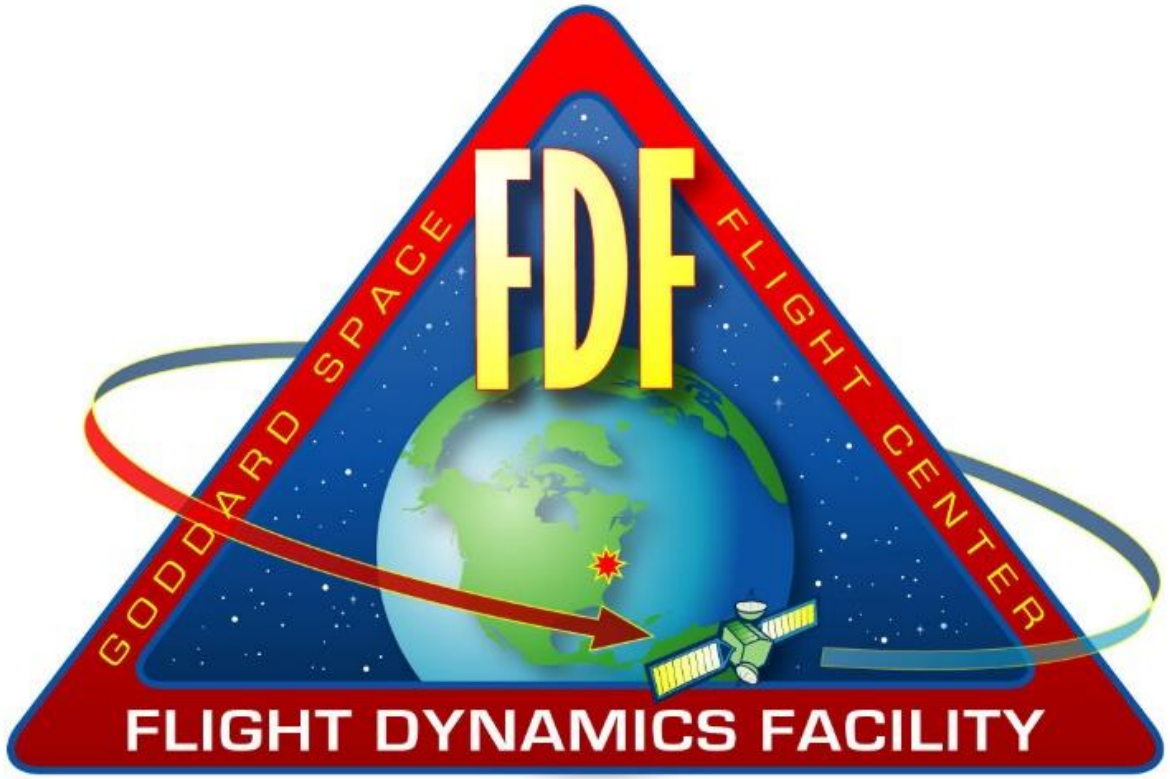
ISSFD 2024

Agenda

- Introduction
  - NASA-GSFC Flight Dynamics Facility
  - JWST Mission Overview
- Orbit Determination
  - Dynamical Modeling
  - Data Processing
  - Results & Accuracy
- Maneuver Planning
  - Targeting Parameters
  - Neutral SRP Calibration
  - Maneuver Performance
- Conclusion

NASA-GSFC Flight Dynamics Facility

- The Flight Dynamics Facility is a customer-funded provider of flight dynamics services to space communications networks, science and exploration programs, and launch vehicle providers
- The FDF's responsibilities span a wide range of flight regimes, encompassing tasks such as orbit determination (OD), maneuver planning, trajectory optimization, covariance and contact analysis, and ground station certification



NASA-GSFC Flight Dynamics Facility

- The Flight Dynamics Facility is a customer-funded provider of flight dynamics services to space communications networks, science and exploration programs, and launch vehicle providers
- The FDF's responsibilities span a wide range of flight regimes, encompassing tasks such as orbit determination (OD), maneuver planning, trajectory optimization, covariance and contact analysis, and ground station certification

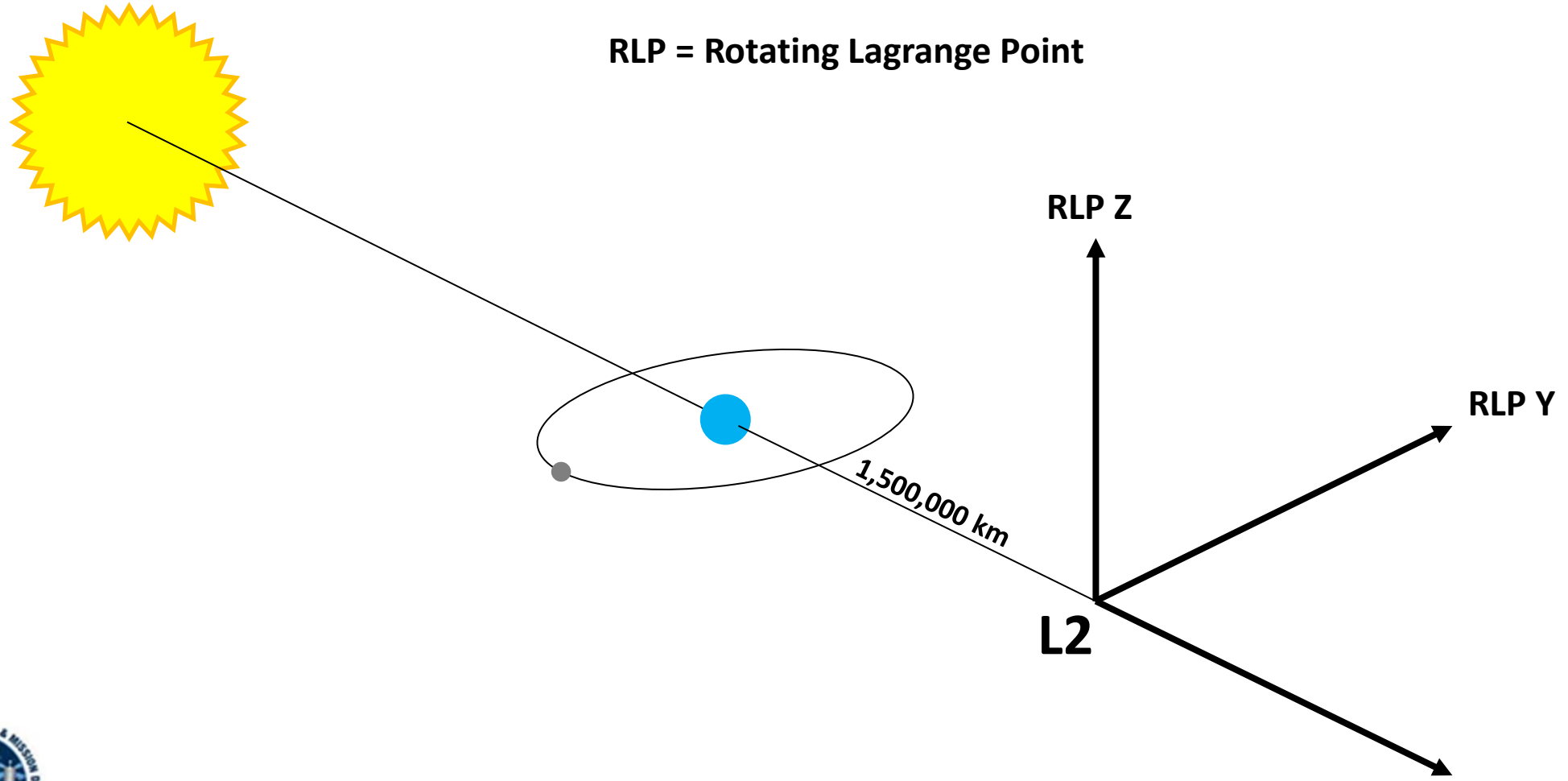
JWST Flight Dynamics Team – NASA-GSFC contractors from Omitron Inc., Pearl River Technologies LLC, and a.i. solutions

Flight Dynamics Facility Support for JWST

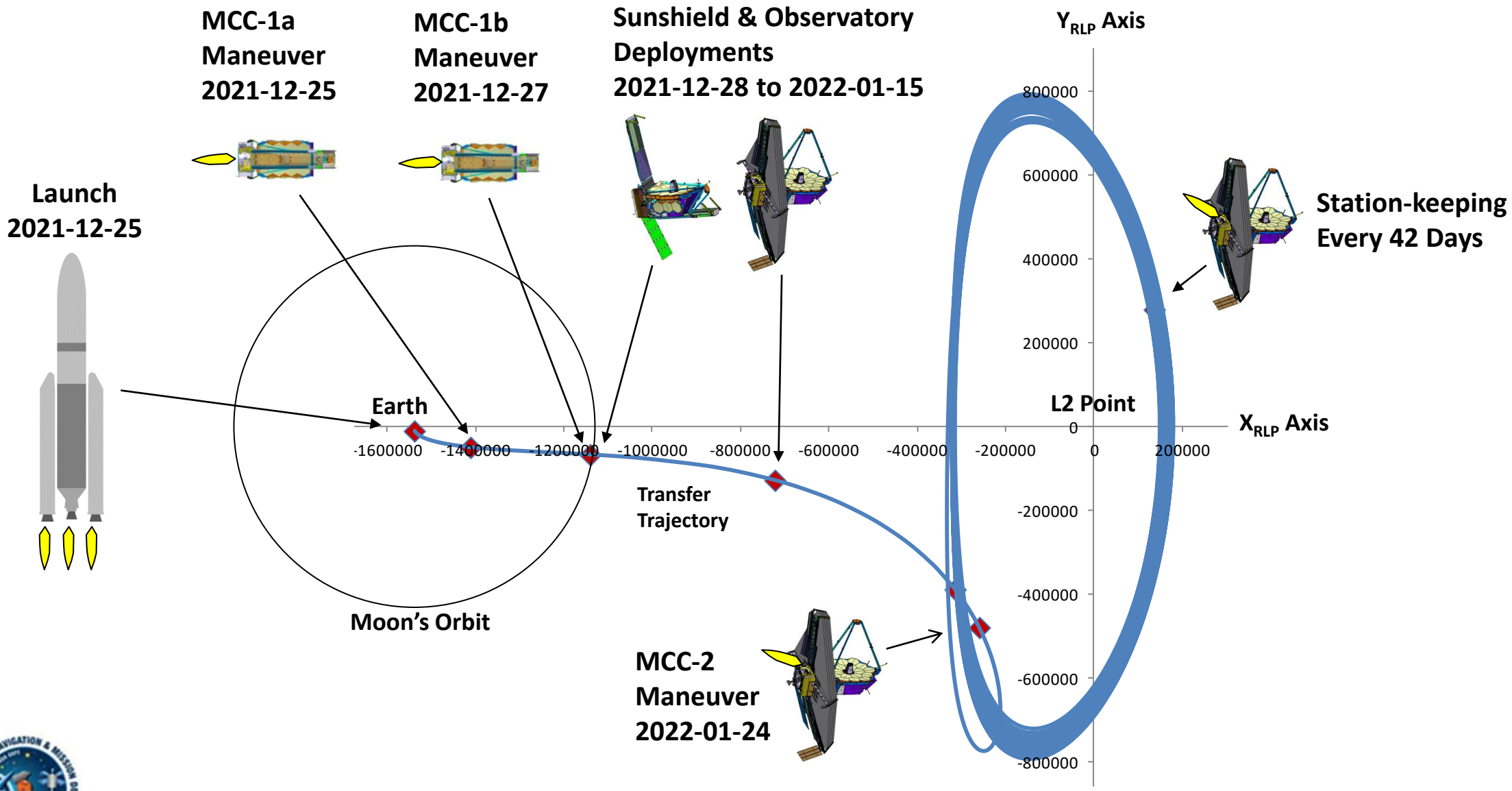
- Pre-Launch Phase
  - Analysis, software development, mission simulations, LV support preparation
- Launch and Early Orbit Phase
  - Orbit determination during critical sunshield and observatory deployment events
  - Mid Course Correction (MCC) maneuver planning
- Science Phase
  - Routine orbit determination and orbit prediction
  - Maneuver planning and optimization for routine station-keeping

JWST Mission Overview

- JWST is located at the Sun-Earth-Moon 2nd Lagrange point



JWST Mission Overview: Launch to Mission Orbit



Orbit Determination

Dynamical Modeling

Data Processing

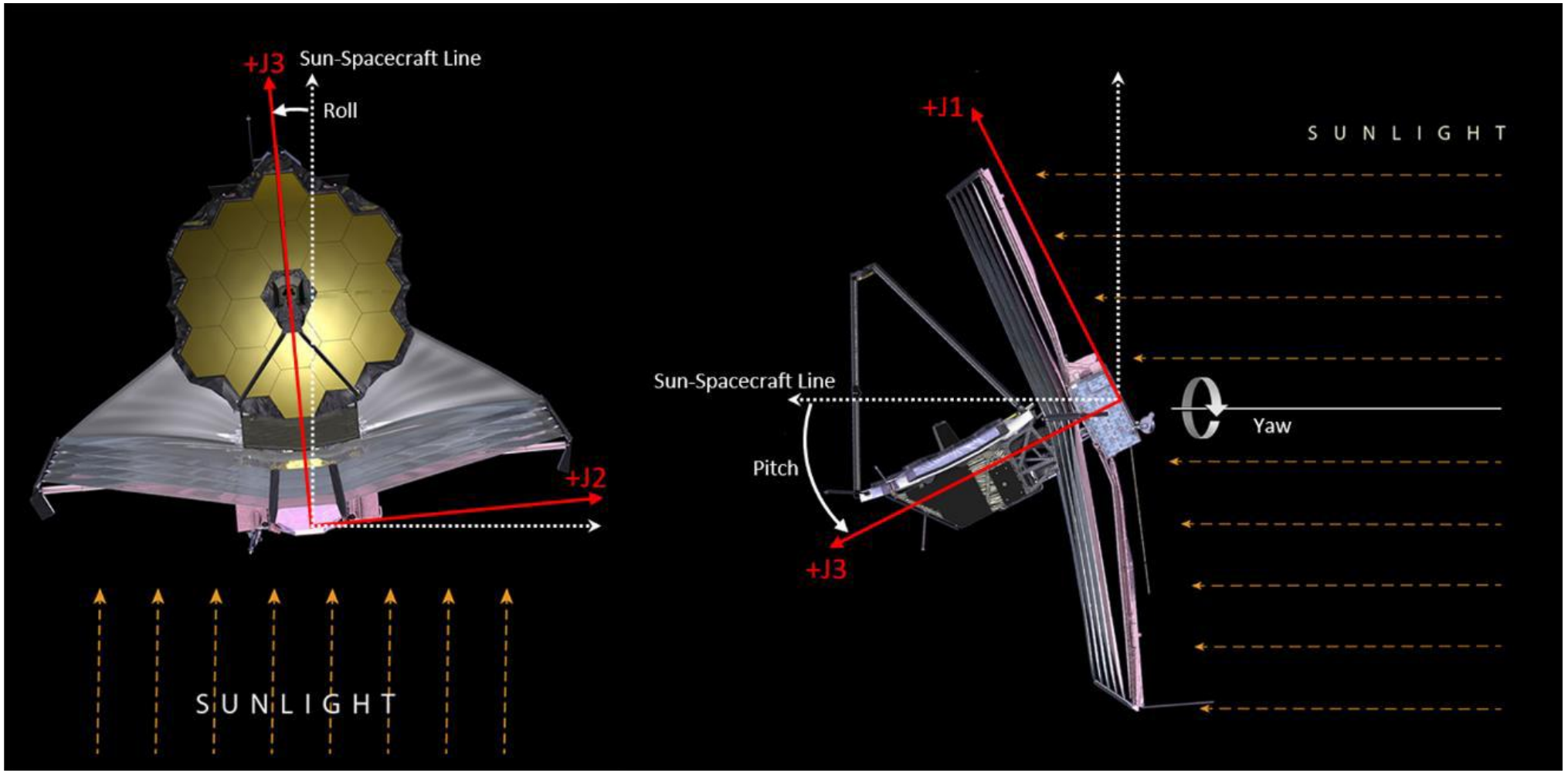
Results & Accuracy

Dynamical Modeling

- Gravitational Force Model
  - Earth Geopotential Model
    - 30x30 EGM96
  - Newtonian Point Masses
    - Sun, Planets, and the Moon
- Non-Gravitational Force Model
  - Solar Radiation Pressure (SRP)
    - 49-degree polynomial high-fidelity light reflection model
    - Time history of definitive attitude

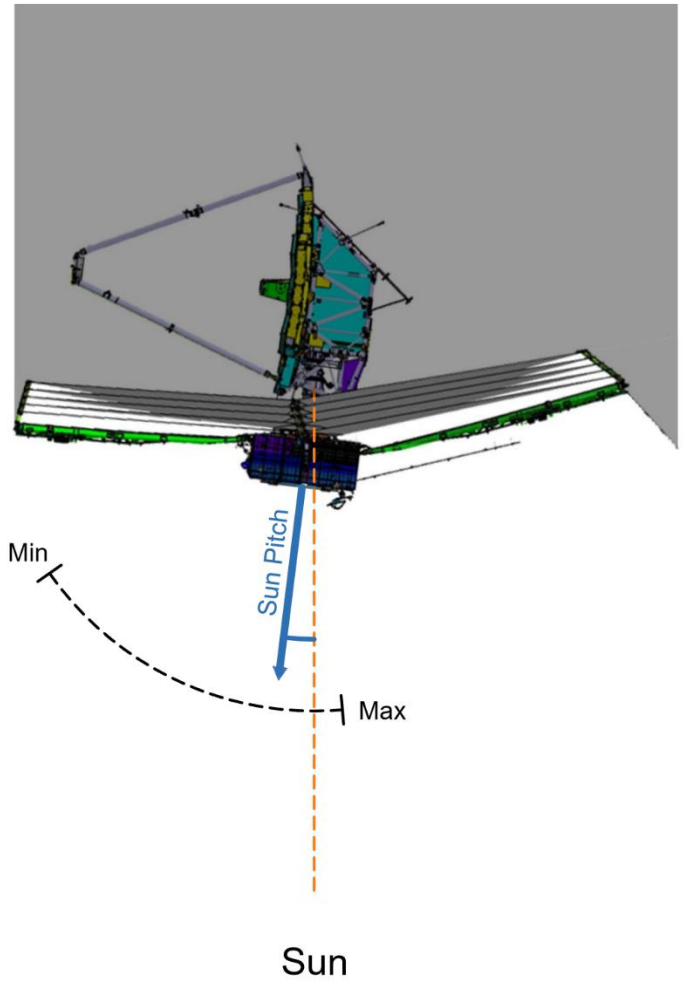
SRP Overview

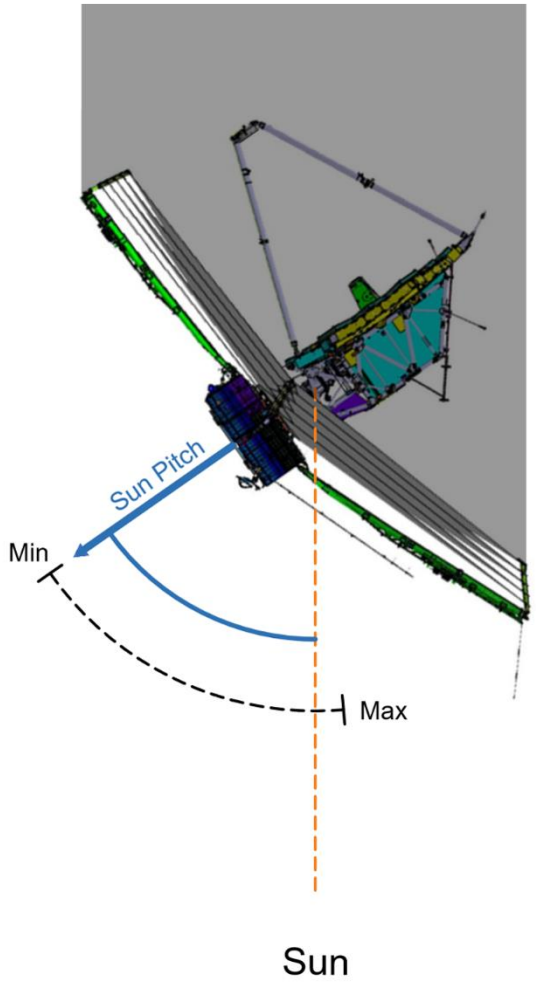
- SRP significantly influences JWST due to the large Sun shield



SRP Overview

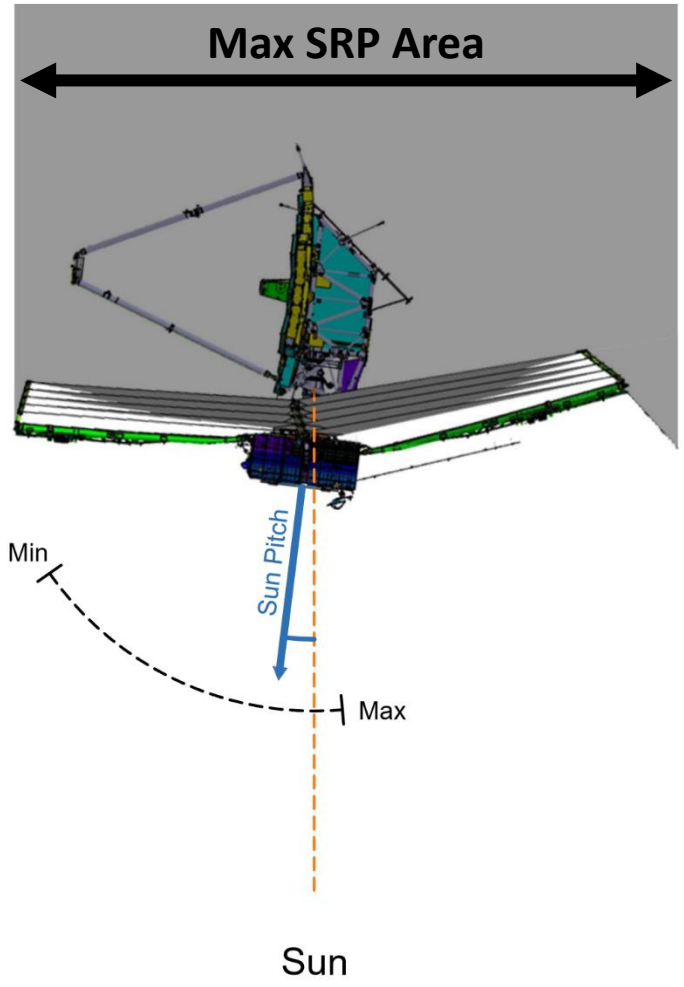
- The Sun Pitch of JWST primarily determines the SRP impact

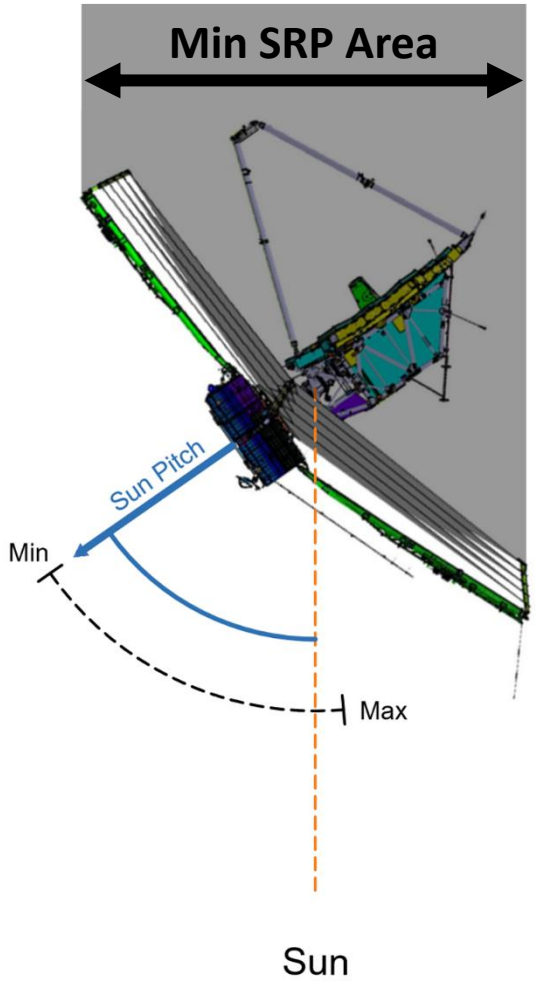




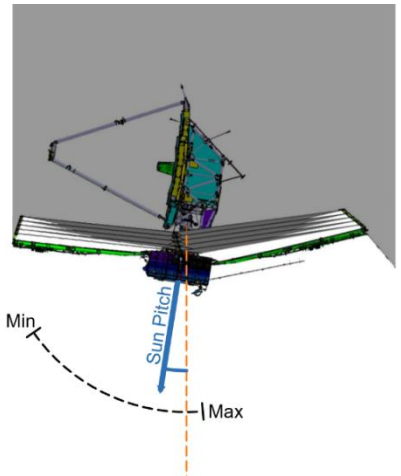
SRP Overview

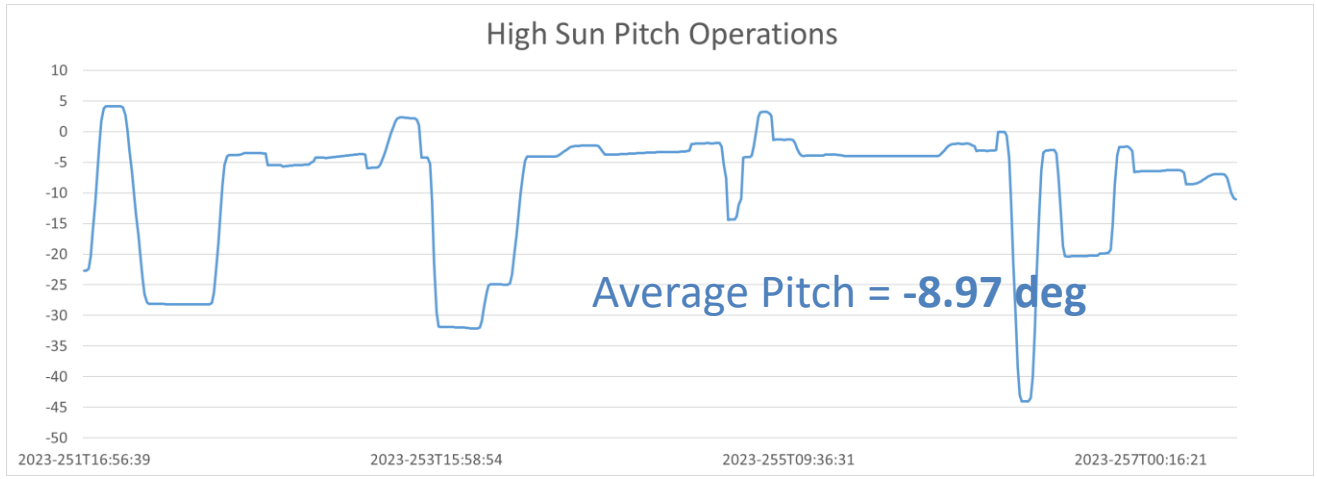
- The Sun Pitch of JWST primarily determines the SRP impact

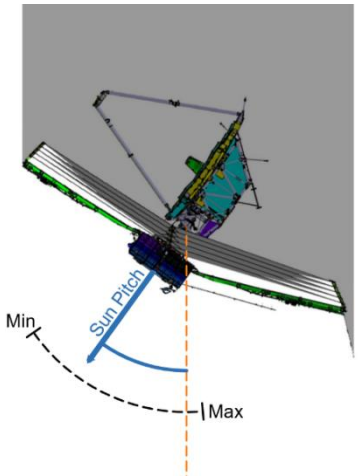


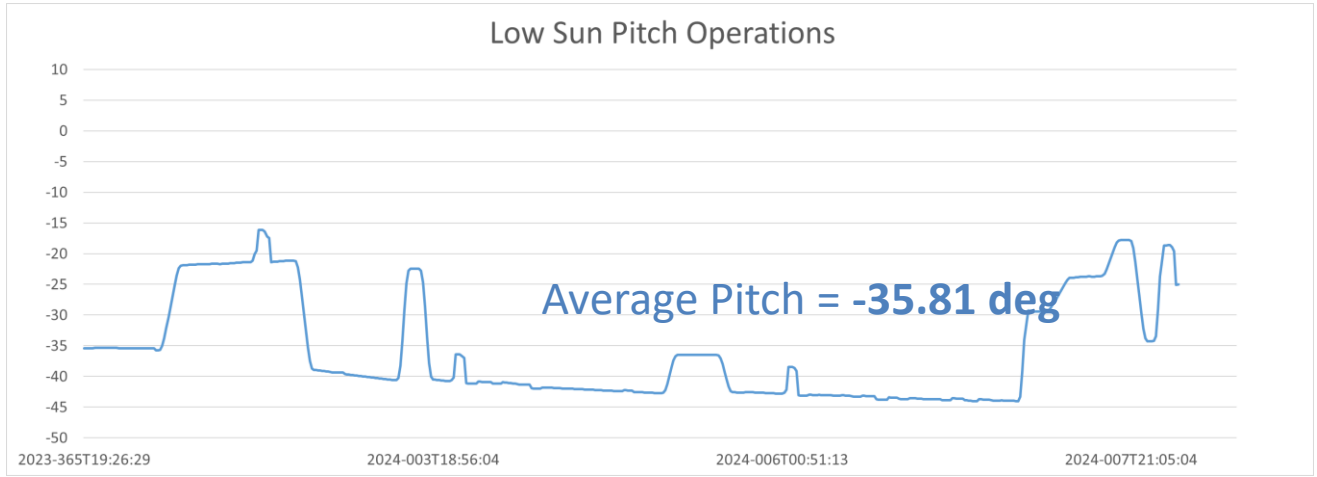


SRP Overview





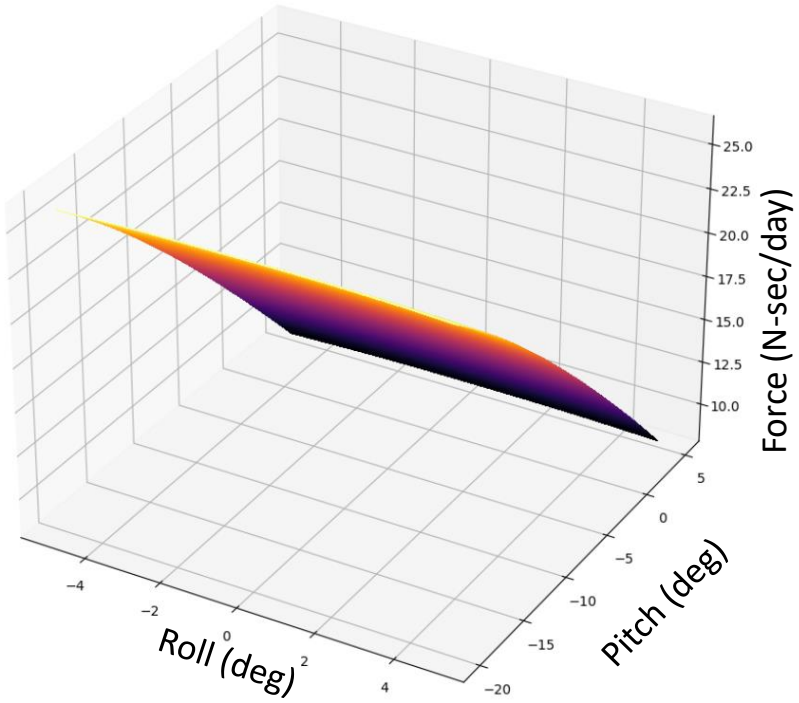




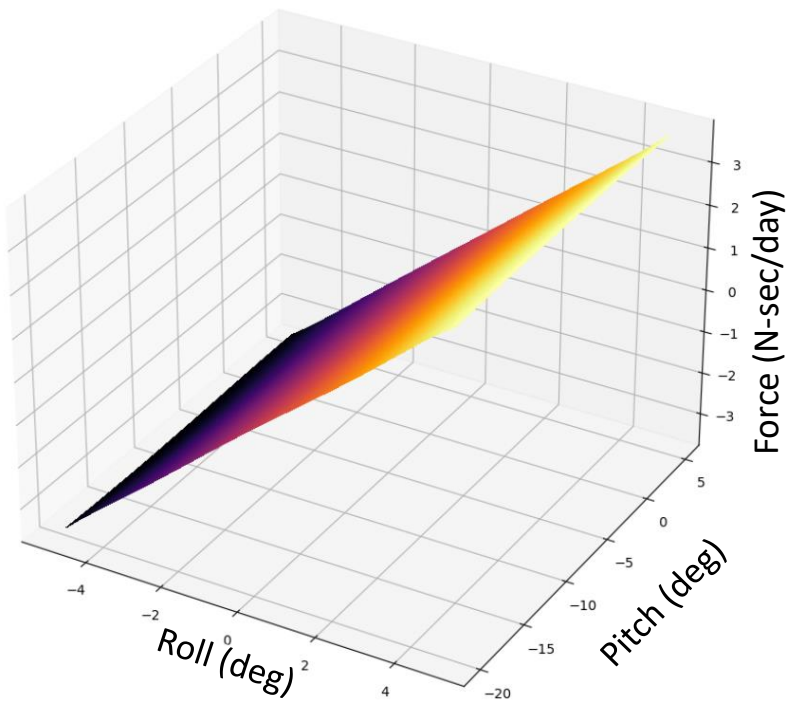
SRP Force

- The force resulting from SRP is highly dependent on attitude

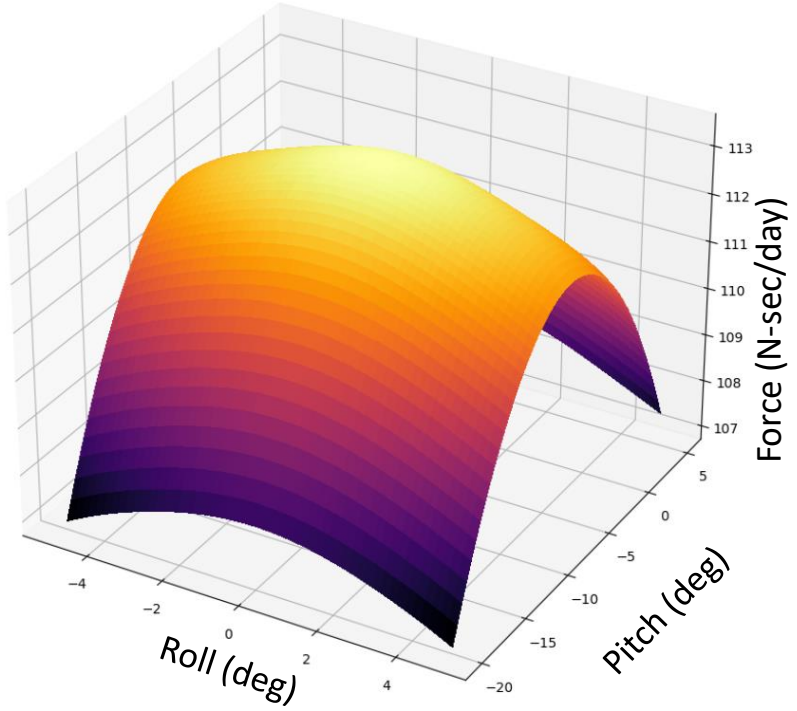
J1 Direction



J2 Direction



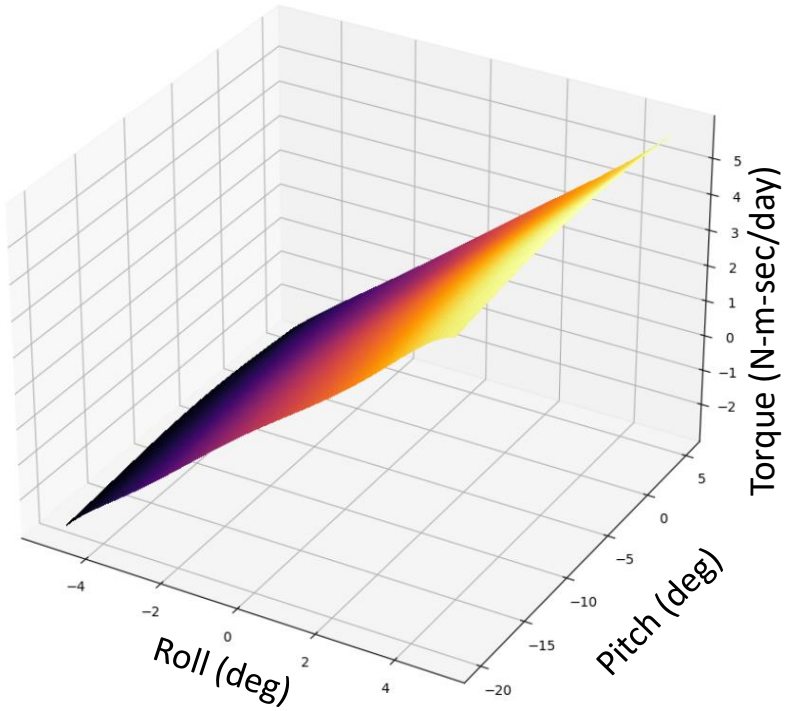
J3 Direction



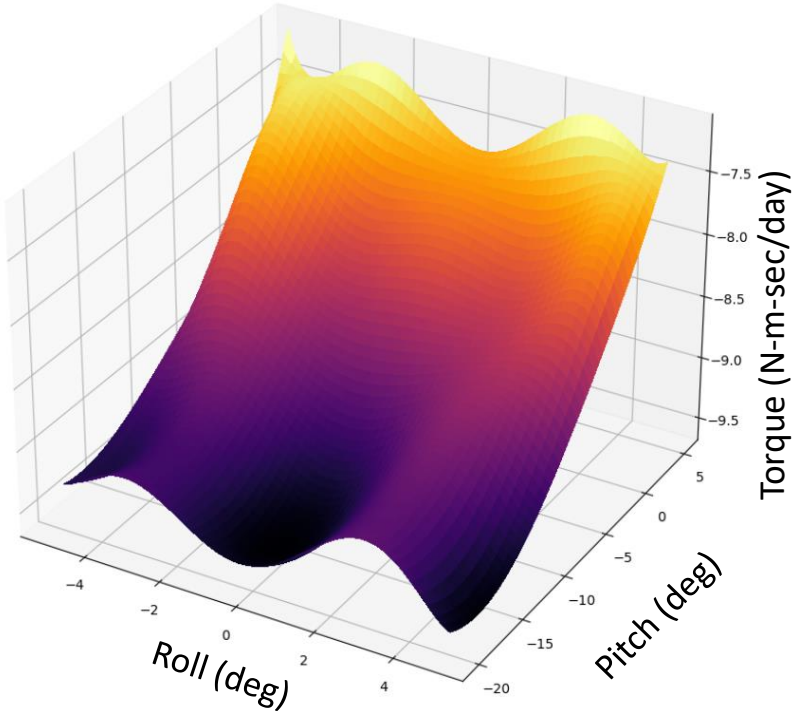
SRP Torque

- The SRP applies a torque to JWST, also dependent on attitude

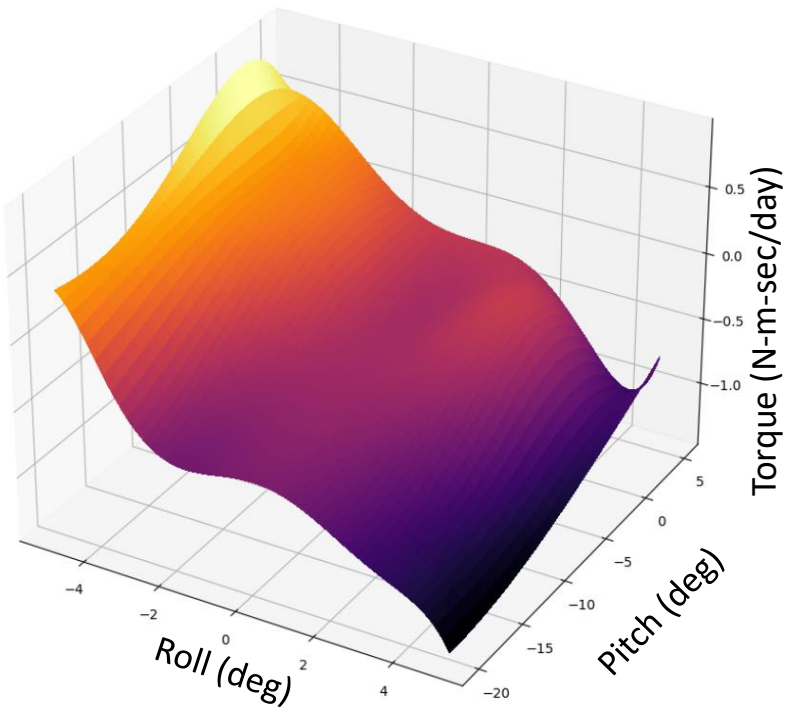
J1 Direction



J2 Direction



J3 Direction



Orbit Determination

Dynamical Modeling

Data Processing

Results & Accuracy

Data Processing

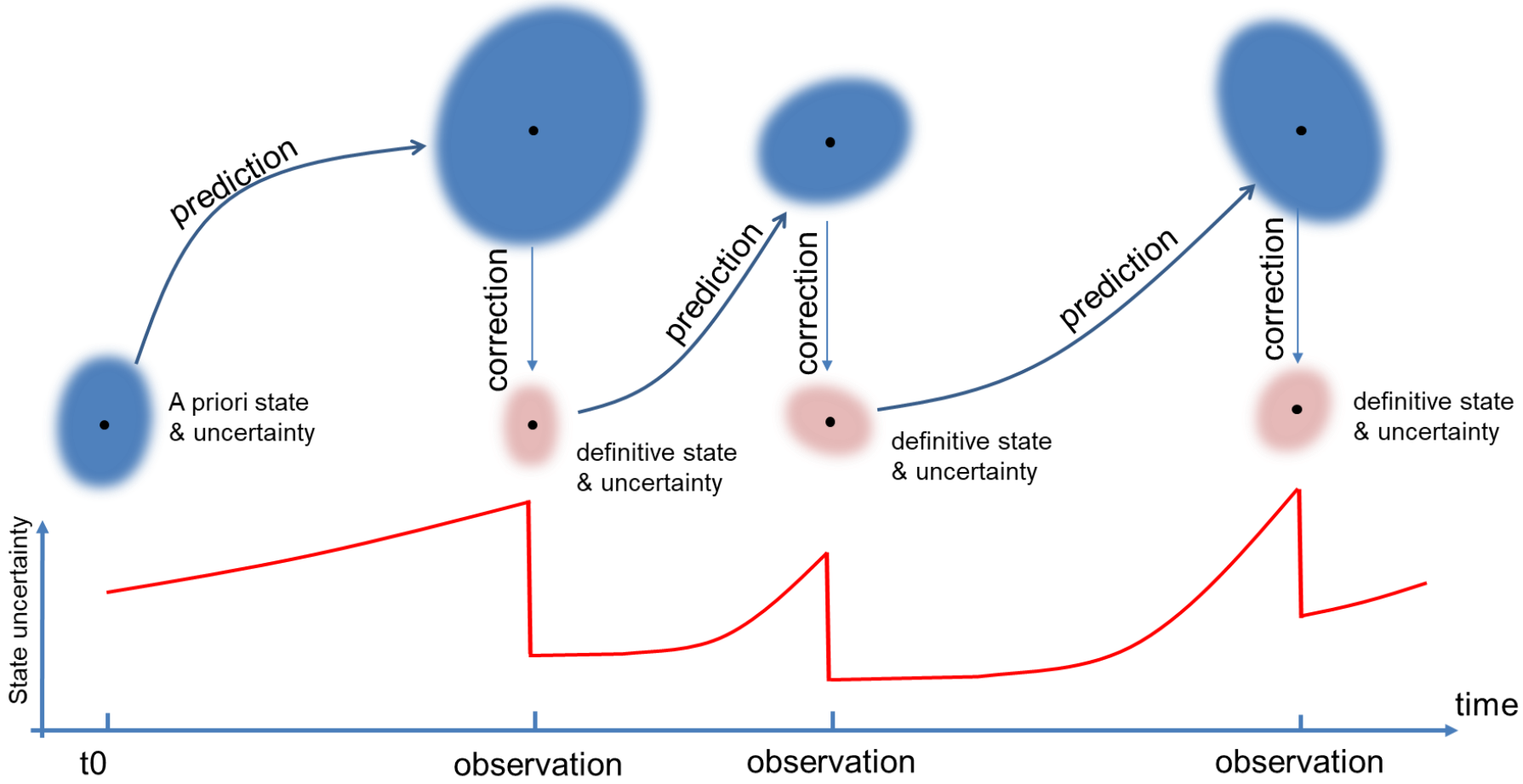
- Measurements
  - DSN regularly tracks JWST with Goldstone, Canberra, and Madrid Stations
    - The FDF uses S-band TRK-2-34 tracking data to accurately compute JWST OD
      - Sequential Range data type
      - Total Count Phase (TCP) data type
  - Corrections
    - Earth's troposphere and ionosphere media
    - Transponder delay

Data Processing

- Filter Tuning
  - Extended Kalman Filter (EKF)
    - 14-day data arc
      - 7-day overlapping period
      - Restart records are used to start the filter
    - Smoother is employed to refine the estimation backward in time
      - The backward smoothing process results in a cohesive and smooth ephemeris over the entire OD span
  - Estimation parameters
    - Orbit state and uncertainty
    - Cr in the direction of the J3 axis

Data Processing

- The EKF combines measurements and prediction to produce corrections to the estimated state and uncertainty



Orbit Determination

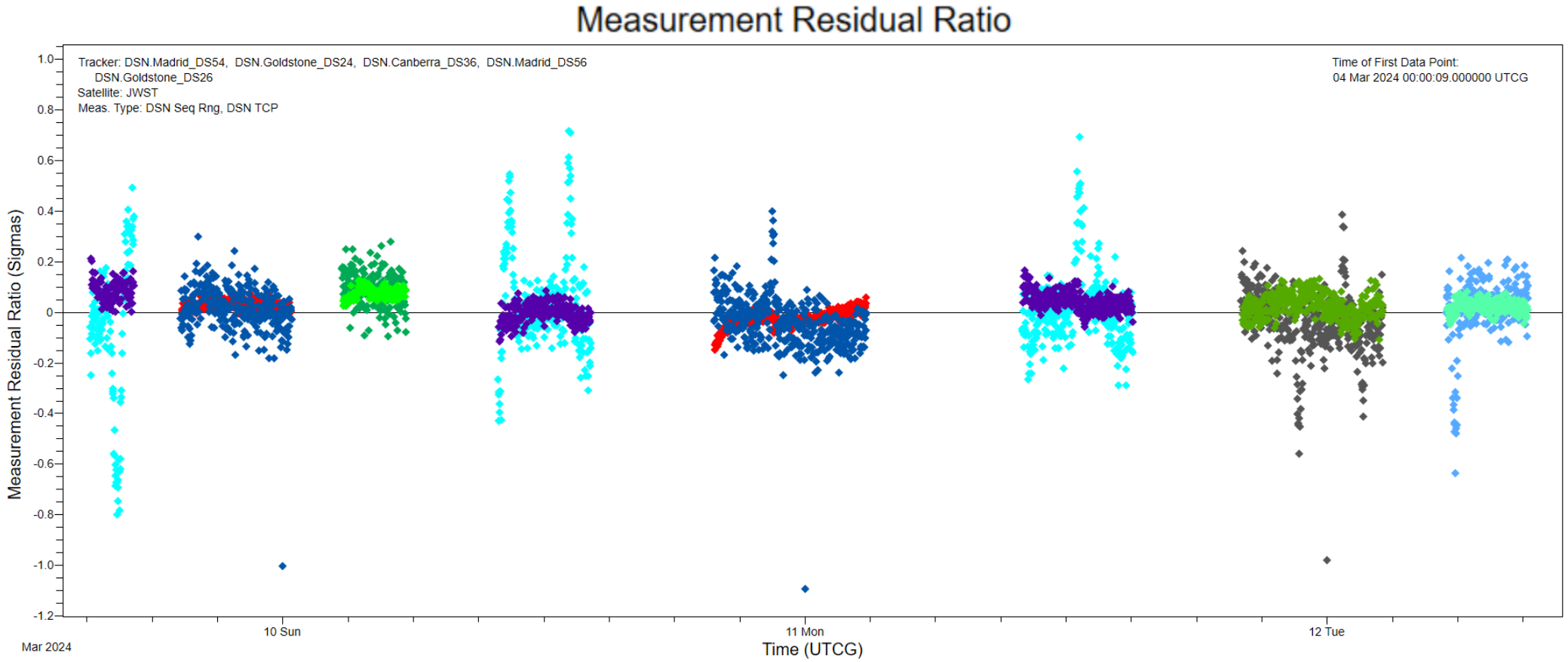
Dynamical Modeling

Data Processing

Results & Accuracy

Orbit Accuracy

- Residual ratios <3σ show the measurements fit the solution

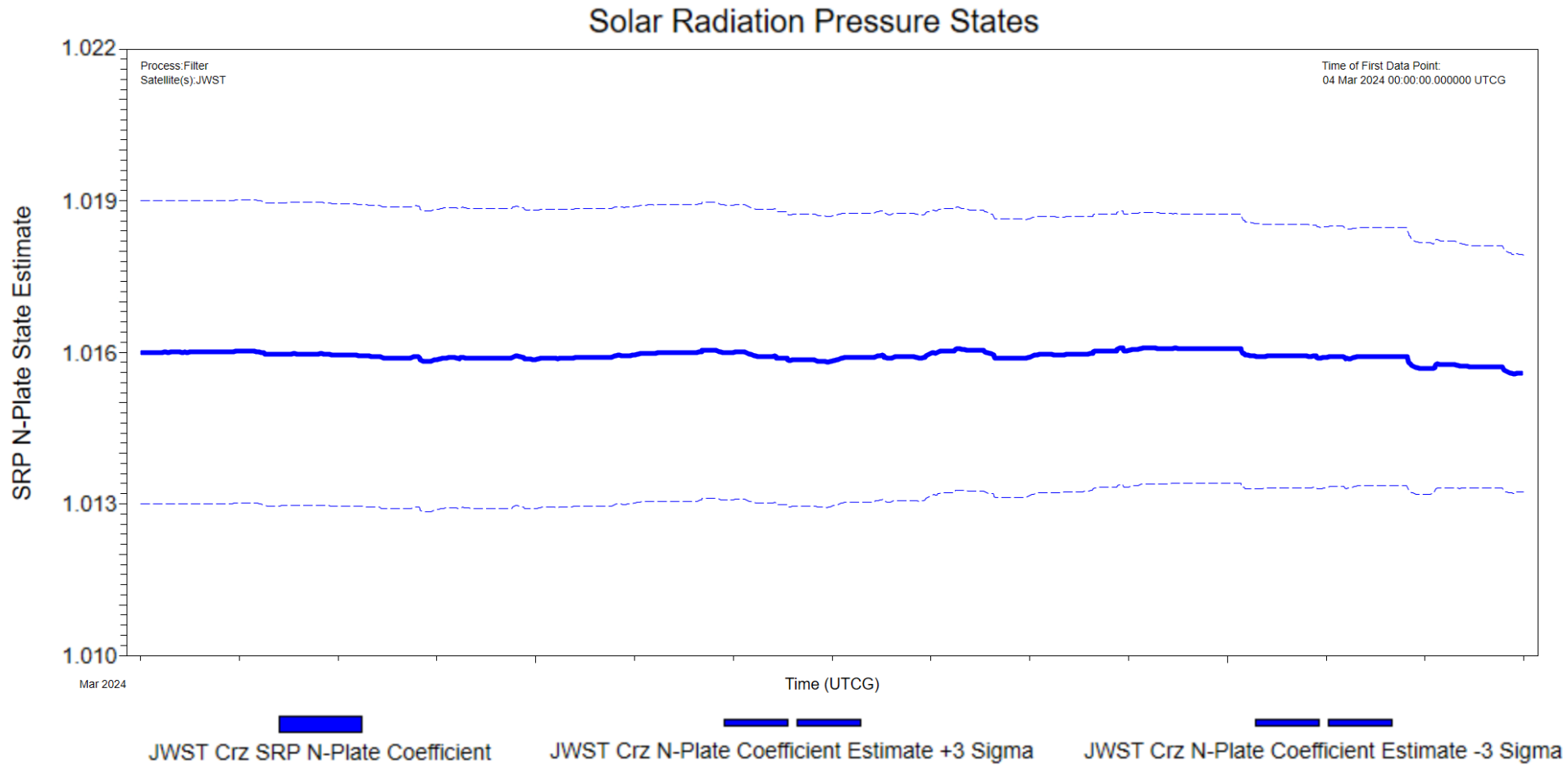


DSN Seq. Range Residuals

DSN TCP Residuals

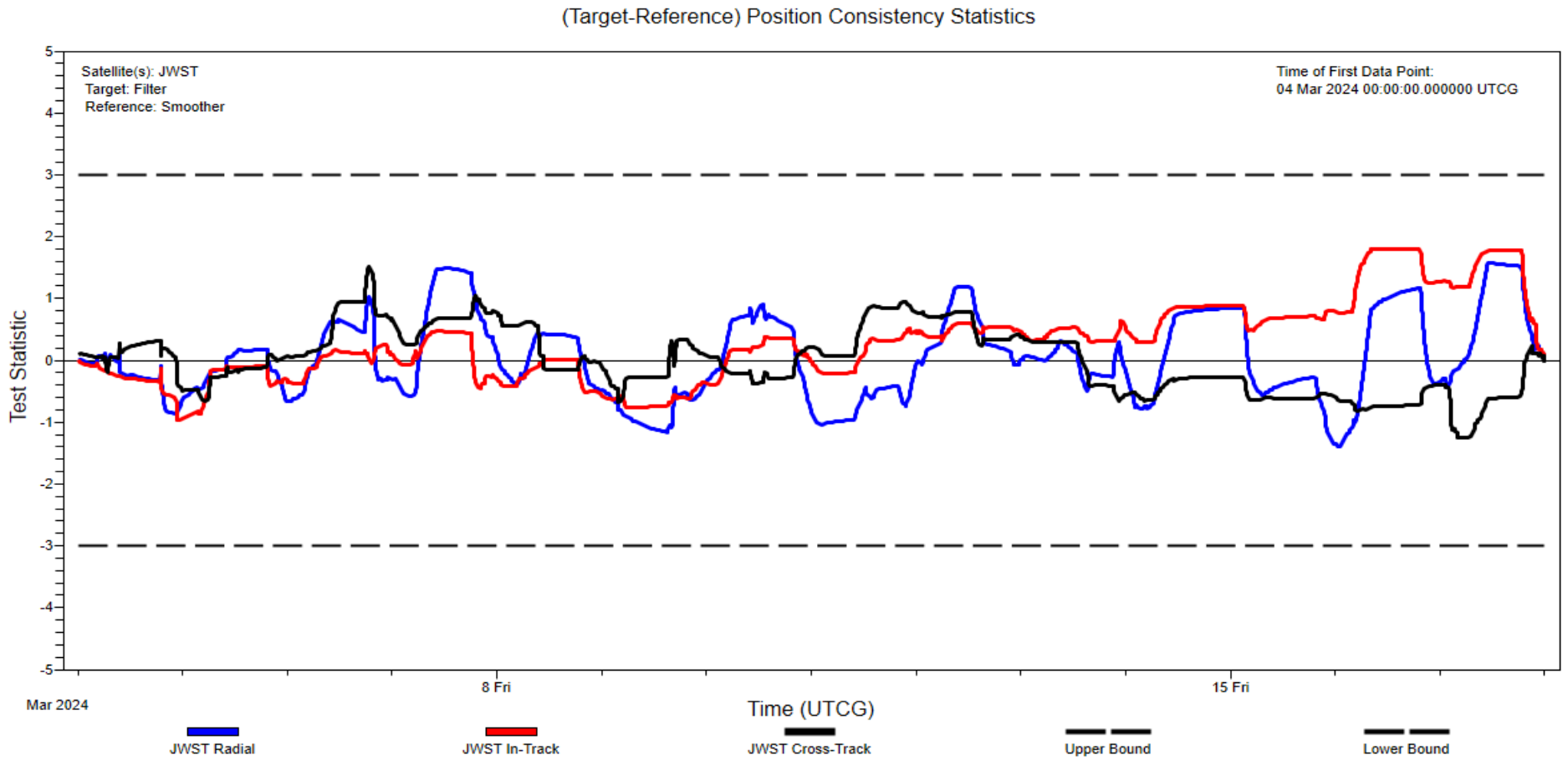
Orbit Accuracy

- SRP State estimate is stable



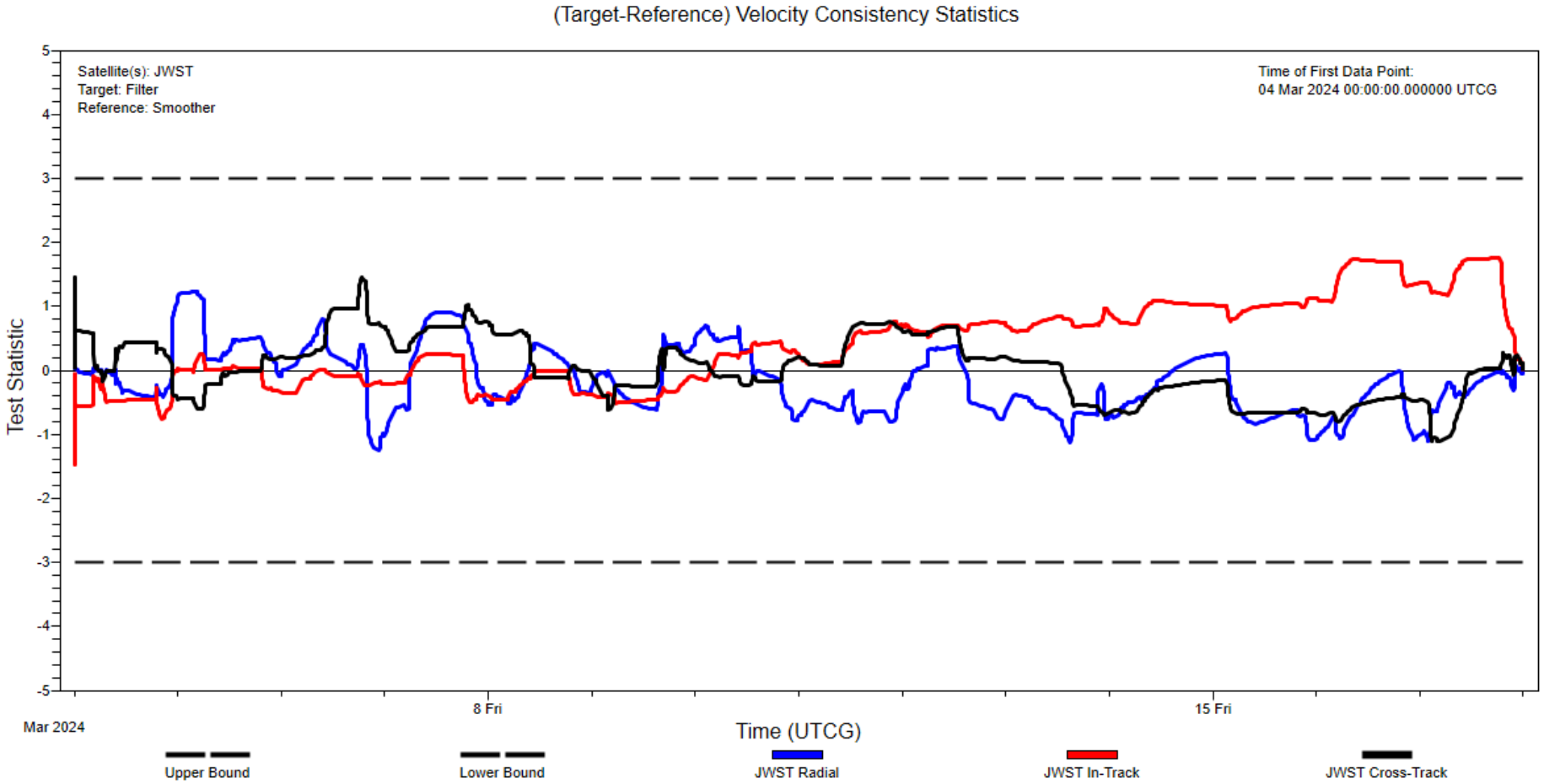
Orbit Accuracy

- The filter and smoother position estimates are consistent



Orbit Accuracy

- The filter and smoother velocity estimates are consistent



Maneuver Planning

Targeting Parameters

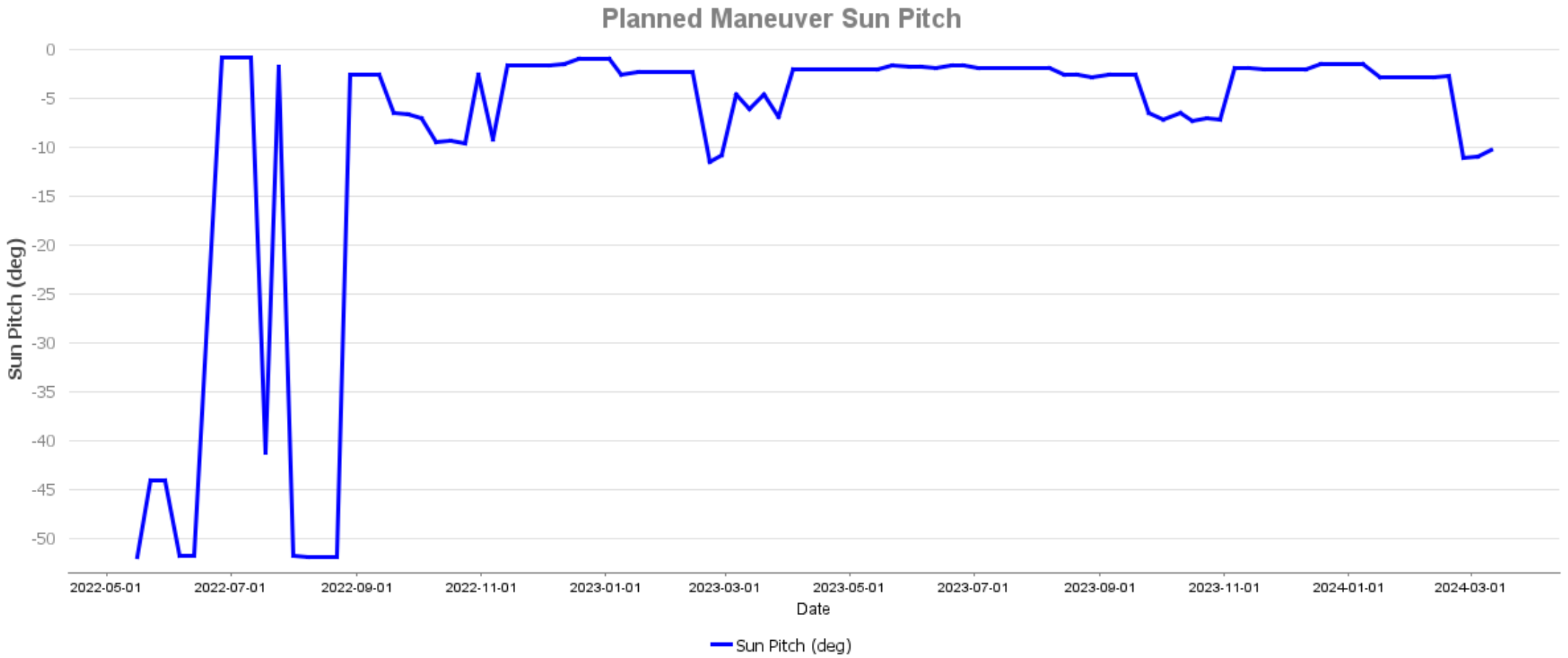
Neutral SRP Calibration

Maneuver Performance

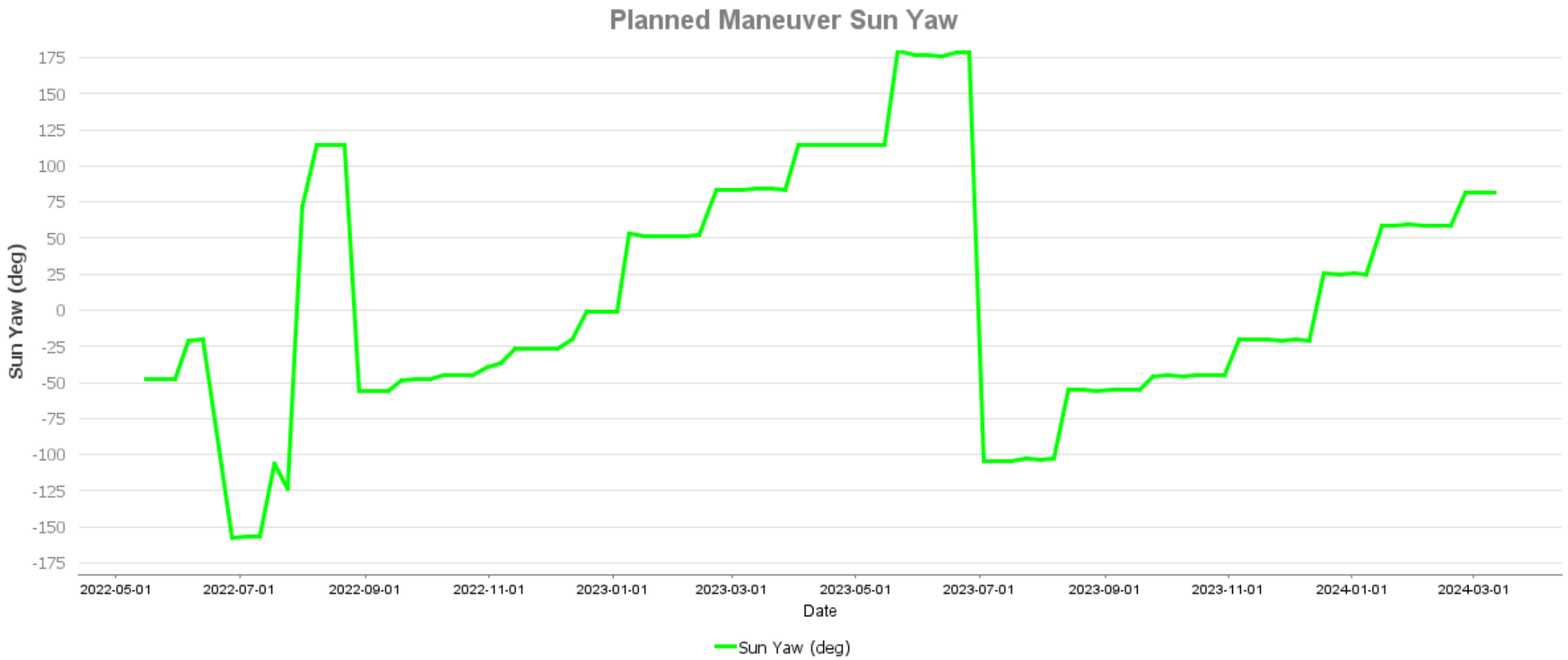
Maneuver Planning

- JWST conducts regular station-keeping (SK) maneuvers for orbit maintenance
  - These maneuvers are necessary due to the inherent instability of the L2 libration point
- Planning a maneuver involves:
  - Applying targeting constraints to a definitive OD state to ascertain the delta-v
  - Estimating finite burn duration
  - Short- and long-term trajectory predictions
    - Long-term trajectory predictions model a series of impulsive balancing maneuvers
    - Balancing maneuvers are targeted to occur twice per orbit to simulate the overall effect of SKs for multi-year predictions

Maneuver Planning



Maneuver Planning



Maneuver Planning

Targeting Parameters

Neutral SRP Calibration

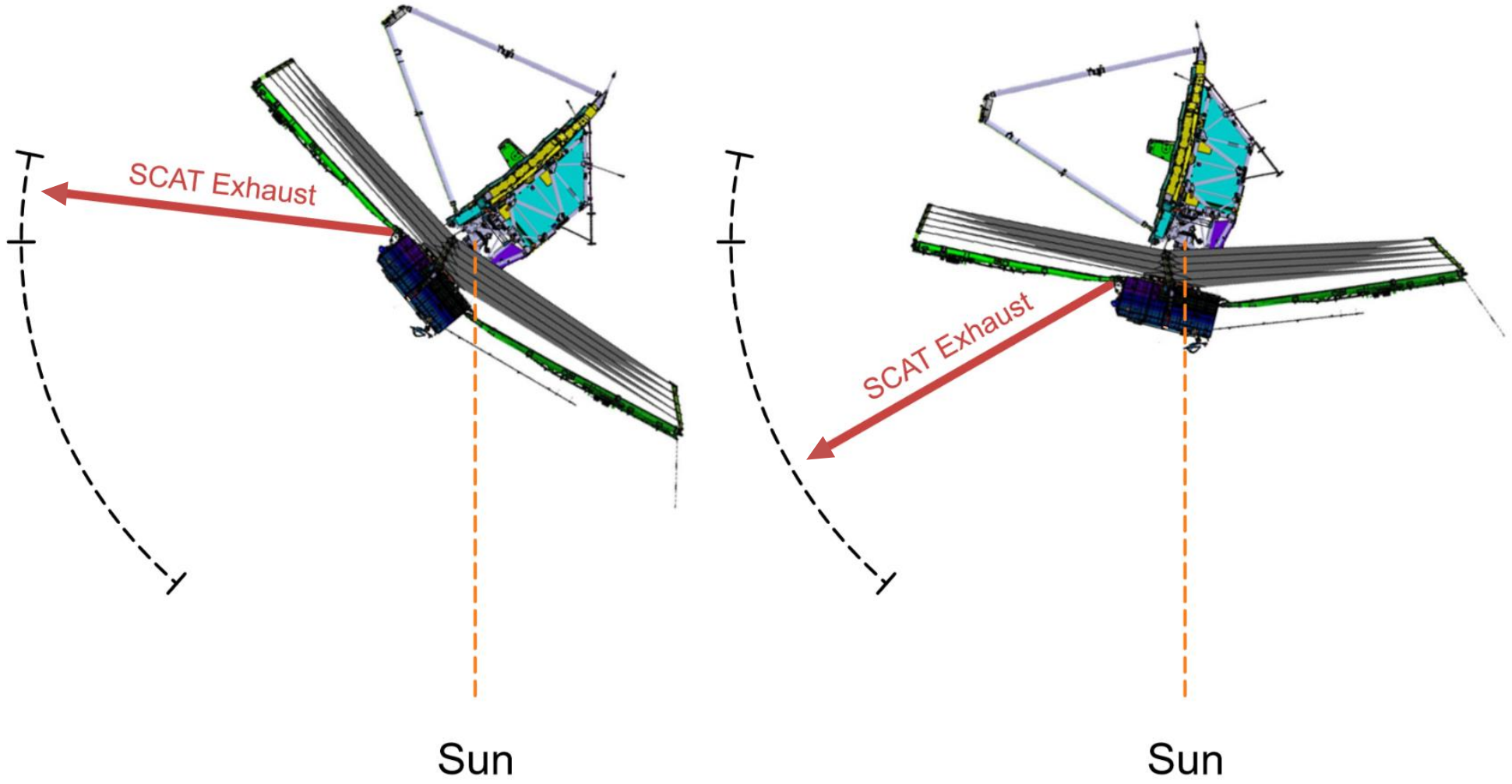
Maneuver Performance

Targeting Parameters

- Anti-Sunward maneuvers
- Consecutive perpendicular RLP X crossings
- Post-maneuver attitude and SRP J3 coefficient

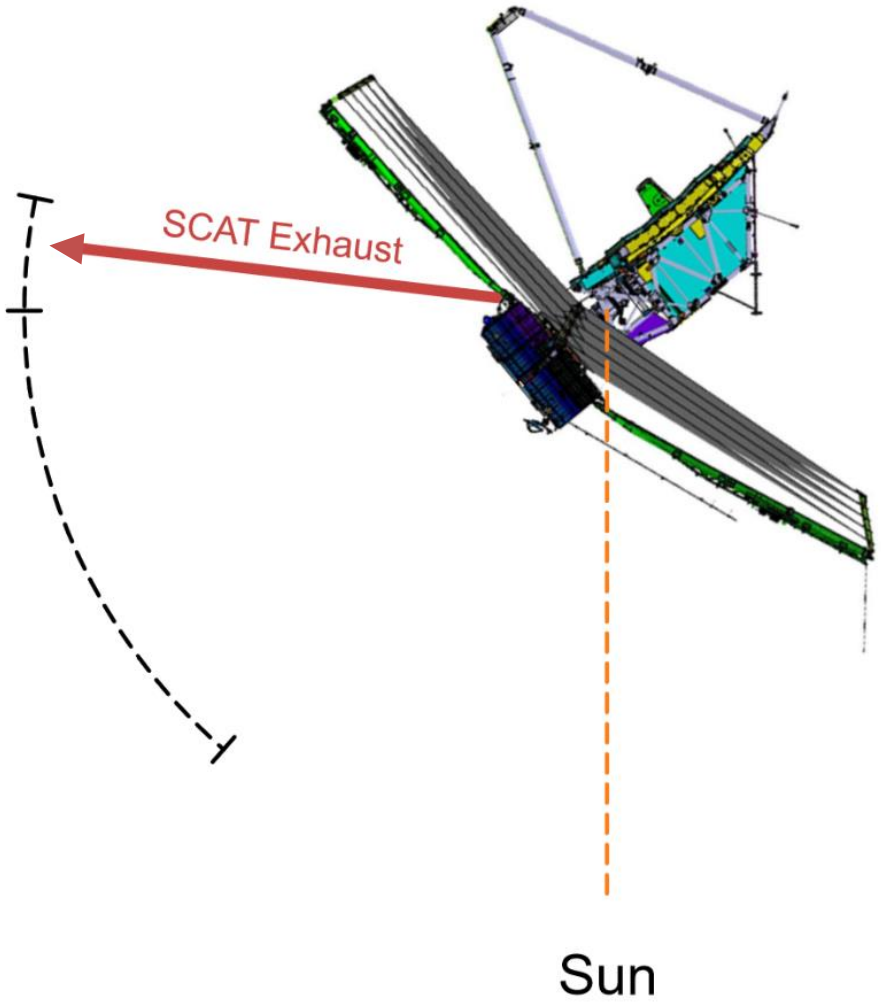
Targeting Parameters

- SCAT = Secondary Combustion Augmented Thrusters

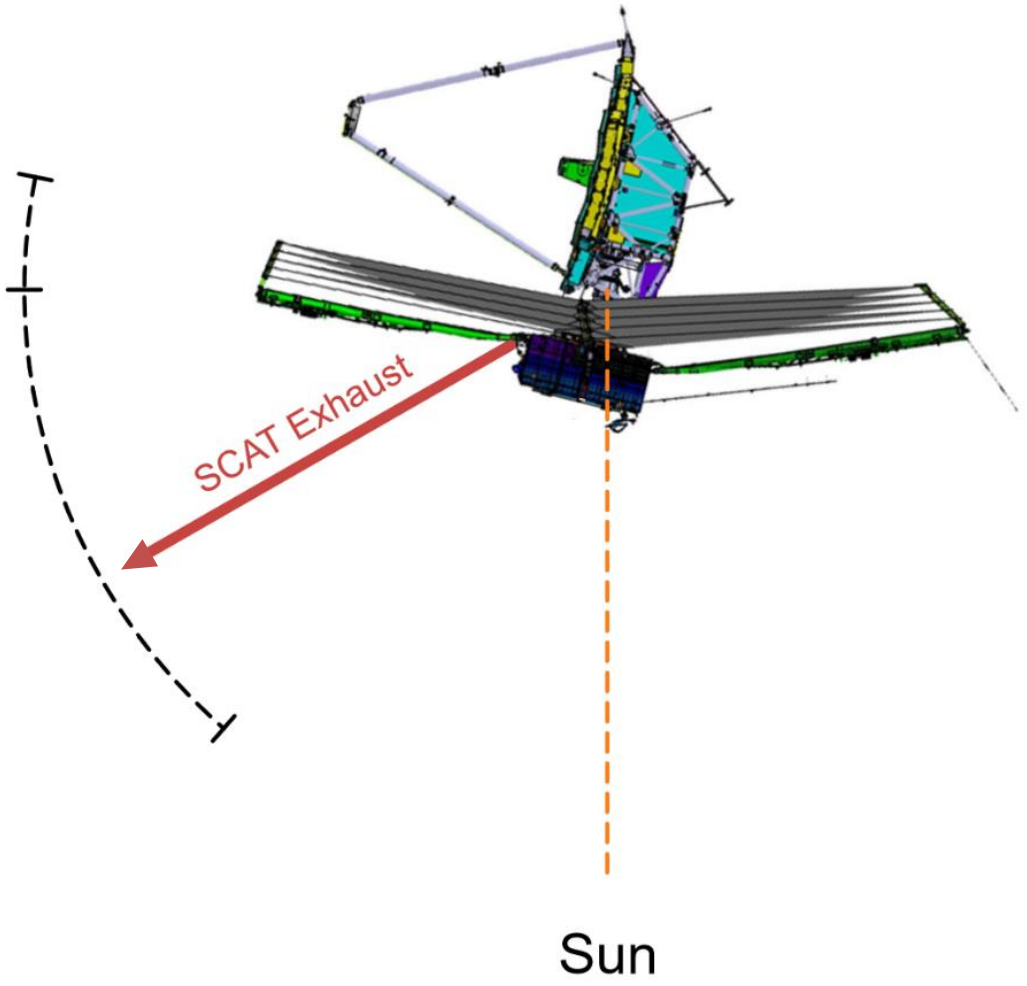


Targeting Parameters

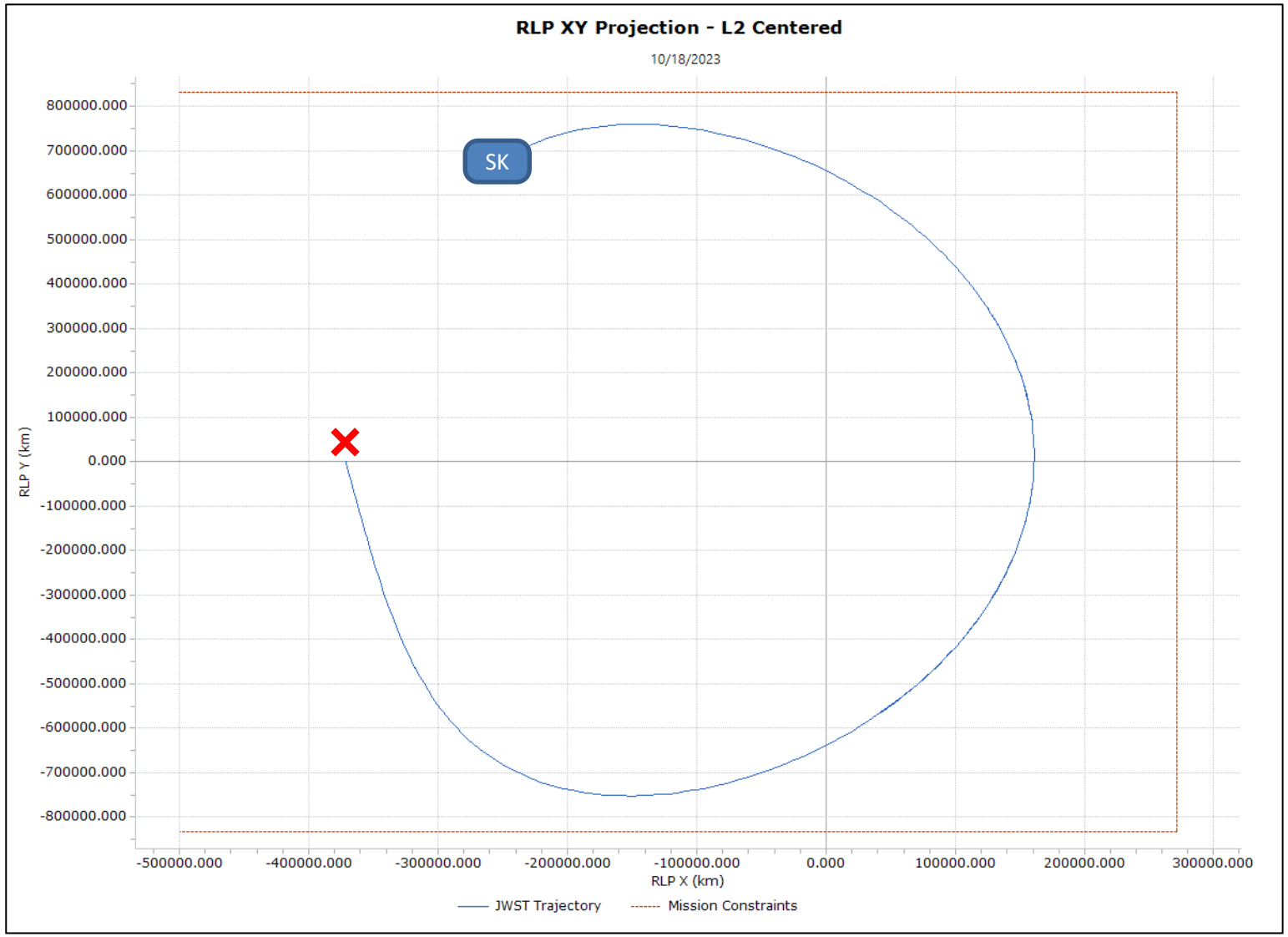
Sunward Maneuver ⊘



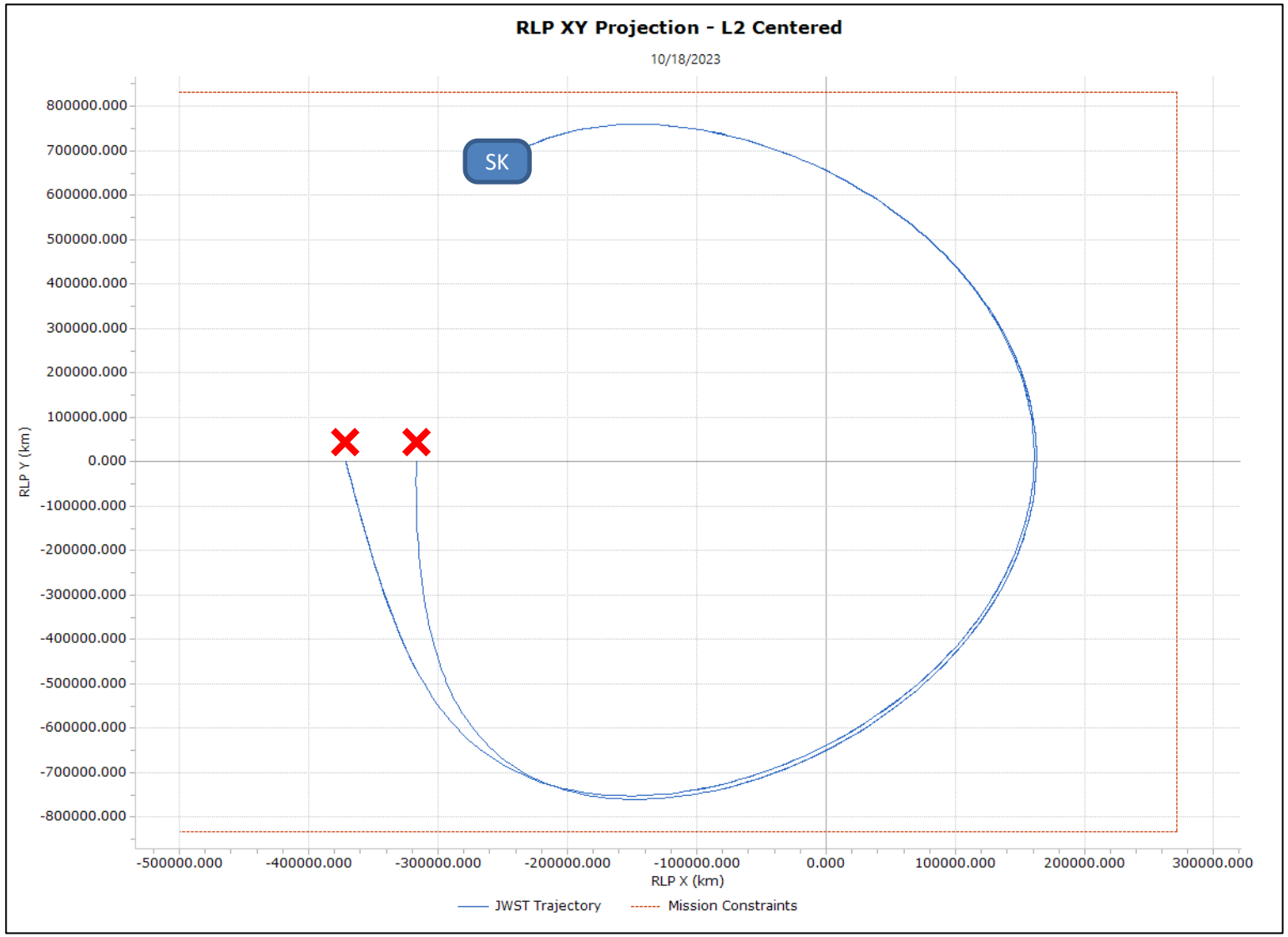
Anti-Sunward Maneuver ✓



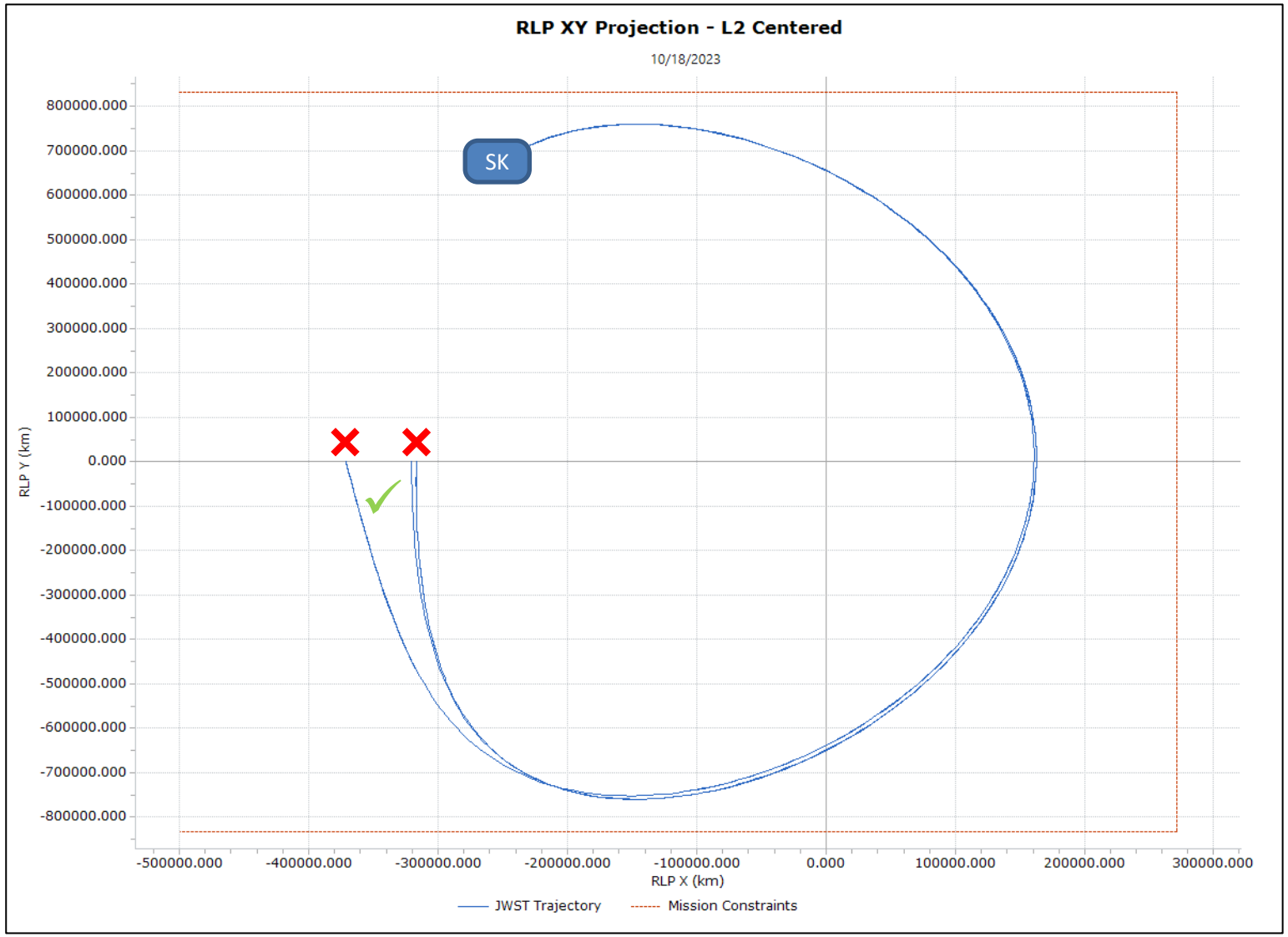
Station-Keeping Maneuver Targeting – Crossing 2 / Iteration 1



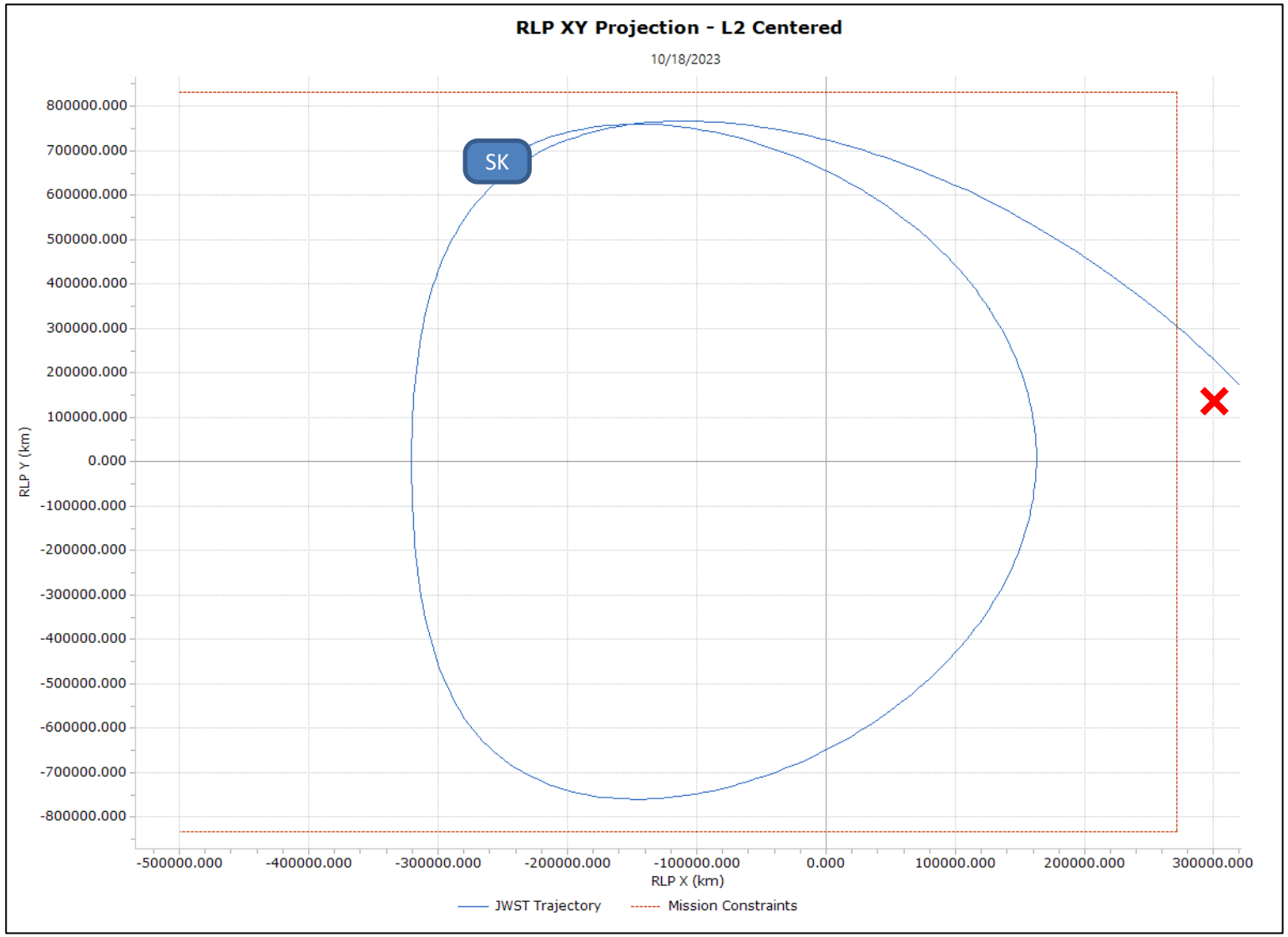
Station-Keeping Maneuver Targeting – Crossing 2 / Iteration 2



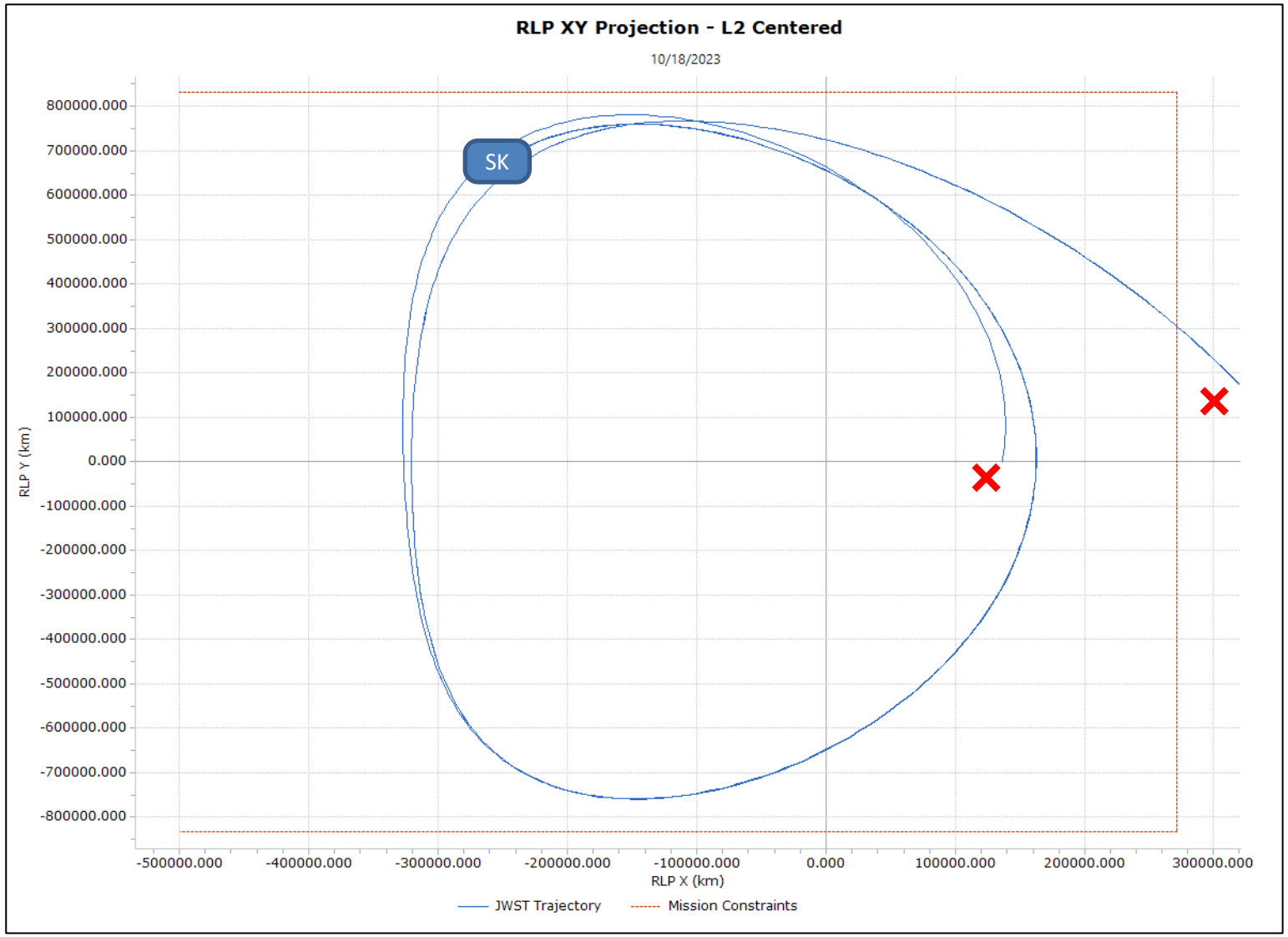
Station-Keeping Maneuver Targeting – Crossing 2 / Iteration 3



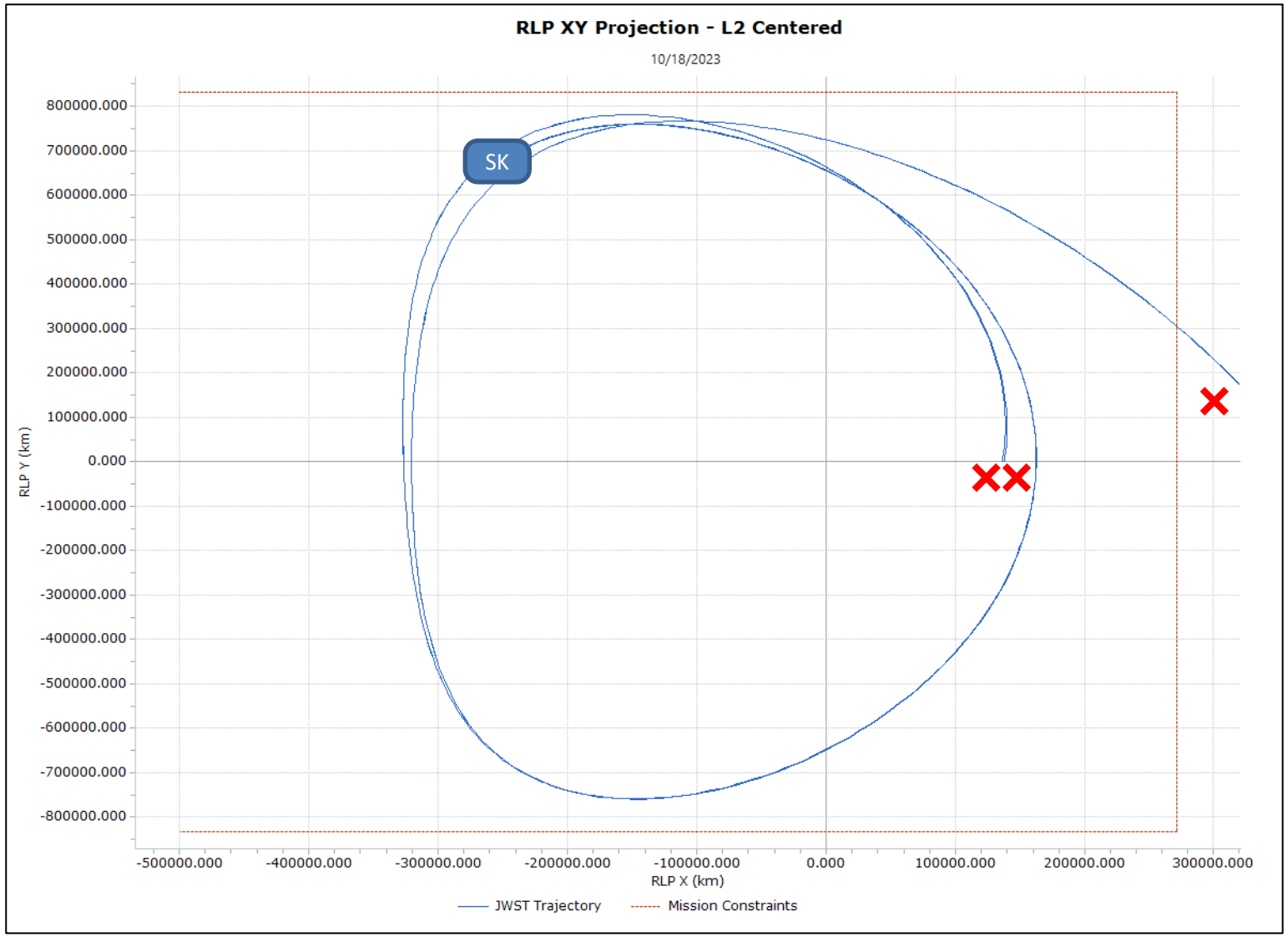
Station-Keeping Maneuver Targeting – Crossing 3 / Iteration 1



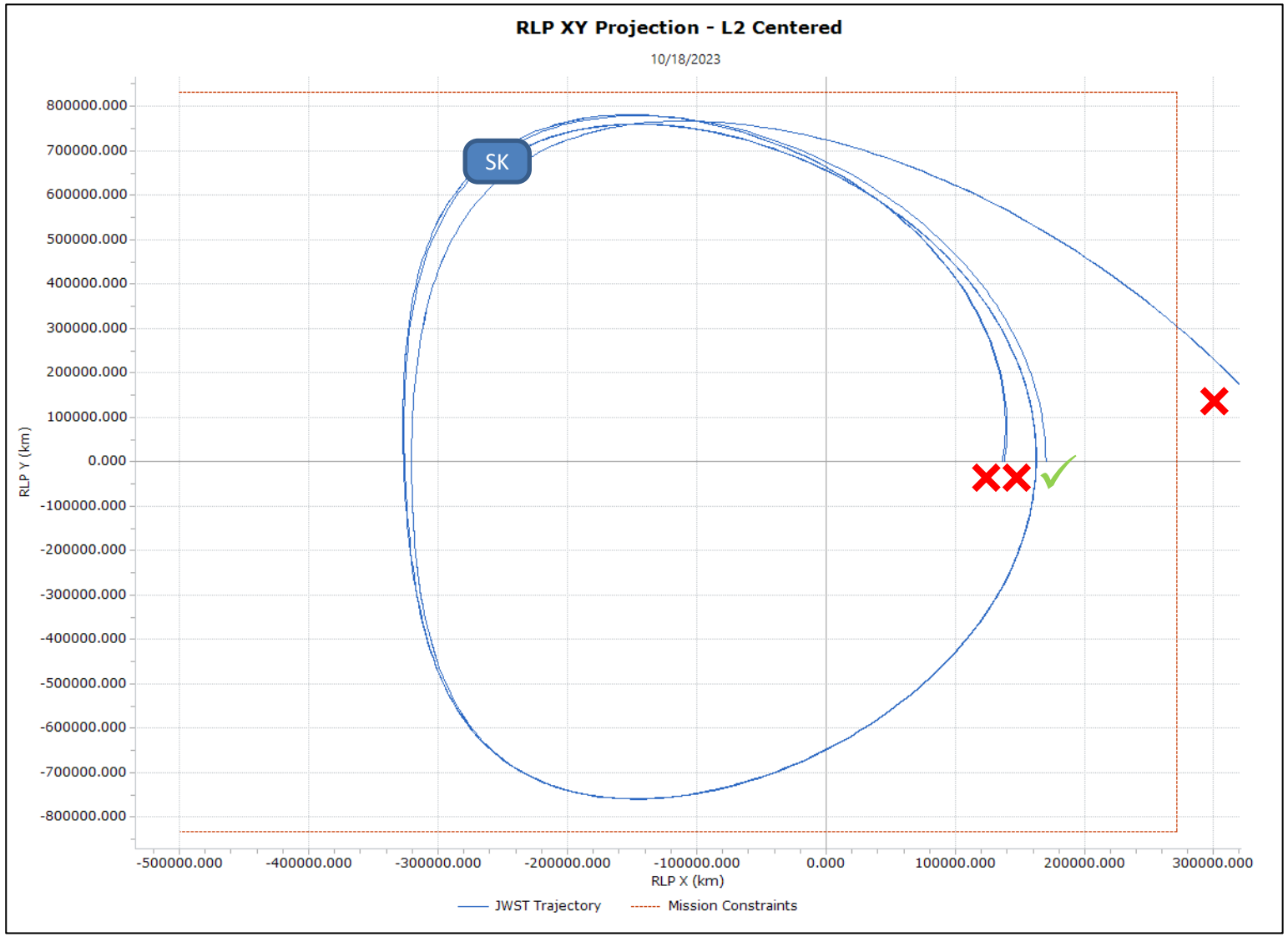
Station-Keeping Maneuver Targeting – Crossing 3 / Iteration 2



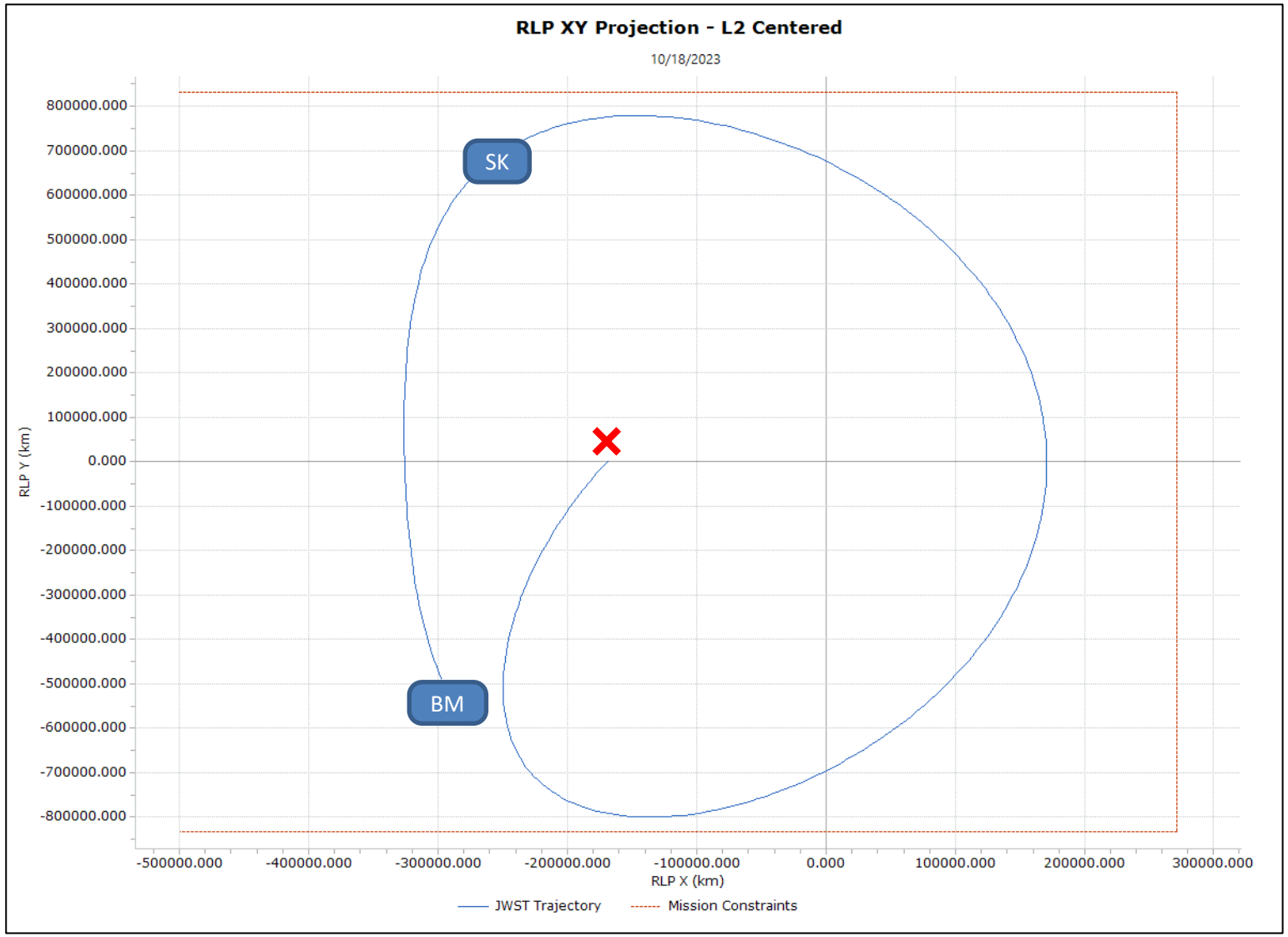
Station-Keeping Maneuver Targeting – Crossing 3 / Iteration 3



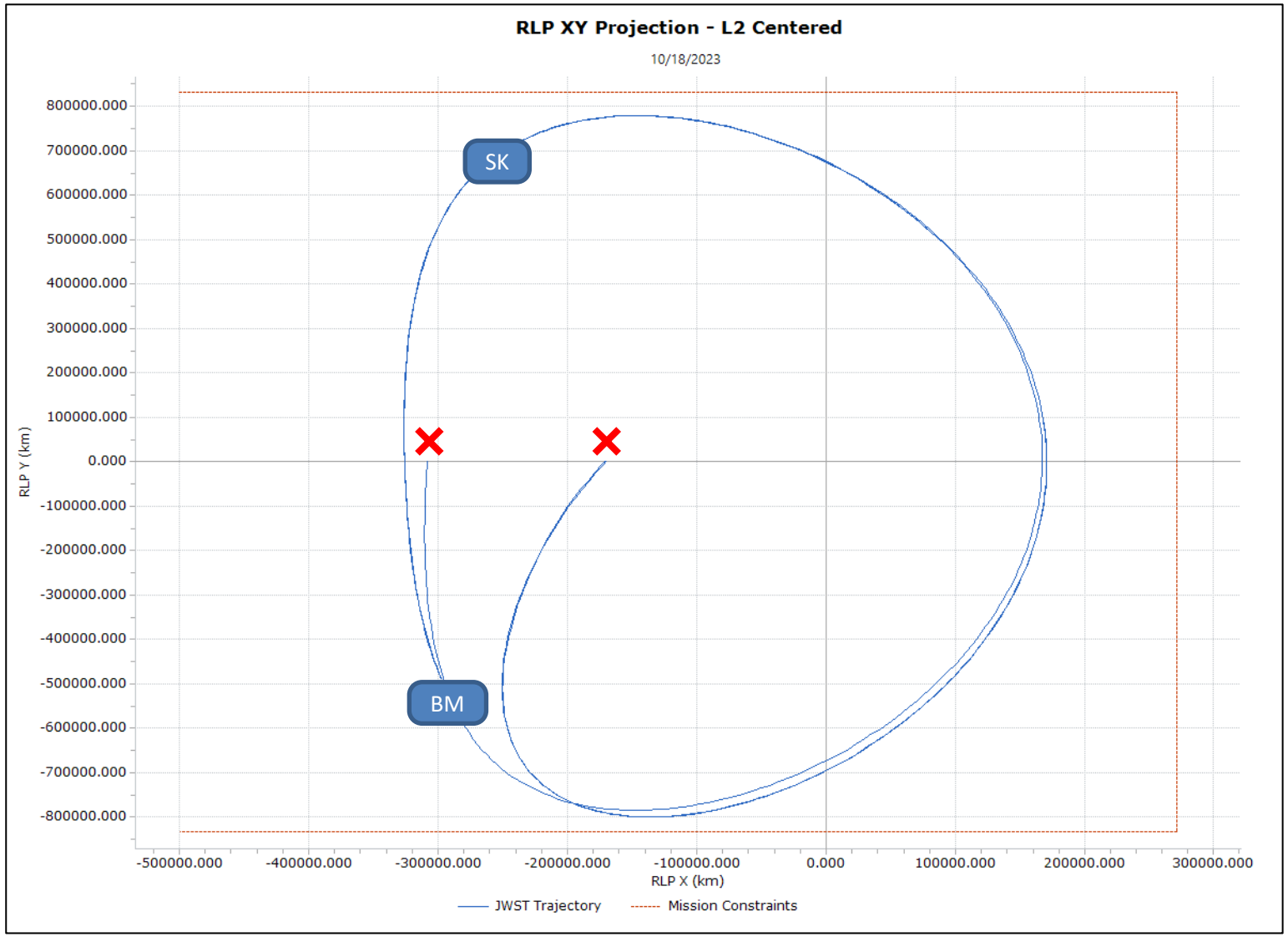
Station-Keeping Maneuver Targeting – Crossing 3 / Iteration 4



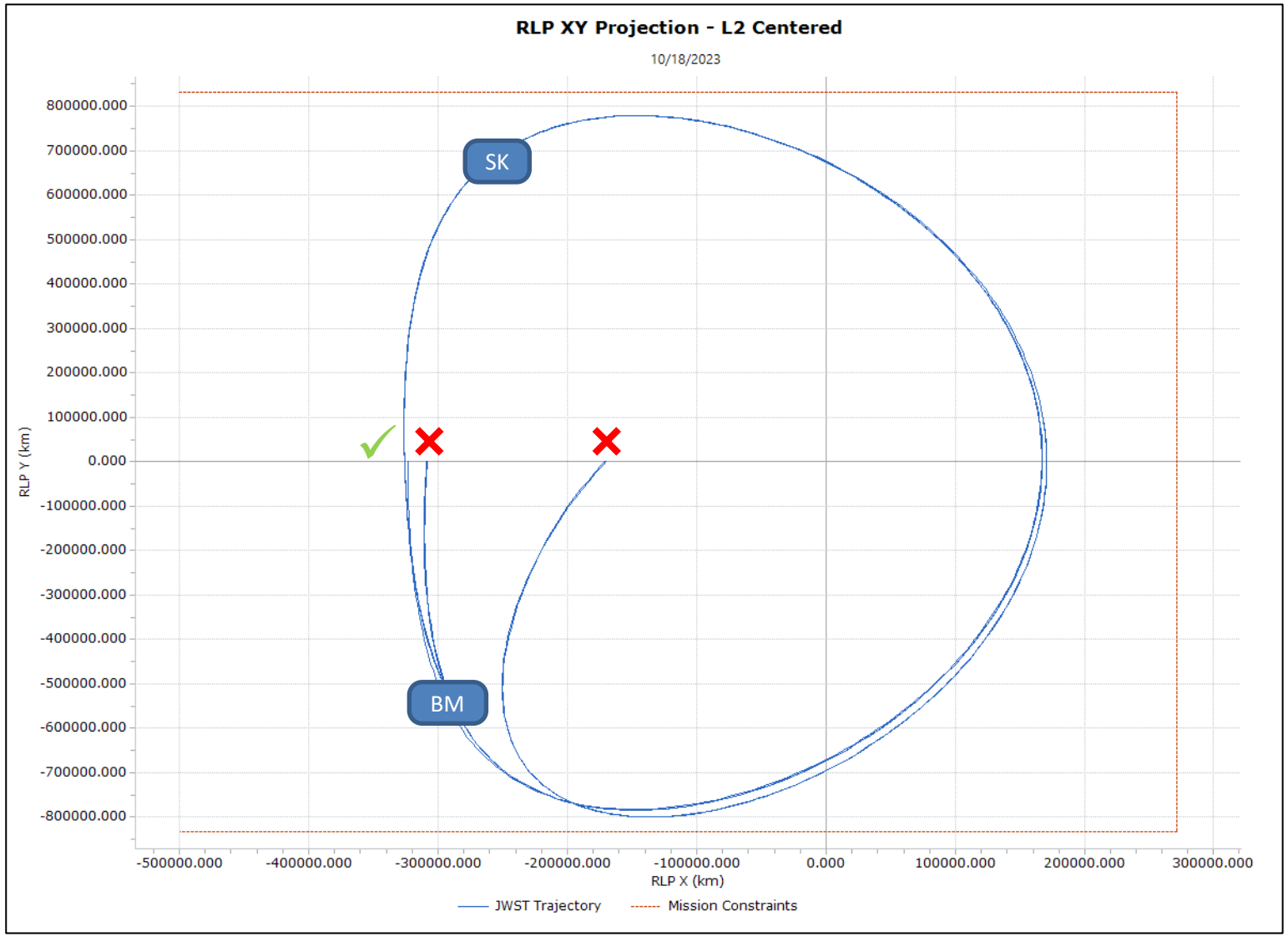
Balancing Maneuver Targeting – Crossing 3 / Iteration 1



Balancing Maneuver Targeting – Crossing 3 / Iteration 2



Balancing Maneuver Targeting – Crossing 3 / Iteration 3

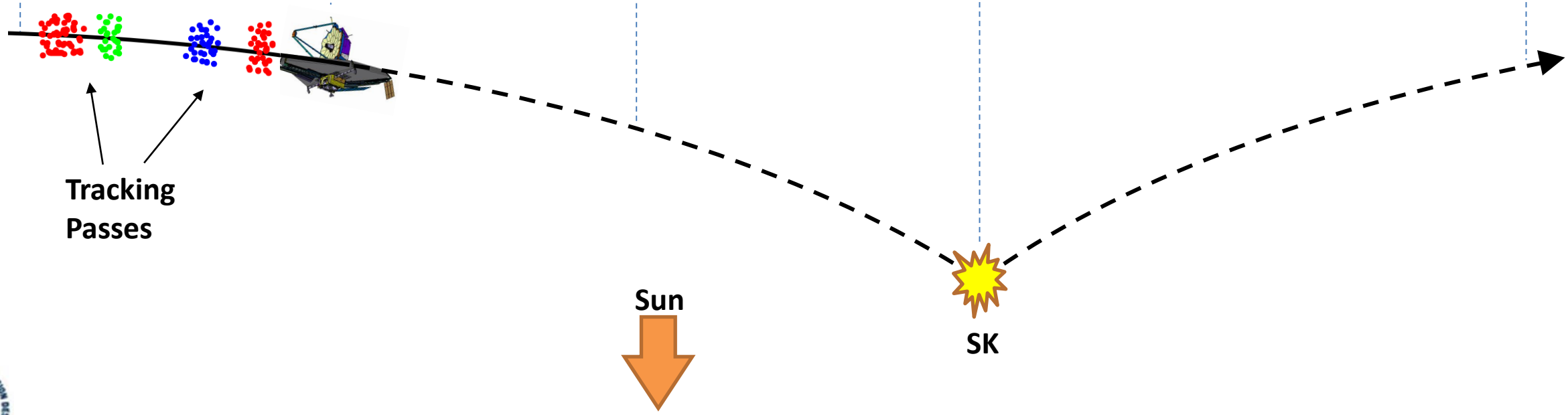


Targeting Parameters

- Because JWST's attitude influences its dynamics heavily (due to SRP), it becomes necessary to carefully model the predictive attitude
- However, long term predictive attitude is not readily available
  - Simplified long term predictive attitude strategy must be used
- The following slides described this strategy

Targeting Parameters

	Definitive Orbit	Pre-Maneuver Orbit Prediction	Pre-Maneuver Orbit Prediction	Post-Maneuver Orbit Prediction
Attitude Model	Attitude History Data	Short Range Attitude Plan (SRAP)	Sun-Pointing Neutral	Sun-Pointing Neutral
Cr_Z	Definitive (~1.02)	Definitive (~1.02)	Neutral (~0.94)	Definitive (~1.02)



Maneuver Planning

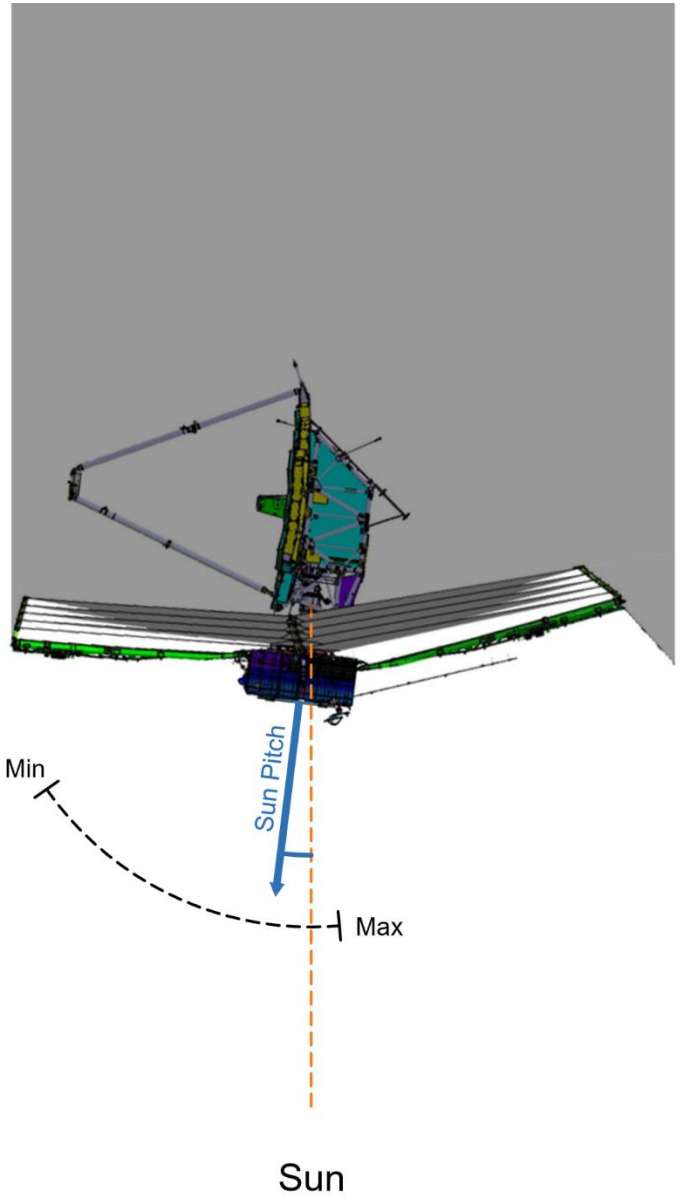
Targeting Parameters

Neutral SRP Calibration

Maneuver Performance

Neutral SRP Calibration

- The Sun-Pointing Neutral (SPN) attitude mode aligns the net SRP force along the JWST-to-Sun vector
  - Makes it independent of JWST's angle of rotation about this vector
  - Particularly useful for long-term orbit predictions
  - Assumes SRP-Max conditions when combined with definitive SRP coefficient

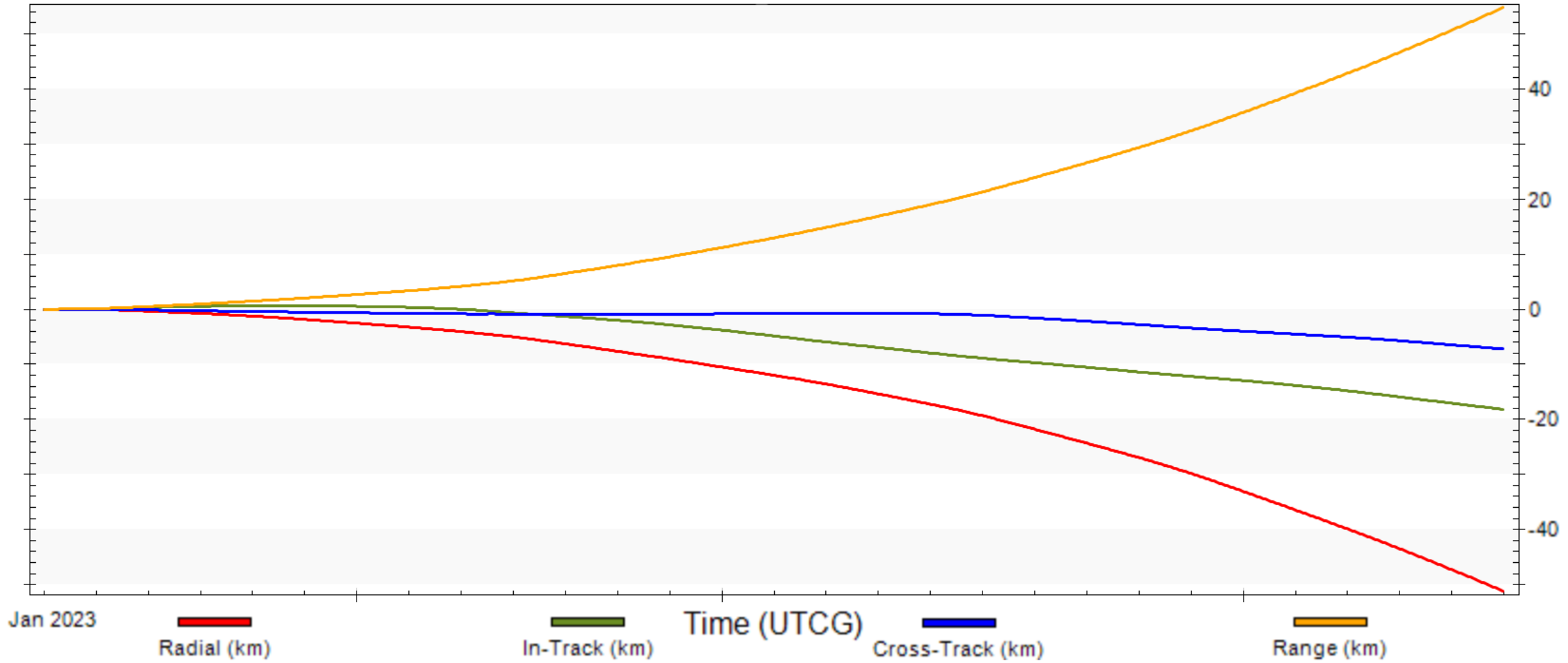


Neutral SRP Calibration

- Calibration of the neutral SRP coefficient is achieved by performing iterative SPN propagation tests
  - Goal: Determine the value that minimizes the prediction error versus the definitive trajectory
  - The optimal neutral SRP coefficient correlates with the average sun pitch angle of the spacecraft
- The neutral SRP calibration results are aggregated to produce the final coefficient to be used for maneuver targeting and trajectory prediction

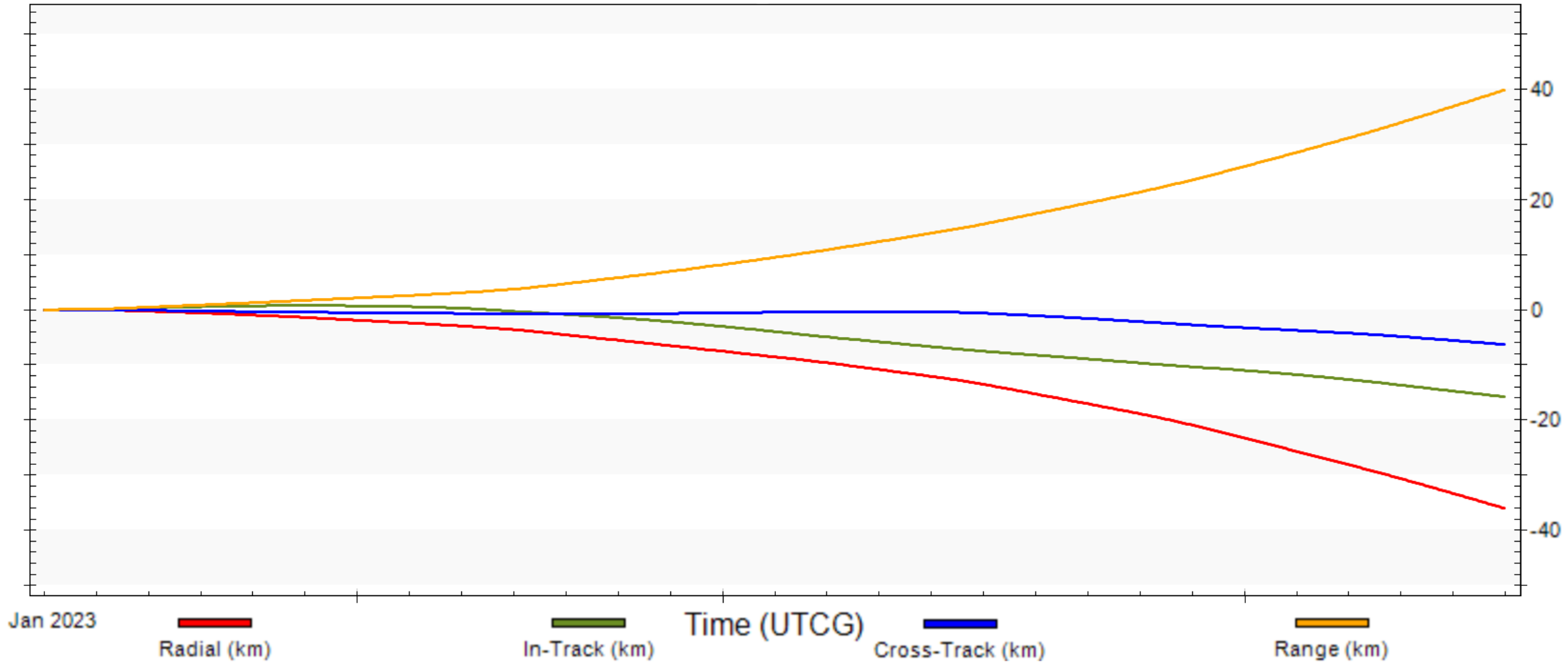
Neutral SRP Calibration

Cr_Z = 1.02187 **Max ΔR = 55.0 km**



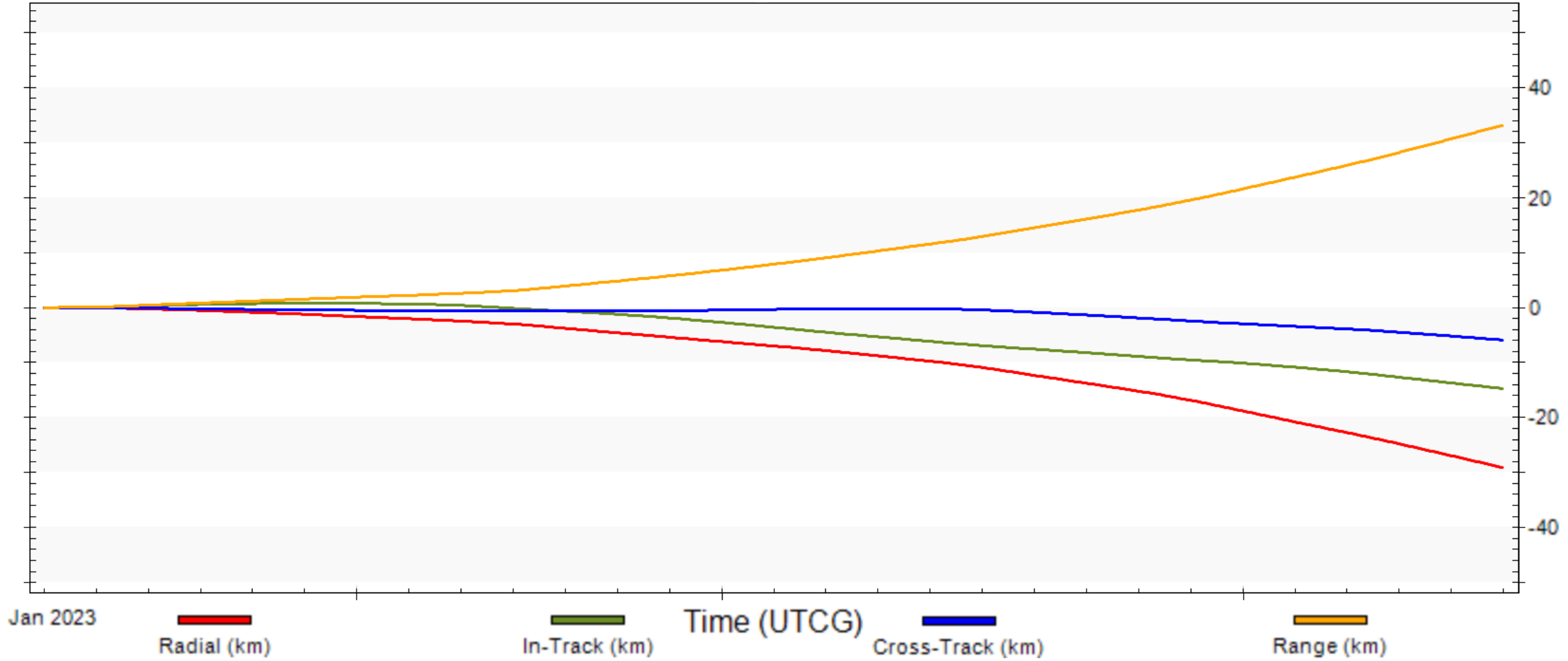
Neutral SRP Calibration

Cr_Z = 1.00 **Max ΔR = 40.0 km**



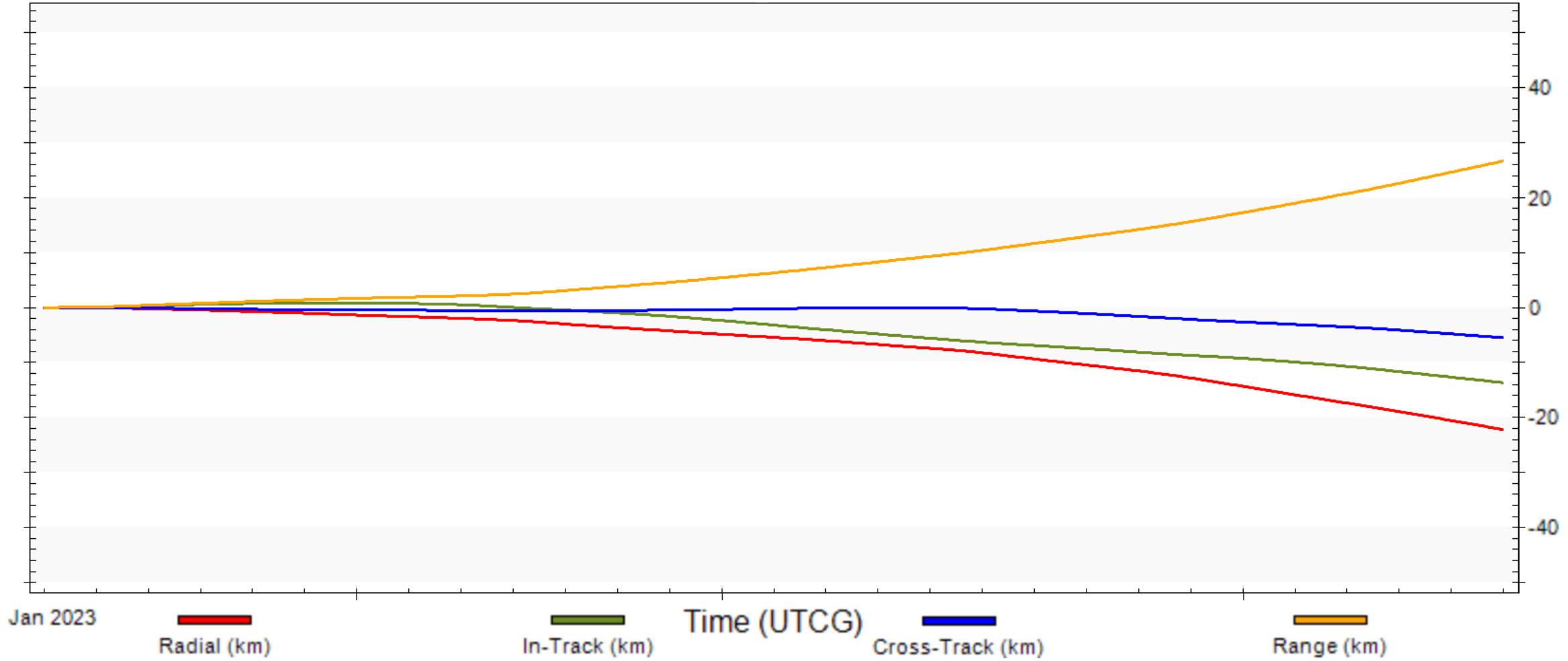
Neutral SRP Calibration

Cr_Z = 0.99 **Max ΔR = 33.0 km**



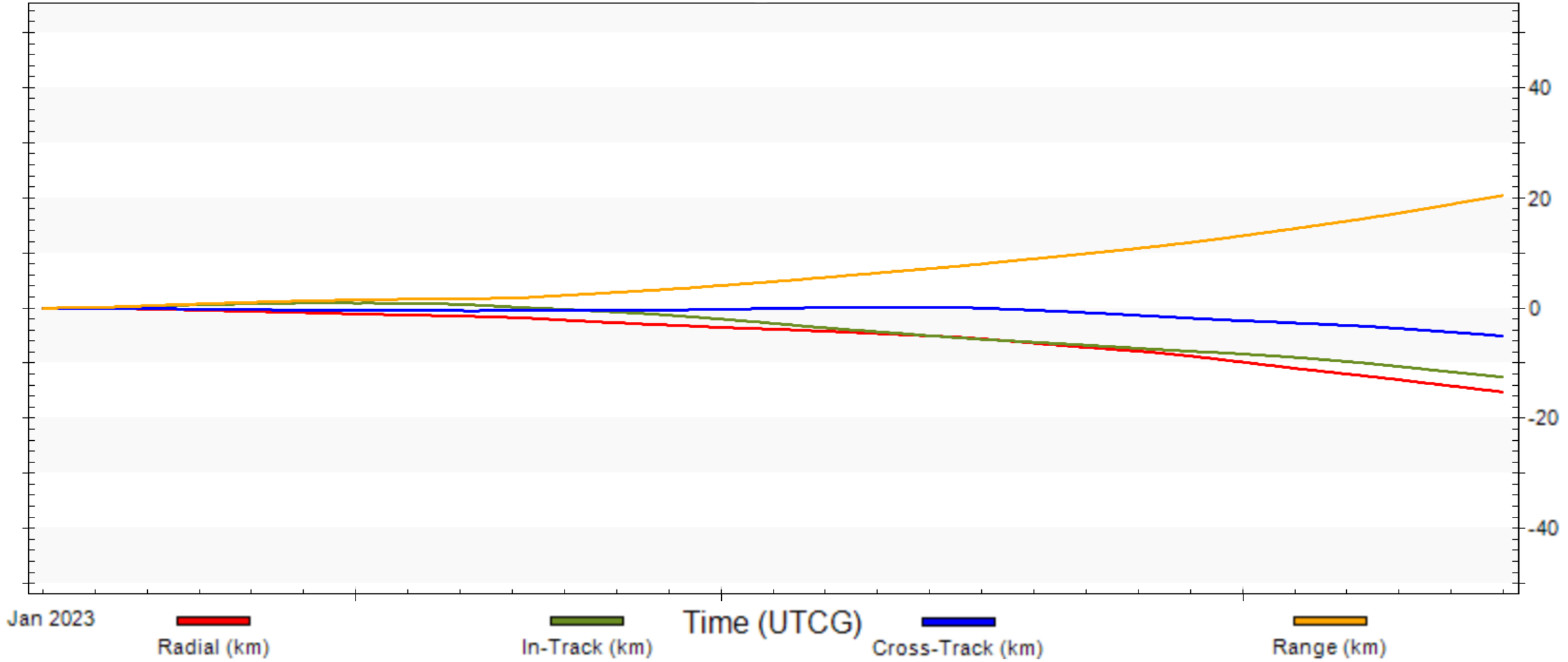
Neutral SRP Calibration

Cr_Z = 0.98 **Max ΔR = 26.5 km**



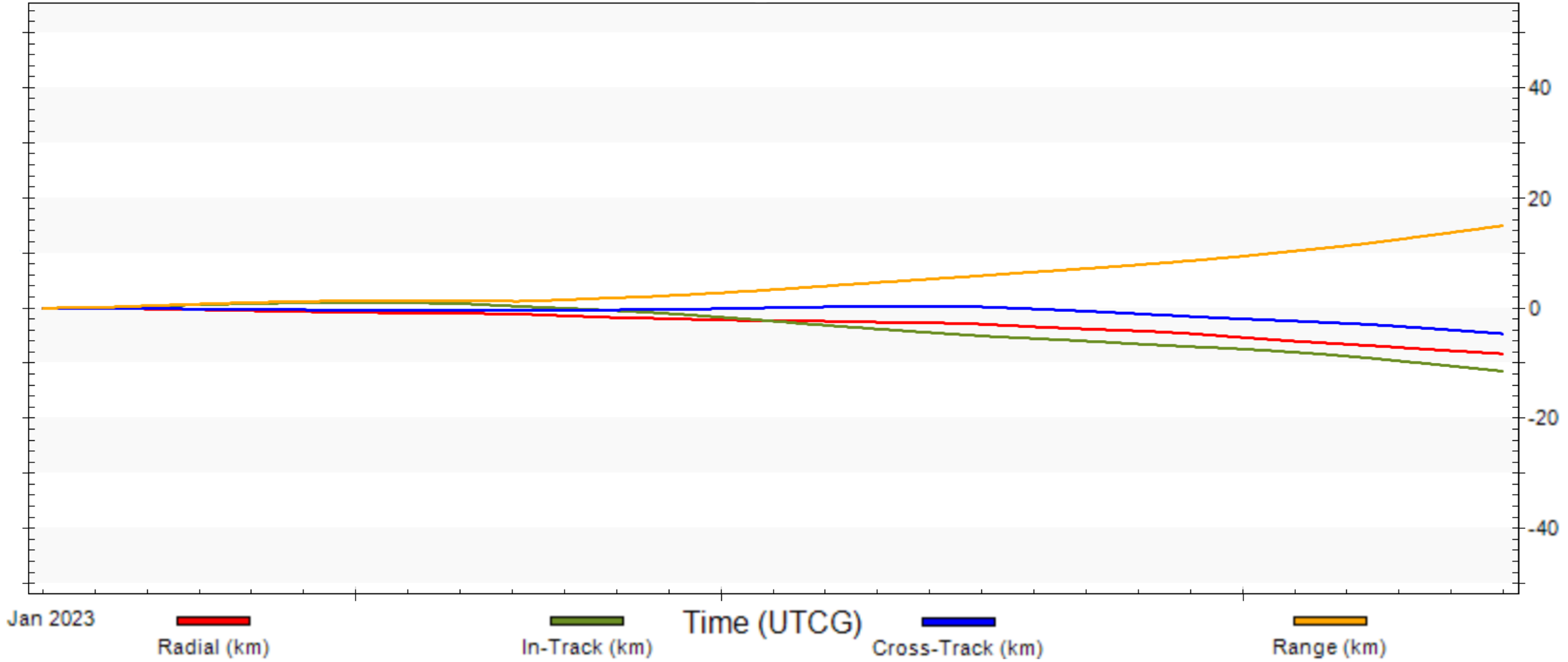
Neutral SRP Calibration

Cr_Z = 0.97 **Max ΔR = 20.0 km**



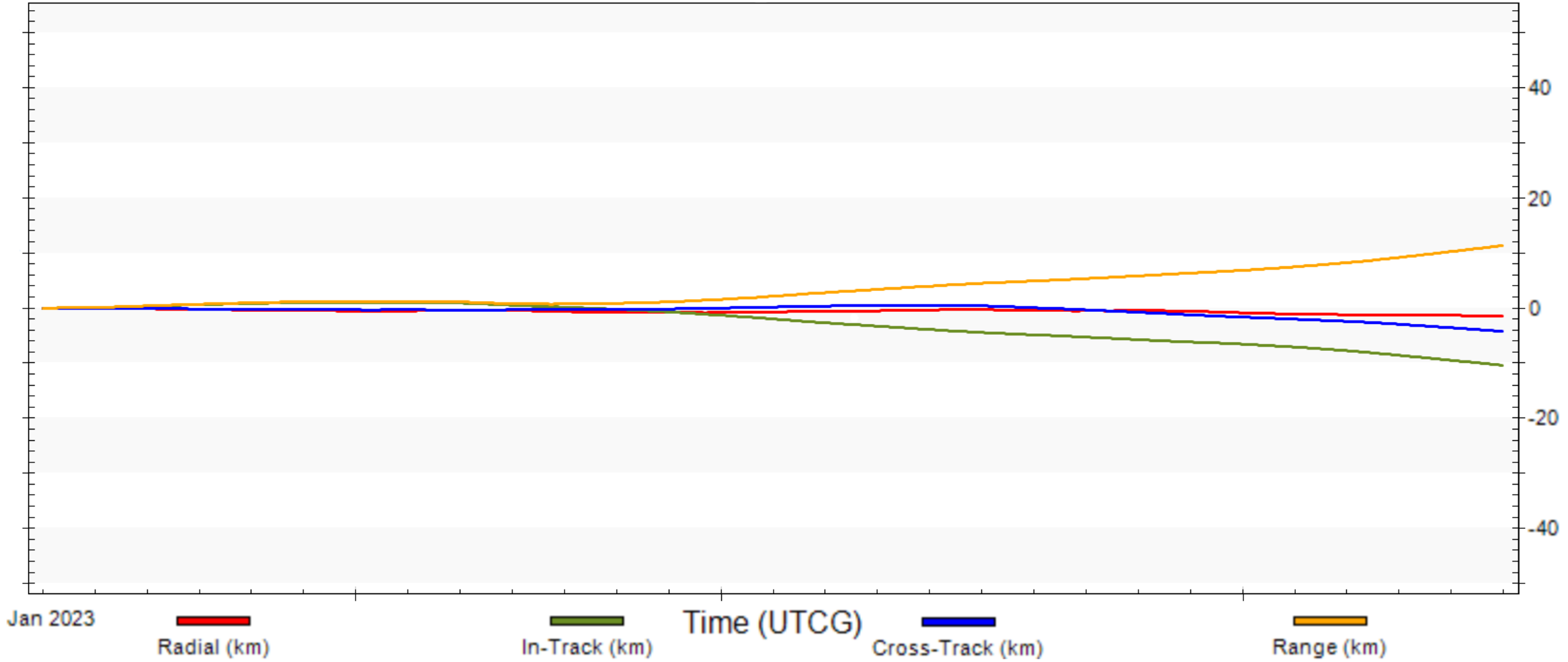
Neutral SRP Calibration

Cr_Z = 0.96 **Max ΔR = 15.0 km**



Neutral SRP Calibration

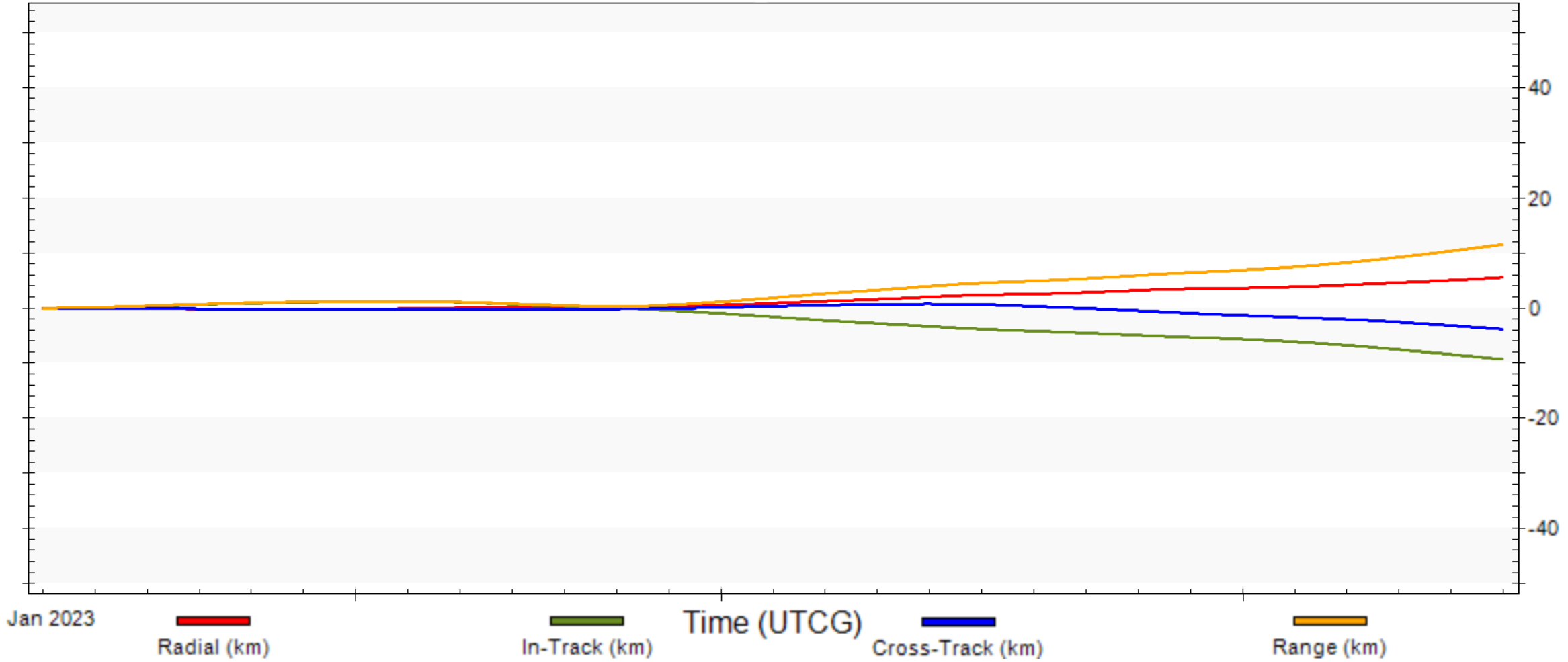
Cr_Z = 0.95 **Max ΔR = 11.5 km**



Neutral SRP Calibration

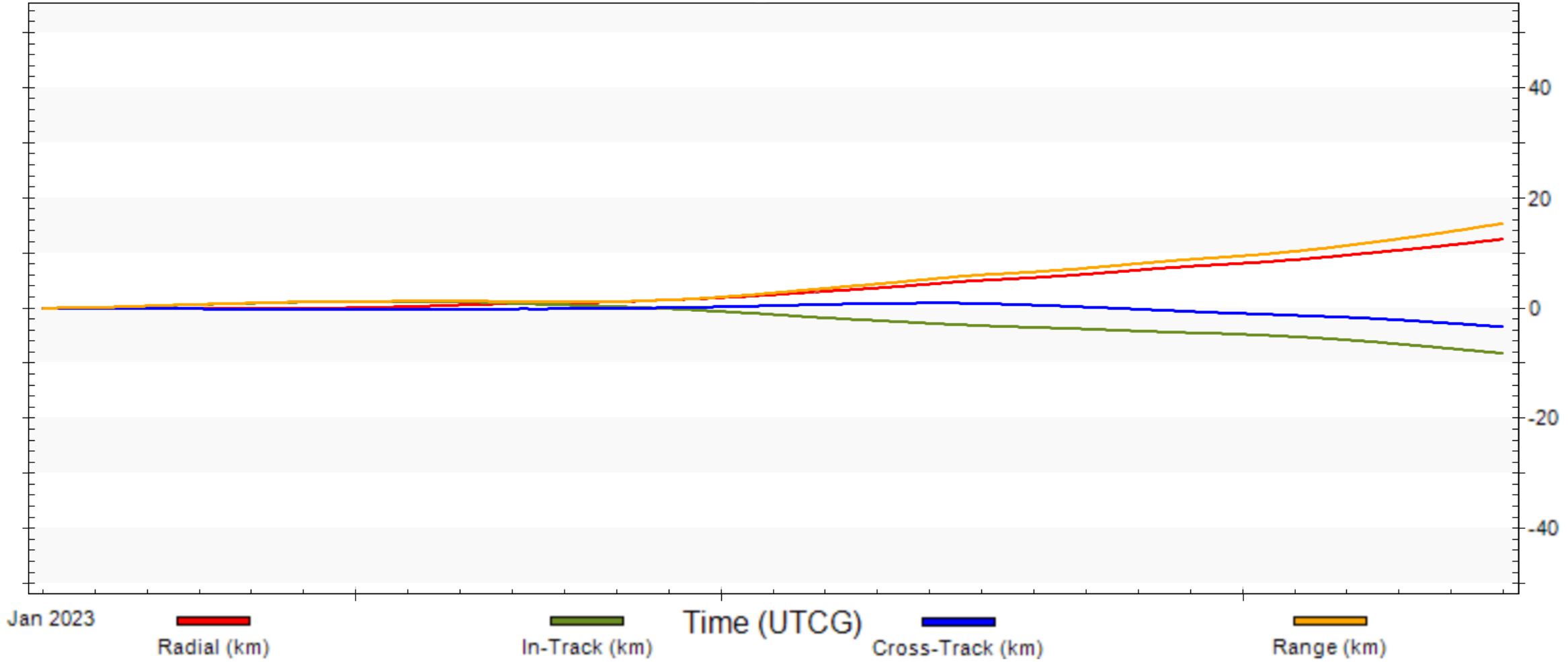
Cr_Z = 0.94

Max ΔR = 11.5 km



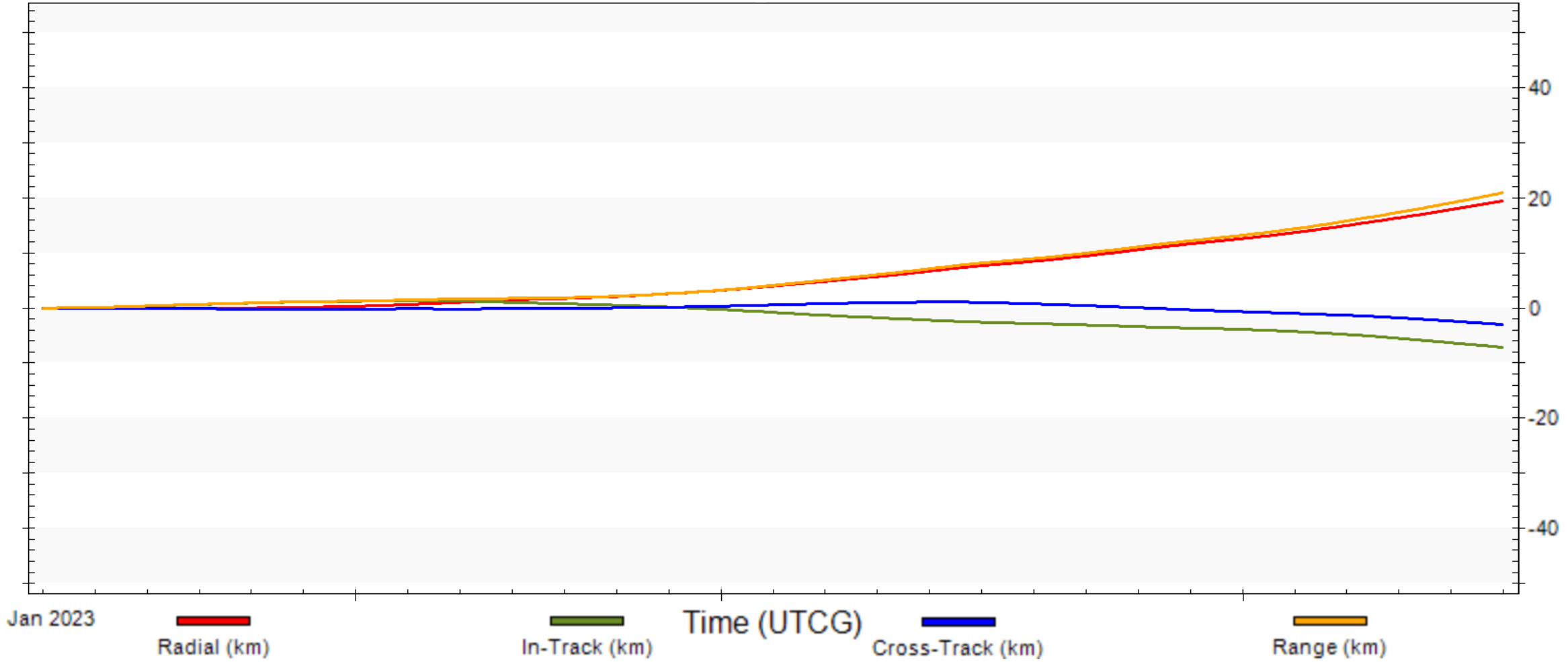
Neutral SRP Calibration

Cr_Z = 0.93 **Max ΔR = 16.0 km**



Neutral SRP Calibration

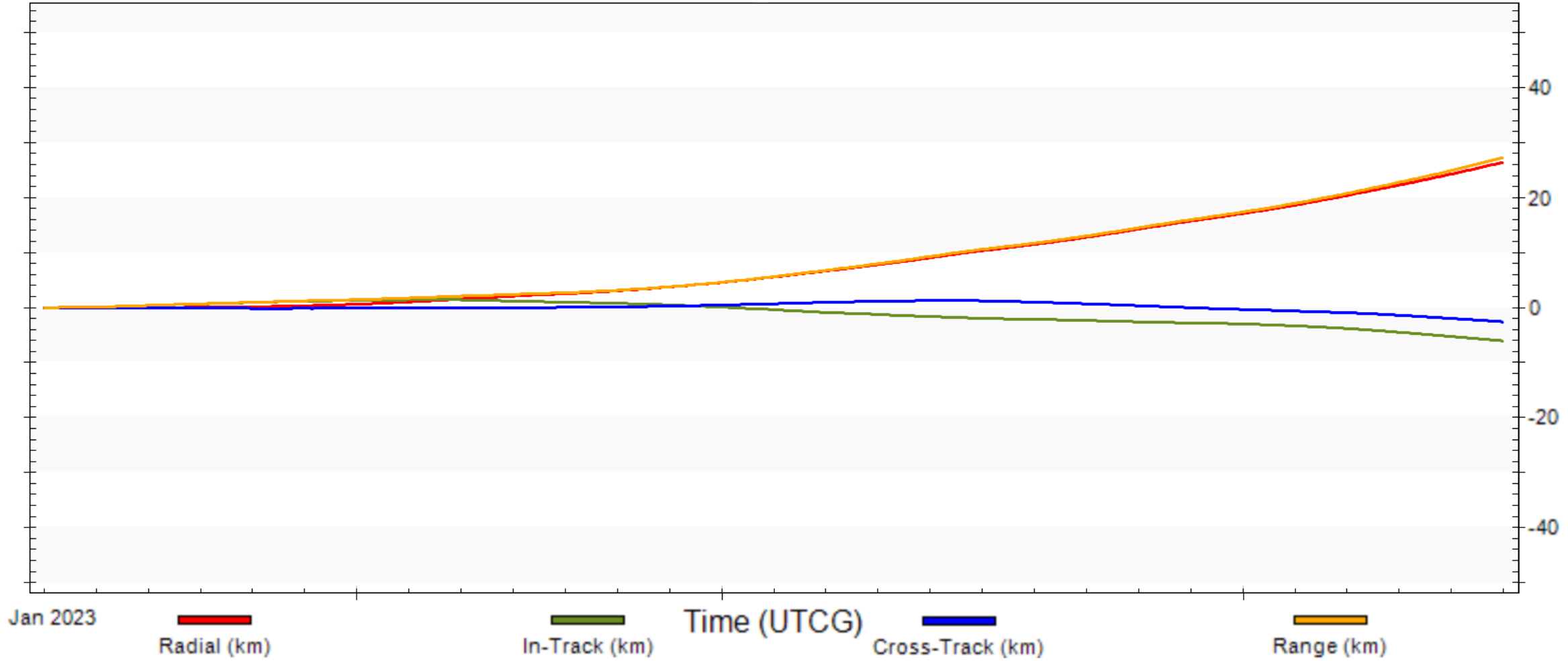
Cr_Z = 0.92 **Max ΔR = 21.0 km**



Neutral SRP Calibration

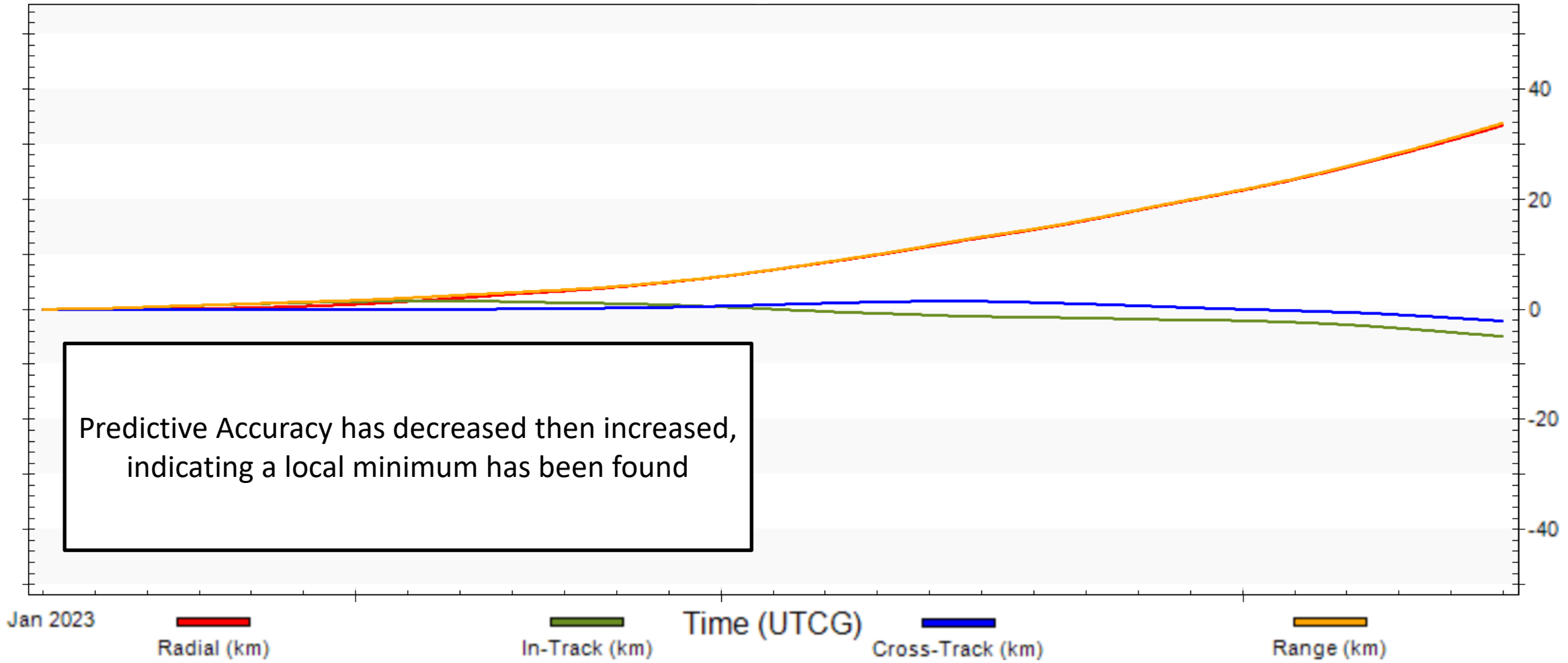
Cr_Z = 0.91

Max ΔR = 27.5 km

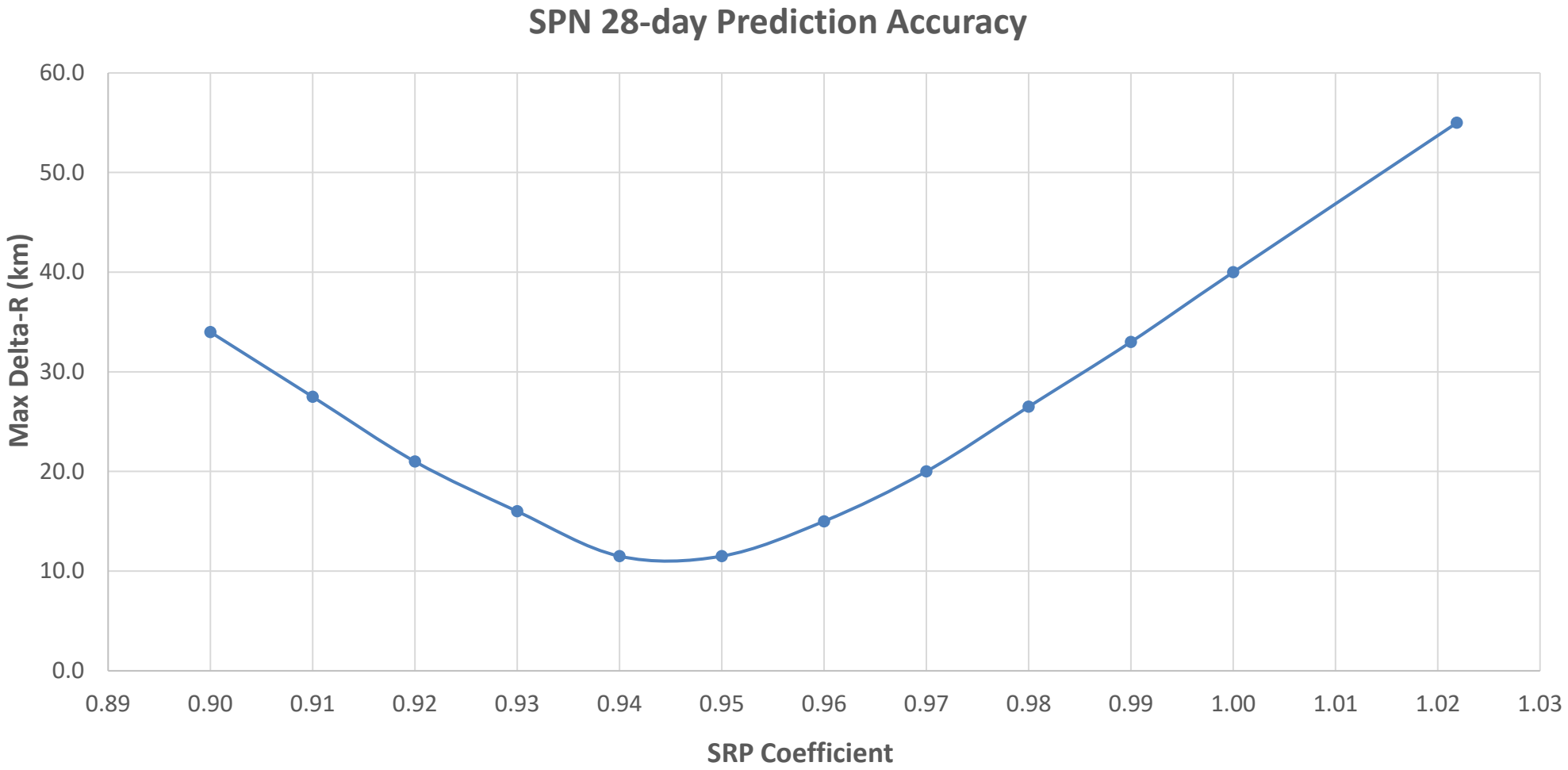


Neutral SRP Calibration

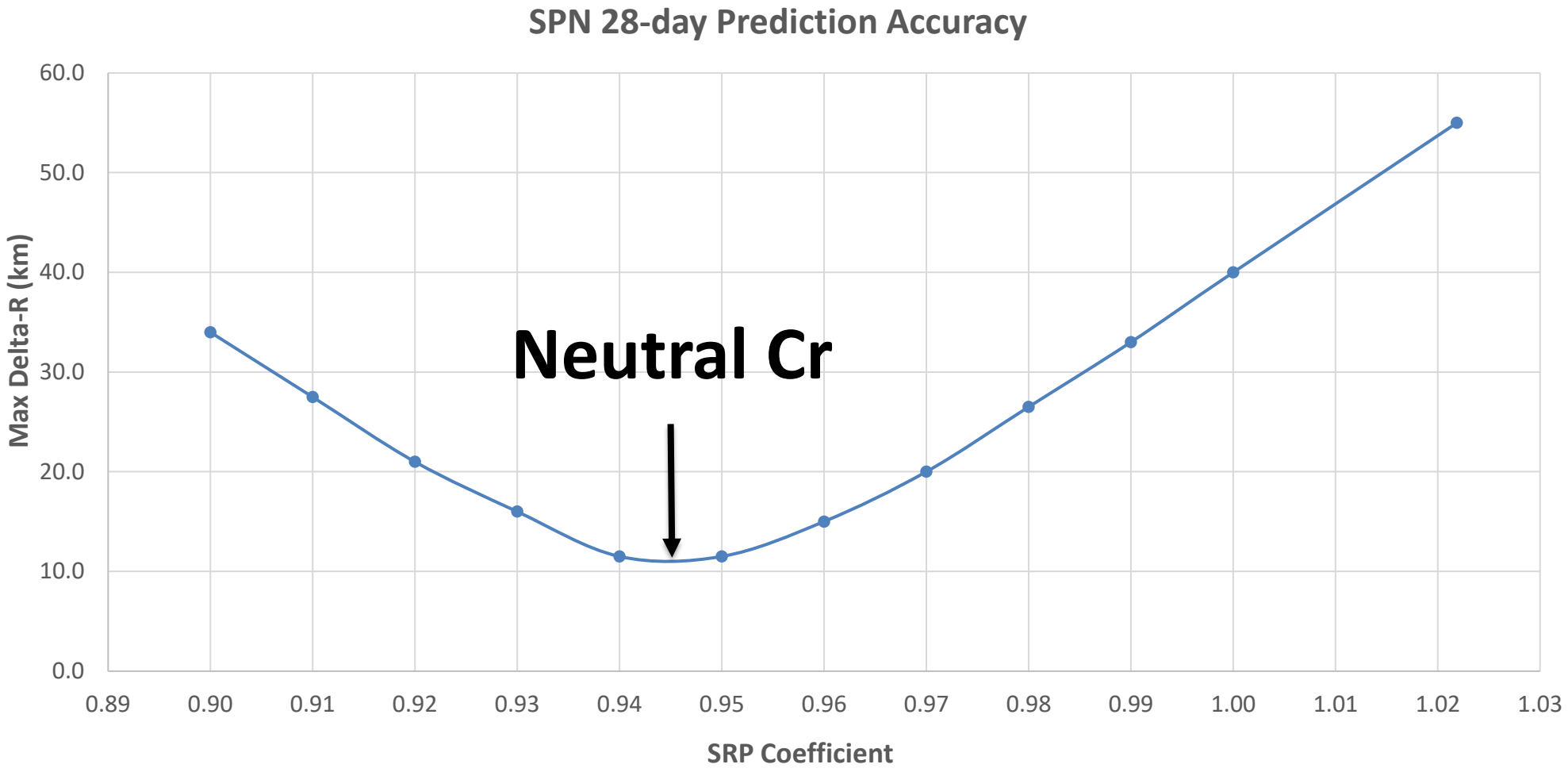
Cr_Z = 0.90 **Max ΔR = 34.0 km**



Neutral SRP Calibration



Neutral SRP Calibration



Maneuver Planning

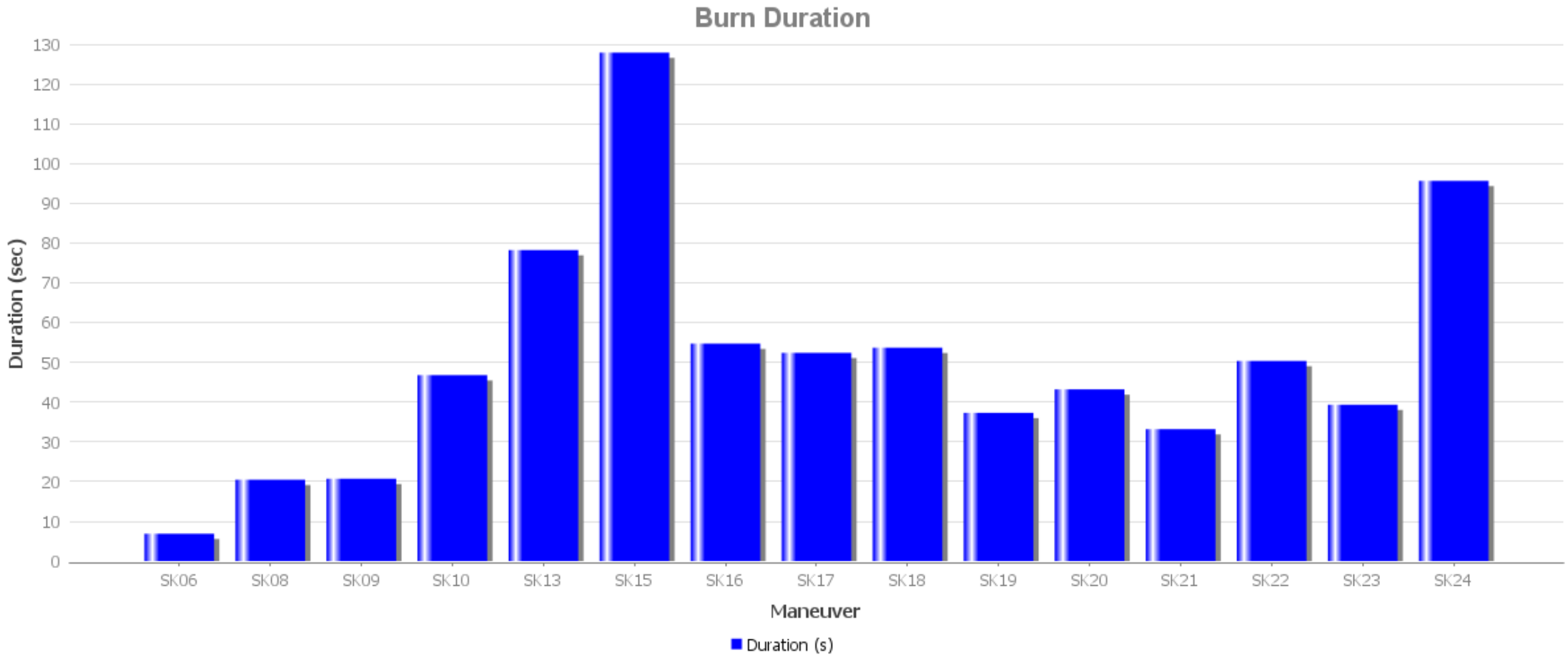
Targeting Parameters

Neutral SRP Calibration

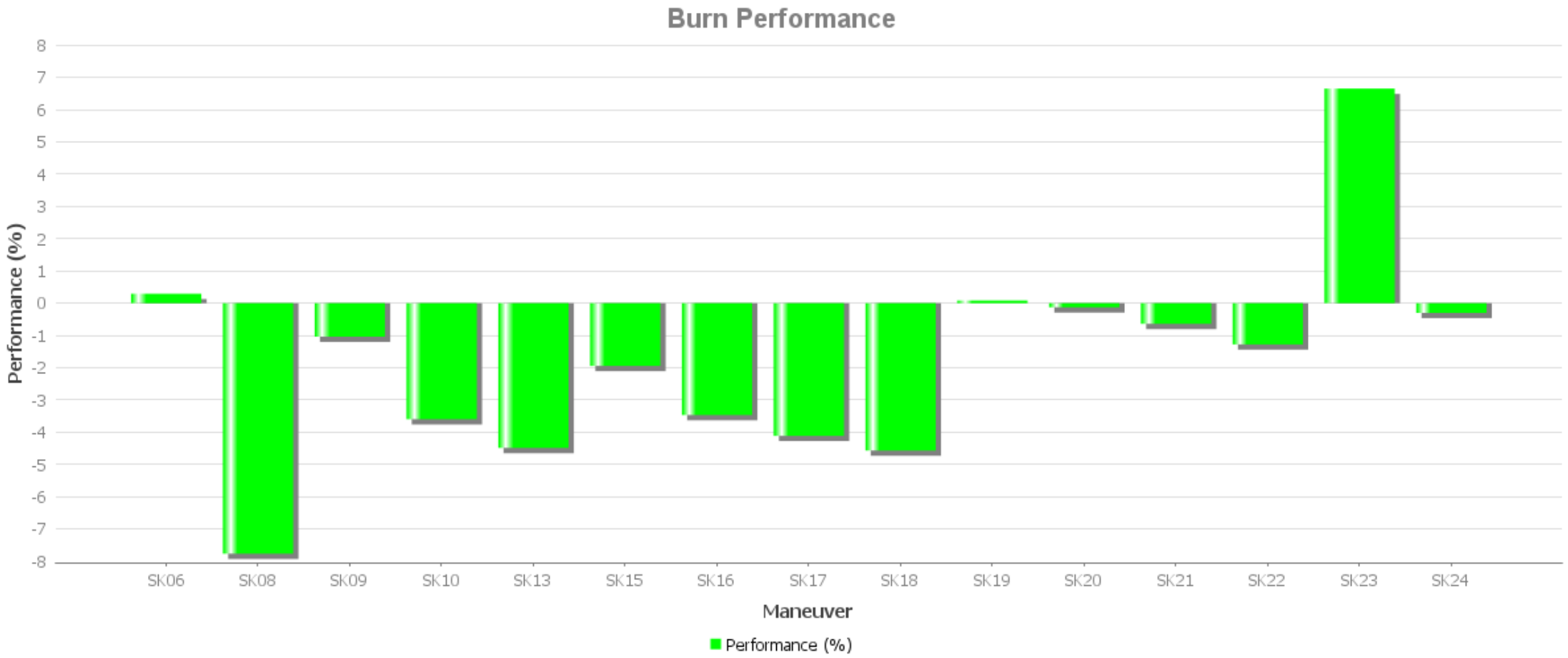
Maneuver Performance

Maneuver Duration

- Maneuver burn duration varies between SKs

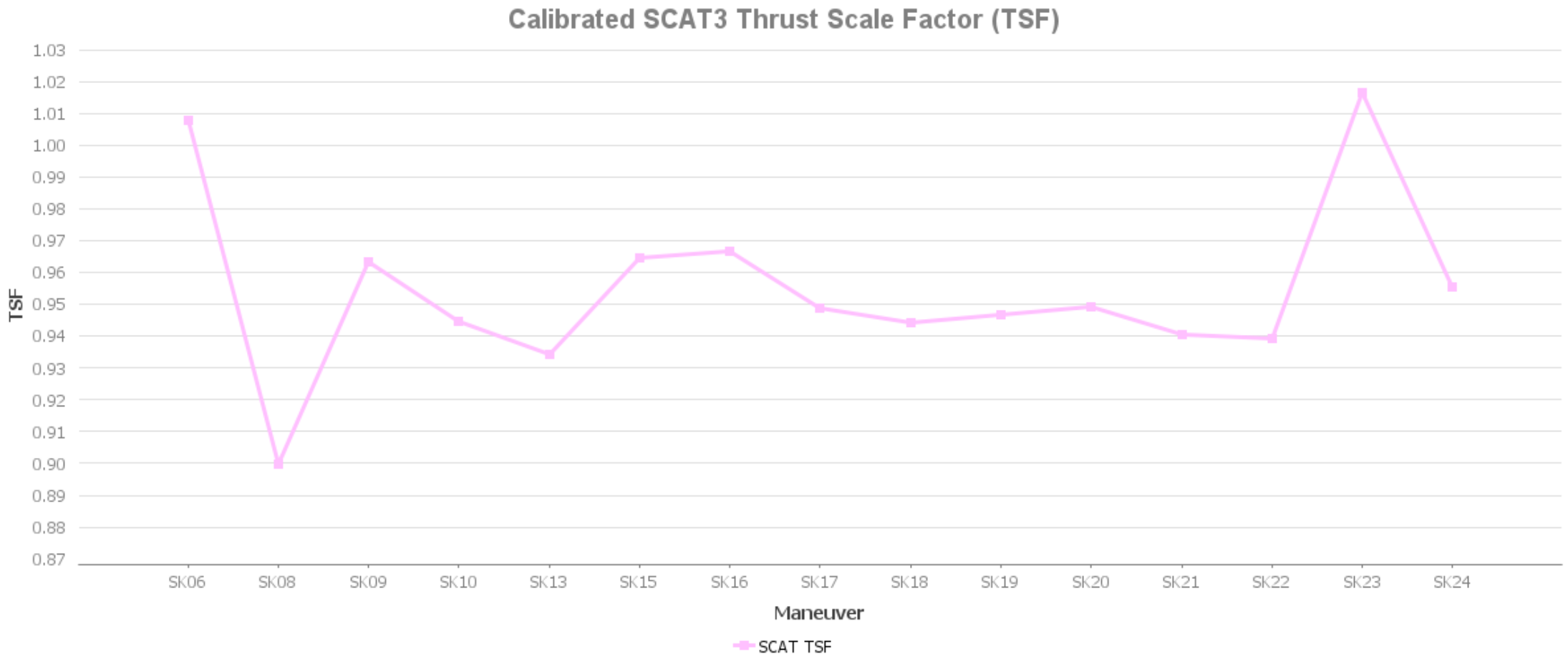


Maneuver Performance



Maneuver Performance

- Thrust Scale Factor Calibration



Conclusion

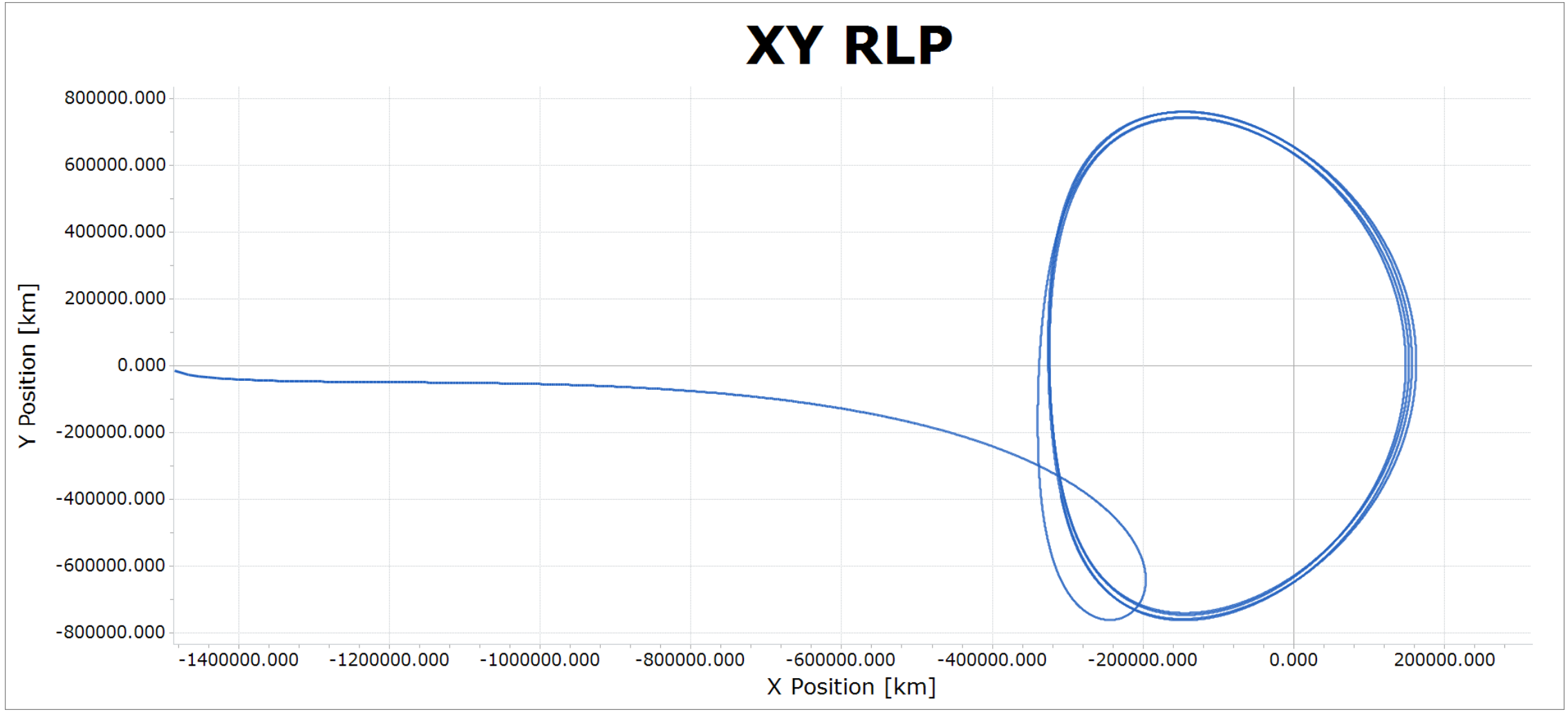
Conclusion

- The JWST has several orbit determination and maneuver planning challenges, due to the Sun shield's large area, attitude profile, and maneuver attitude constraints
- The FDF has overcome these challenges using:
  - Dynamical modelling of the Sun shield during orbit determination
  - Carefully selected station-keeping maneuver targeting parameters
  - Calibration of the Cr to produce more accurate predictions
- The results of FDF analyses have been implemented operationally, showing improved precision in orbit prediction and station-keeping maneuver efficiency
- Efficient station-keeping maneuvers have the potential to extend the mission lifespan, enabling JWST to continue to conduct ground-breaking infrared astronomy for decades to come

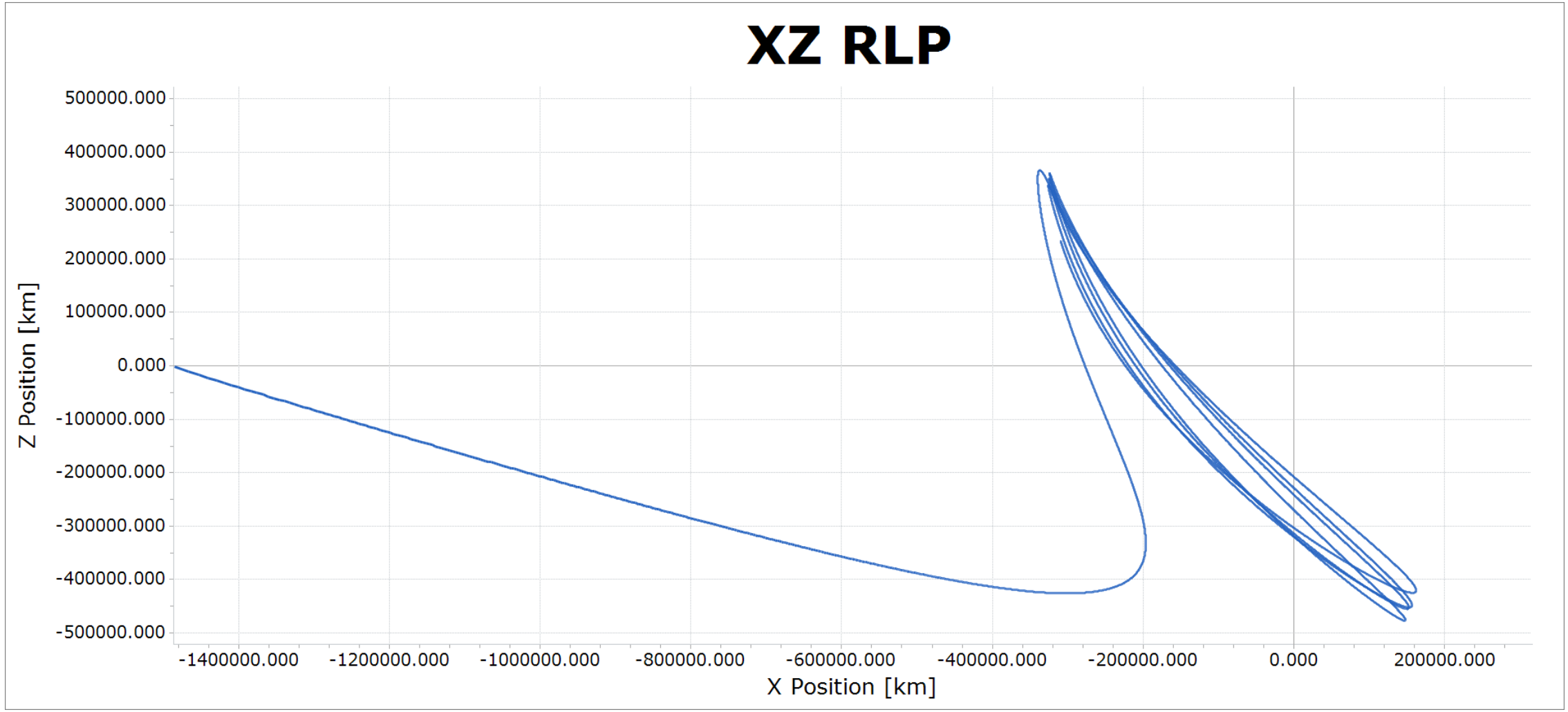
Questions?

Backup Slides

Definitive Mission Orbit



Definitive Mission Orbit



Definitive Mission Orbit