

Near Rectilinear Halo Orbit Determination with Simulated DSN Observations

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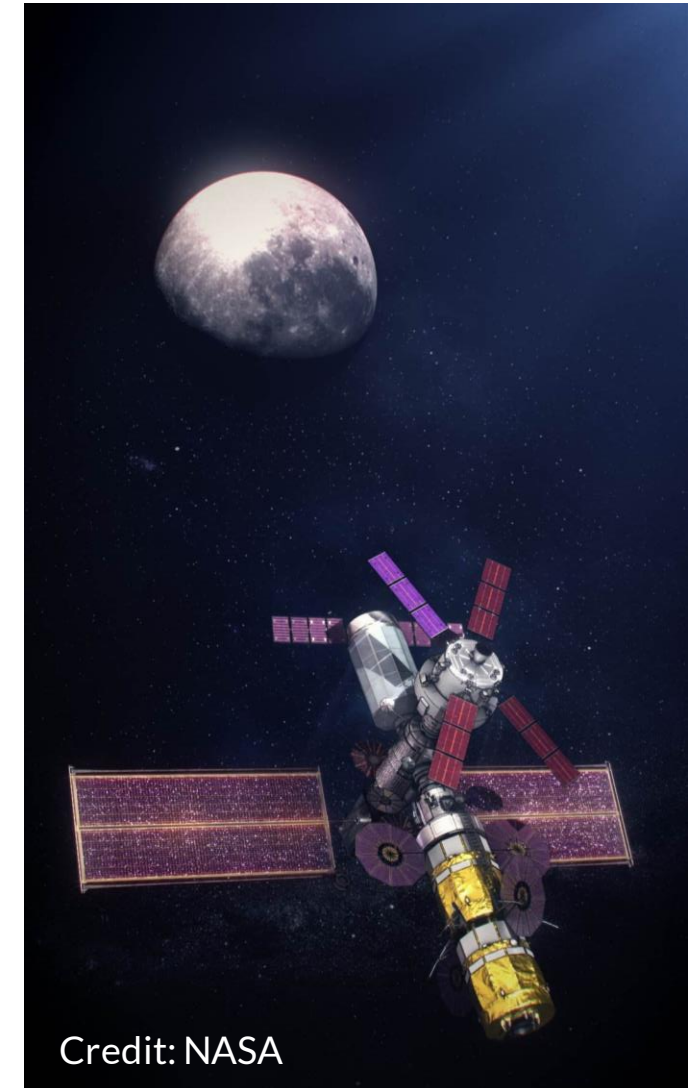
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A large, detailed image of the Moon's surface, showing craters and lunar maria, occupies the left side of the slide.

Introduction & Background

Motivation: Gateway

- NASA's Lunar Gateway "will be a small spaceship in orbit around the Moon that will provide access to more of the lunar surface than ever before with living quarters for astronauts, a lab for science and research, ports for visiting spacecraft, and more." [1]
- Operational orbit is a Near Rectilinear Halo Orbit (NRHO)
 - Loosely-captured, nearly-stable 3-body orbit
 - Perilune radius of $\sim 3,500$ km
 - Apolune radius of $\sim 71,000$ km



Credit: NASA

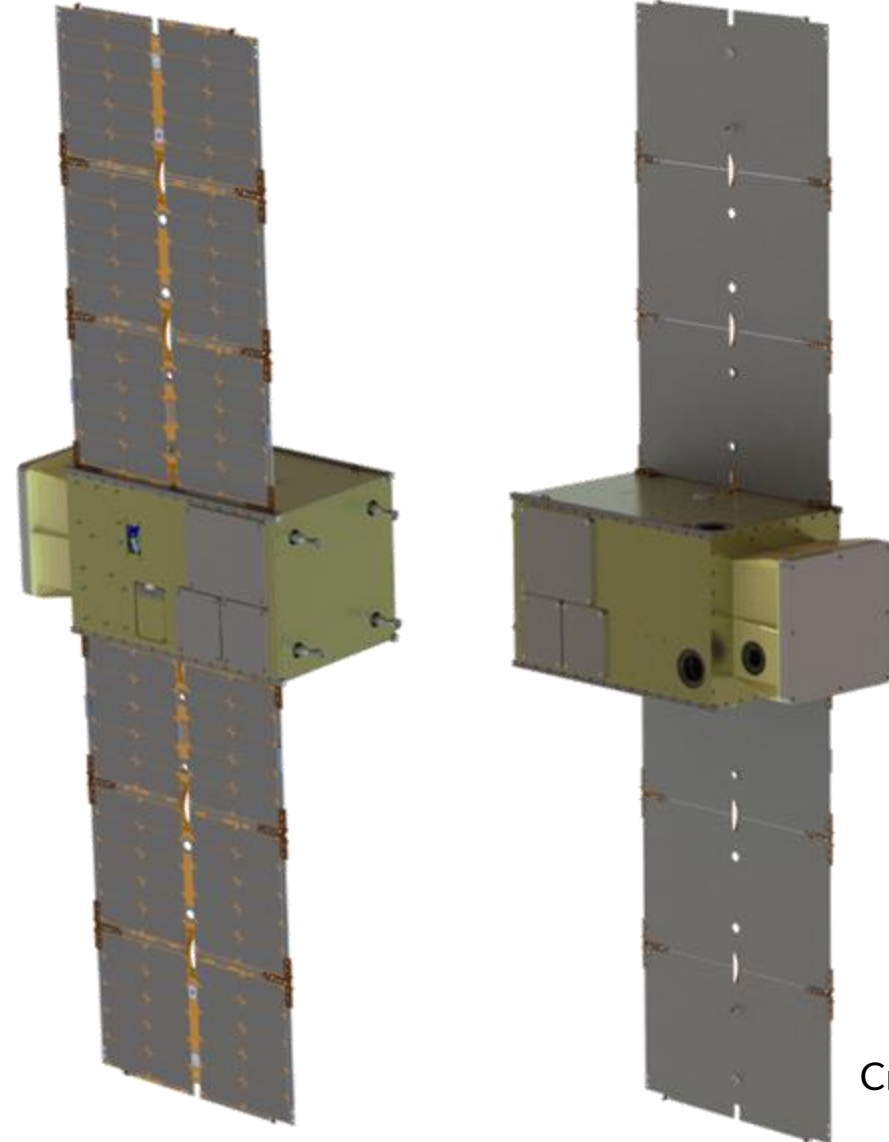
[1] <https://www.nasa.gov/topics/moon-to-mars/lunar-gateway>

Motivation: CAPSTONE



- NASA selected Advanced Space to develop and operate the CubeSat mission CAPSTONE
- Pathfinder mission to demonstrate operations similar to Gateway
- Launching December 2020

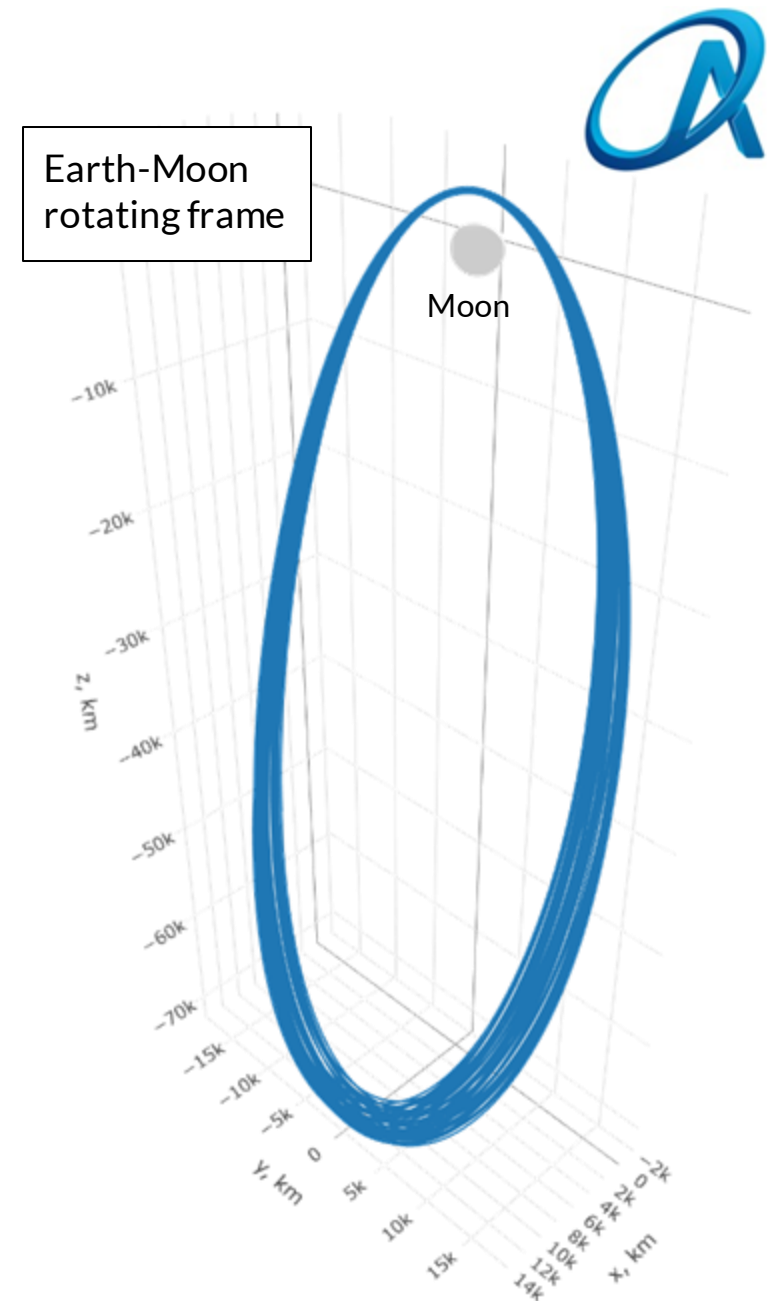
<https://www.nasa.gov/press-release/nasa-funds-cubesat-pathfinder-mission-to-unique-lunar-orbit>



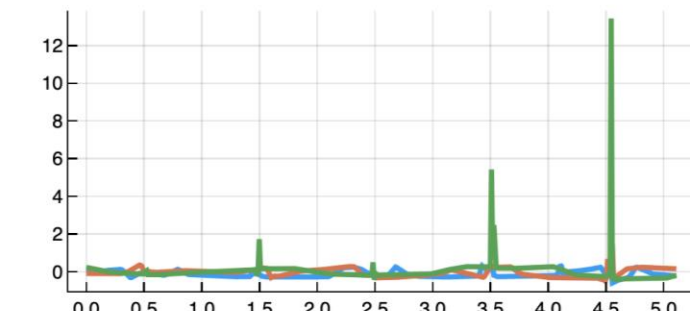
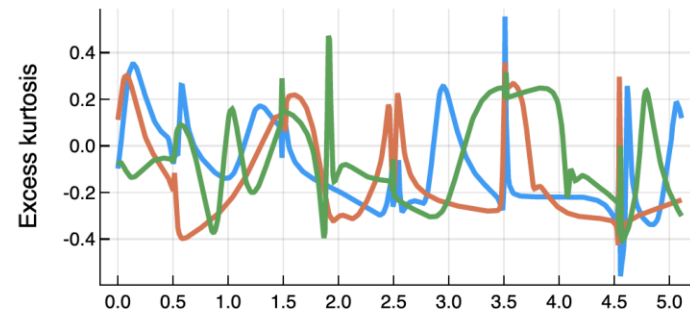
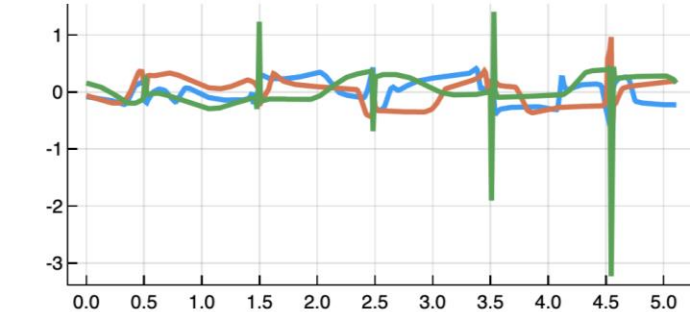
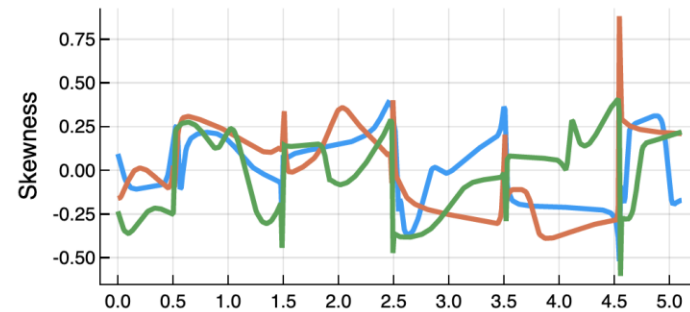
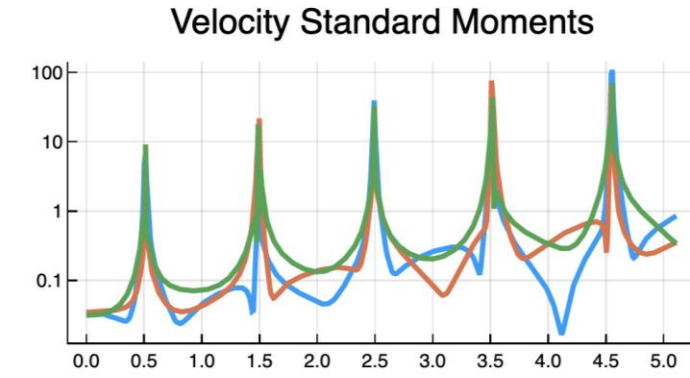
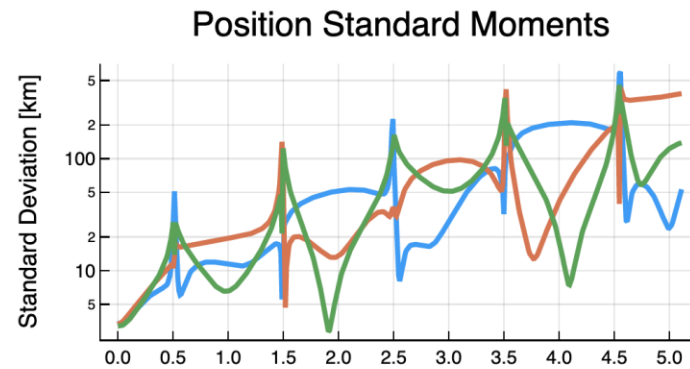
Credit: Tyvak

Background: NRHO

- Key characteristics
- Benefits



Background: NRHO



Orbital Periods (approx. 6.5 days each)

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Connection to Other Papers

- Last conference: Parrish et al., “Survey of Ballistic Lunar Transfers to NRHO”, AAS/AIAA Astrodynamics Specialist Conference, 2019, Portland ME.
 - Studied several families of BLTs and how they evolve over time
 - Assumes perfect OD and maneuver execution
- This conference:
 - Current paper: Near Rectilinear Halo Orbit Determination with Simulated DSN Observations
 - Parrish et al., “BLTs with realistic OD and maneuver execution errors”, Wednesday at 4:00pm.
- Resources available at www.advancedspace.com/blt

What questions are we trying to answer?

- What tracking cadence is necessary to reliably navigate?
- What is the relationship between tracking cadence and navigation solution accuracy?
- Where in the orbit should tracking passes be placed?
- How well do assumptions of linear covariance analyses hold true?
- What set of maneuvers should be used to clean up NRHO insertion error?
- Do the considered stationkeeping algorithms work in a high fidelity simulation?

Dynamics and Assumptions

- Simulation engine: GMAT (design & navigation), Monte (navigation)
- Force model:
 - Point masses of Sun, Earth, and all planets' barycenters, states from DE430
 - Moon 16x16 (filter) or 32x32 (truth) gravity field, GRGM660PRIM model
 - Mass, area, Cr sampled with errors and depend on scenario
 - Impulsive maneuvers
 - Stochastic acceleration
- Maneuvers:
 - Orbit Maintenance Maneuvers (OMMs) – targeted
 - Reaction wheel desaturation maneuvers – stochastic
- Error sources:
 - Orbit determination error
 - Maneuver execution error
 - Dynamics mis-modeling
 - Random desaturation maneuvers

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Navigation Simulation Setup

Navigation Filter Setup

Definition of 3 spacecraft used in simulations



Navigation

Reference

Navigation

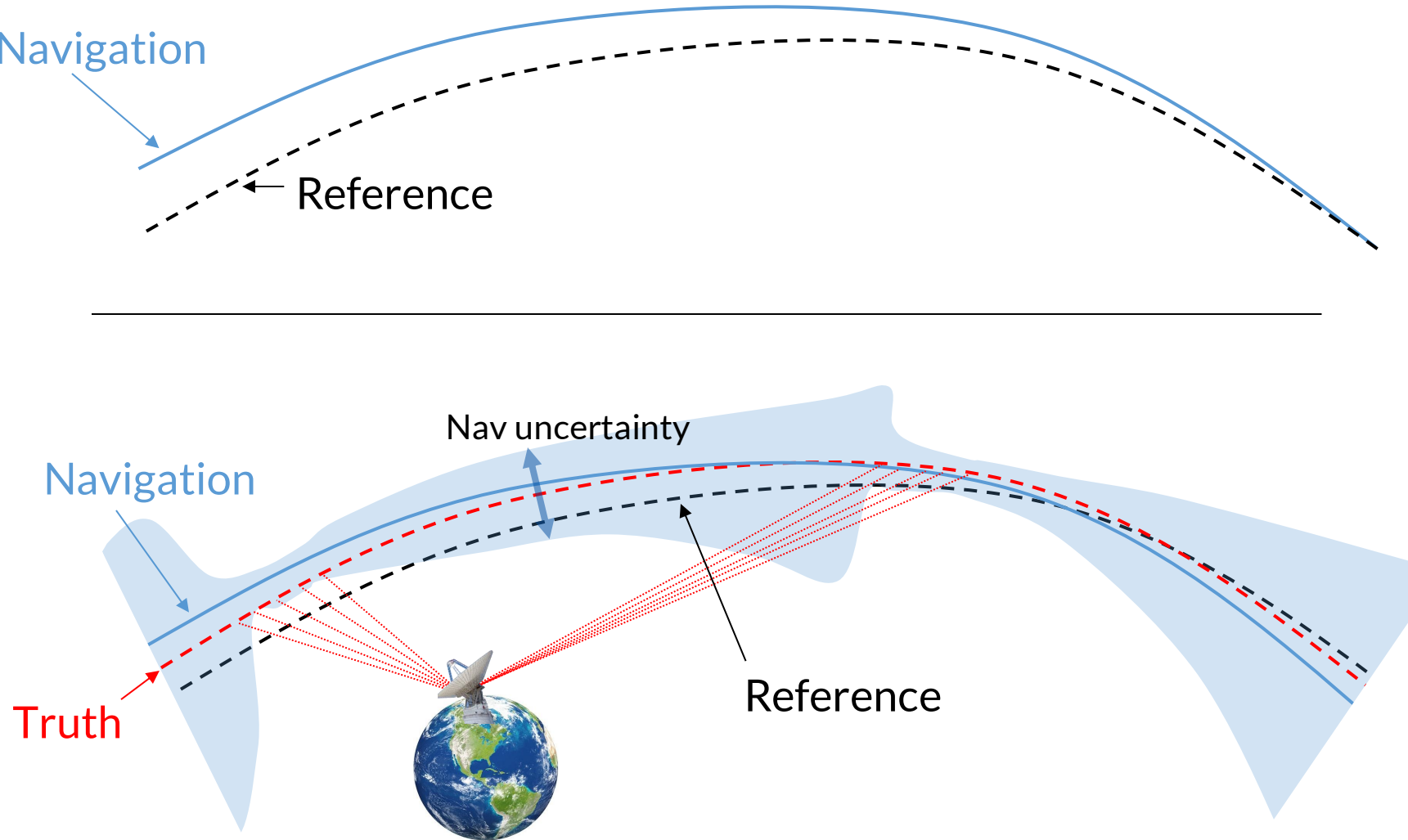
Nav uncertainty

Truth

Reference

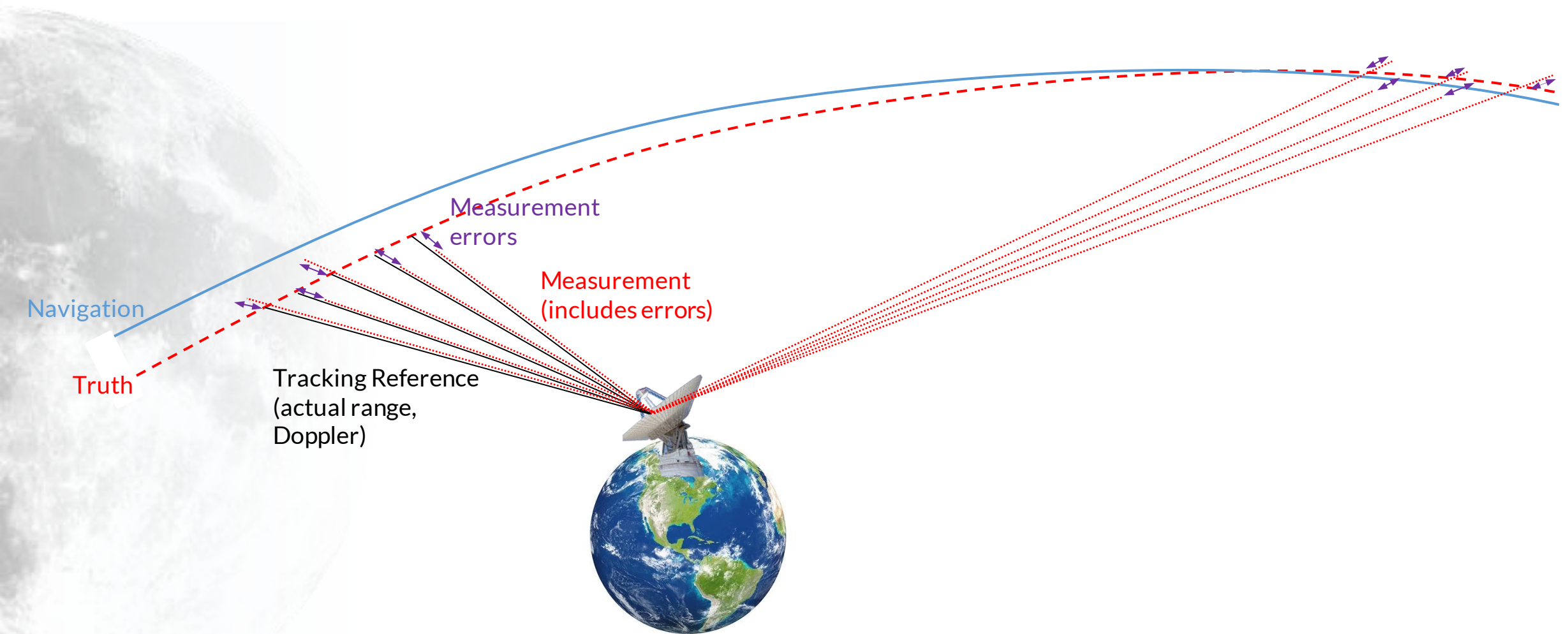
Spacecraft definitions:

- Navigation: Best estimate of where the spacecraft is and will be, with estimated uncertainty. Trajectory correction maneuvers & stationkeeping maneuvers are based on this.
- Truth: Observed, but never known perfectly
- Reference: The spacecraft is guided to stay close to this, but is never actually on this path



Navigation Filter Setup

Measurement Errors



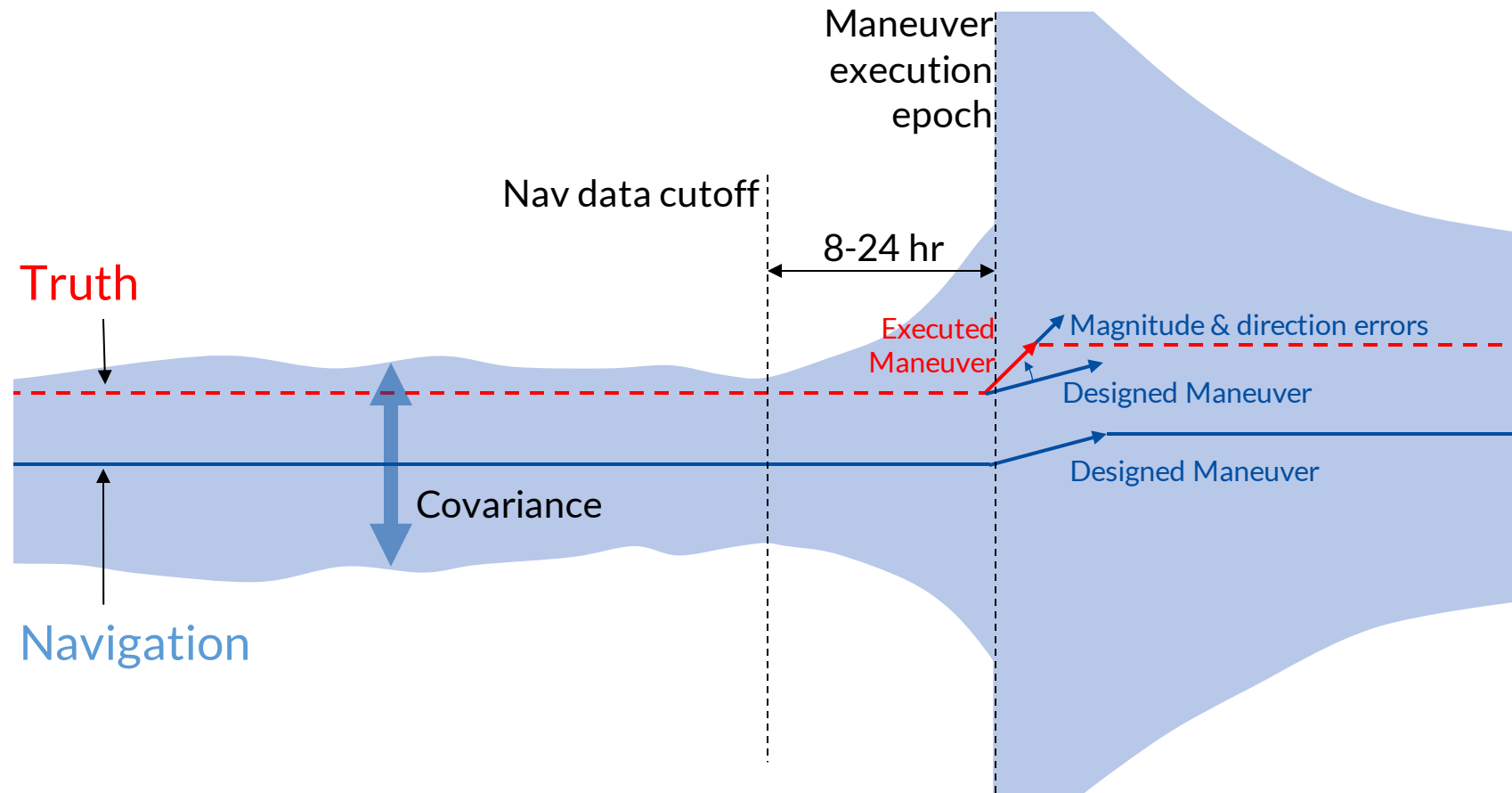
Navigation Filter Setup

Maneuver errors

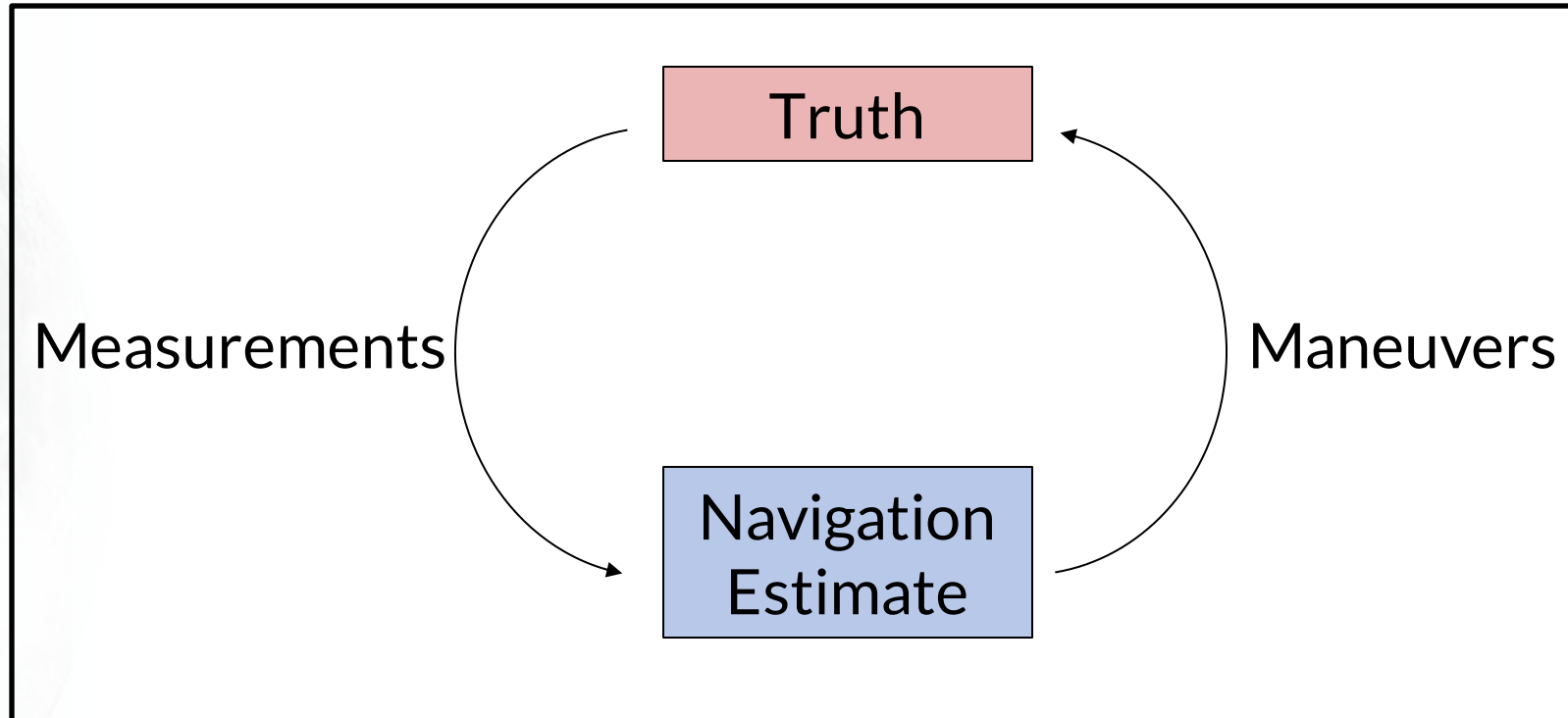


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Navigation Filter Setup

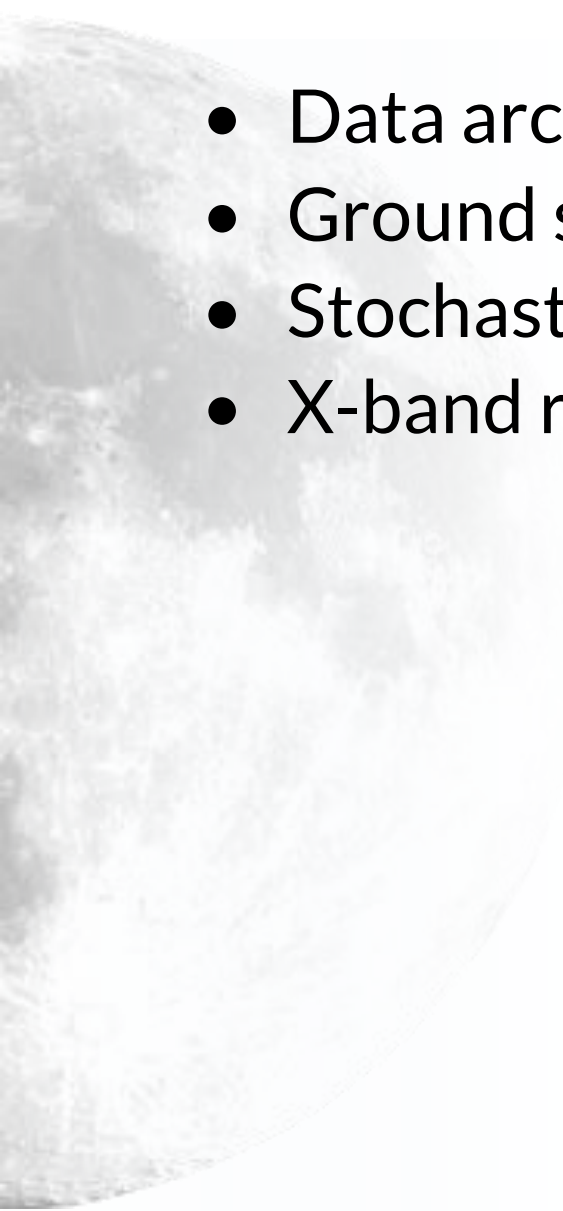


The Truth and Navigation spacecraft are inherently related

Navigation Filter Setup



- Data arc: apolune to apolune
- Ground stations: Deep Space Network
- Stochastic accelerations
- X-band radio



Error Sources

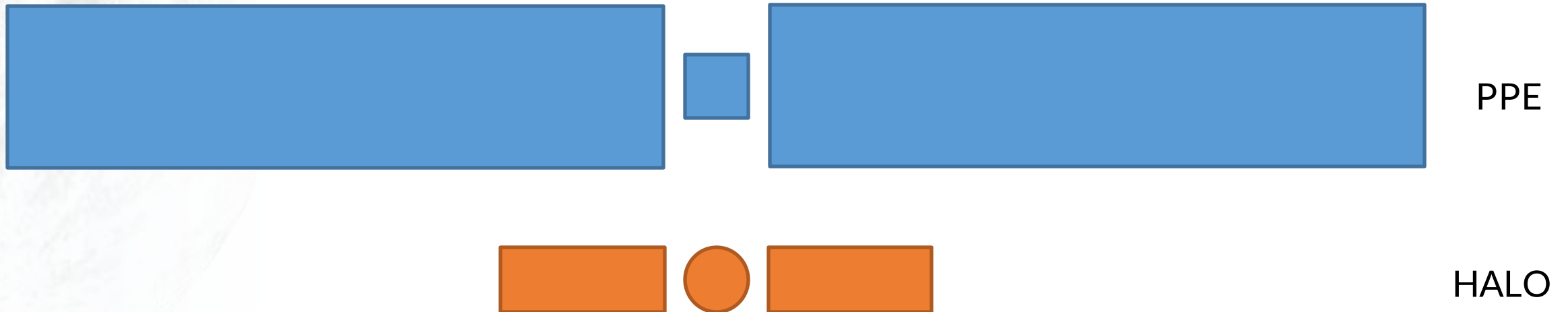


Error source	Uncertainty (3σ)
Mass uncertainty	3%
SRP area	30%
Coefficient of reflectivity	45%
OMM execution error	1.42 mm/s fixed, 1.5% proportional, 1 deg pointing
Measurement bias	7.5 m (range), 2.5 mm/s (range-rate)
Measurement noise	3 m (range), 1 mm/s (range-rate)

Configurations



Gateway Configuration	Mass [kg]	Sun-facing area [m ²]
1) PPE	5700	310
2) PPE + HALO	13700	340



Filter Estimated Parameters

Estimated parameter	3σ a priori state error relative to truth (applied once at start of simulation)
Position in Earth-centered J2000	10 km
Velocity in Earth-centered J2000	10 cm/s
Coefficient of reflectivity	45%
Range measurement bias	1 m
Range-rate measurement bias	1 mm/s

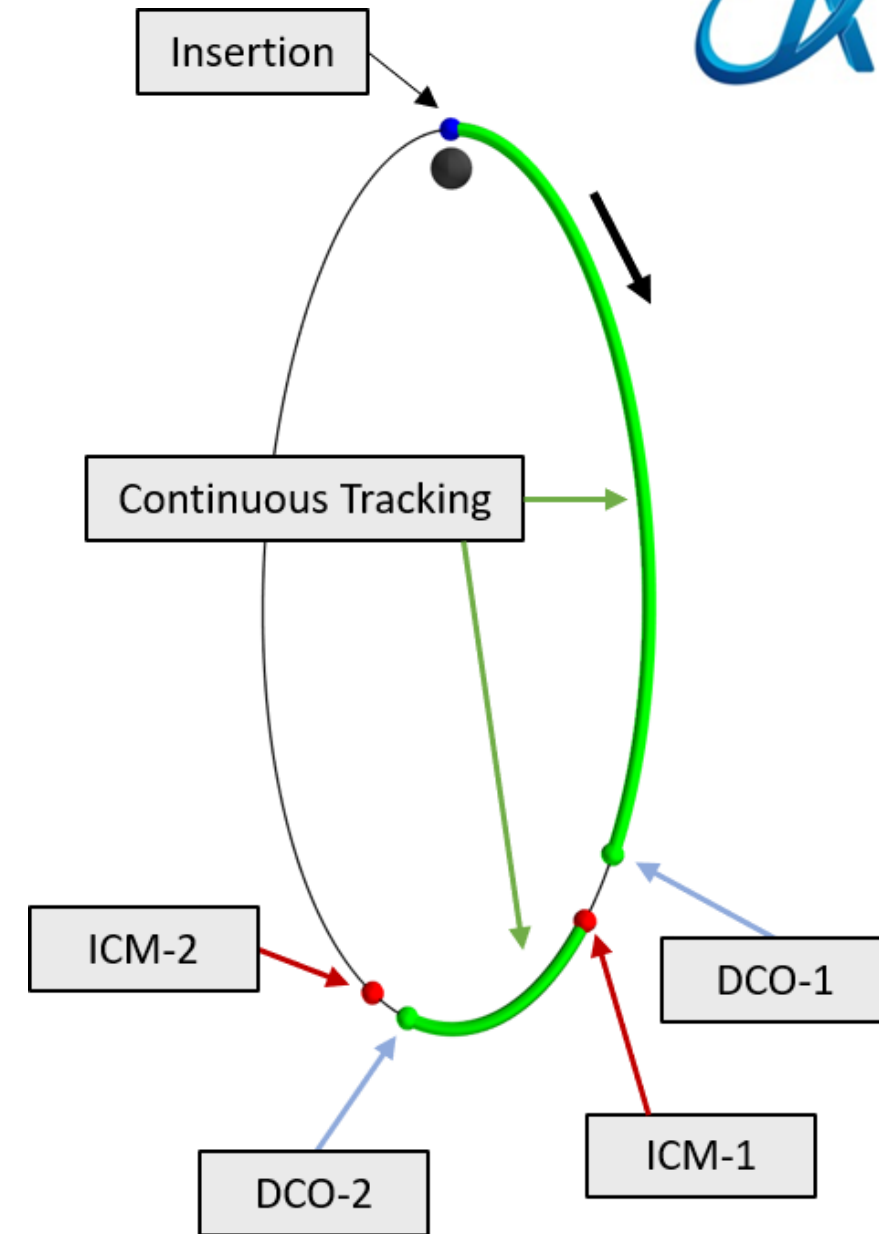
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NRHO Insertion Cleanup

NRHO Insertion Cleanup

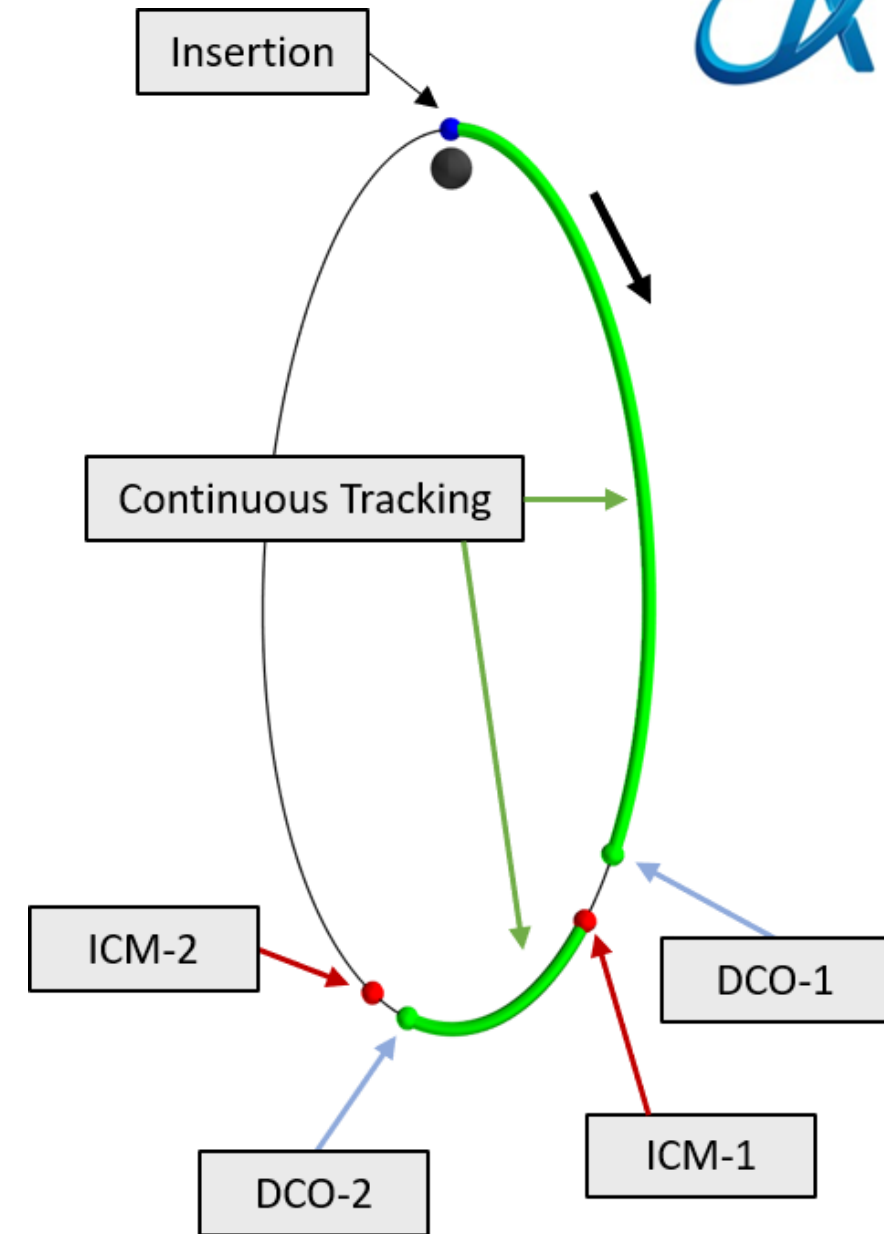


- Insertion states sampled from an empirically-determined distribution
 - Assuming arrival via BLT (ballistic lunar transfer)
 - Insertion maneuver designed 48 hours prior to insertion, along with a final trajectory correction maneuver
 - Position errors ~ 2 km, velocity errors ~ 1 m/s
 - See Parrish et al., “BLTs to NRHO: Operational Considerations”, presented Wednesday
- Events:
 - DCO = Data Cut Off, epoch at which ICM is designed
 - ICM = Insertion Correction Maneuver



NRHO Insertion Cleanup

- Assume two maneuvers to correct for insertion errors. When should they occur? What is the statistical ΔV ?
- Monte Carlo simulations performed, sampling:
 - Insertion state
 - Simulated measurements
 - Maneuver execution
- Batch filter used from each maneuver to DCO
- Preliminary study results:
 - ICM-1 is the larger of the two correction maneuvers
 - Total correction ΔV is minimized when ICM-1 takes place as soon as possible (24 hours after insertion)
 - Best statistical cleanup DV99 (99th % ΔV) is **7.6 m/s**



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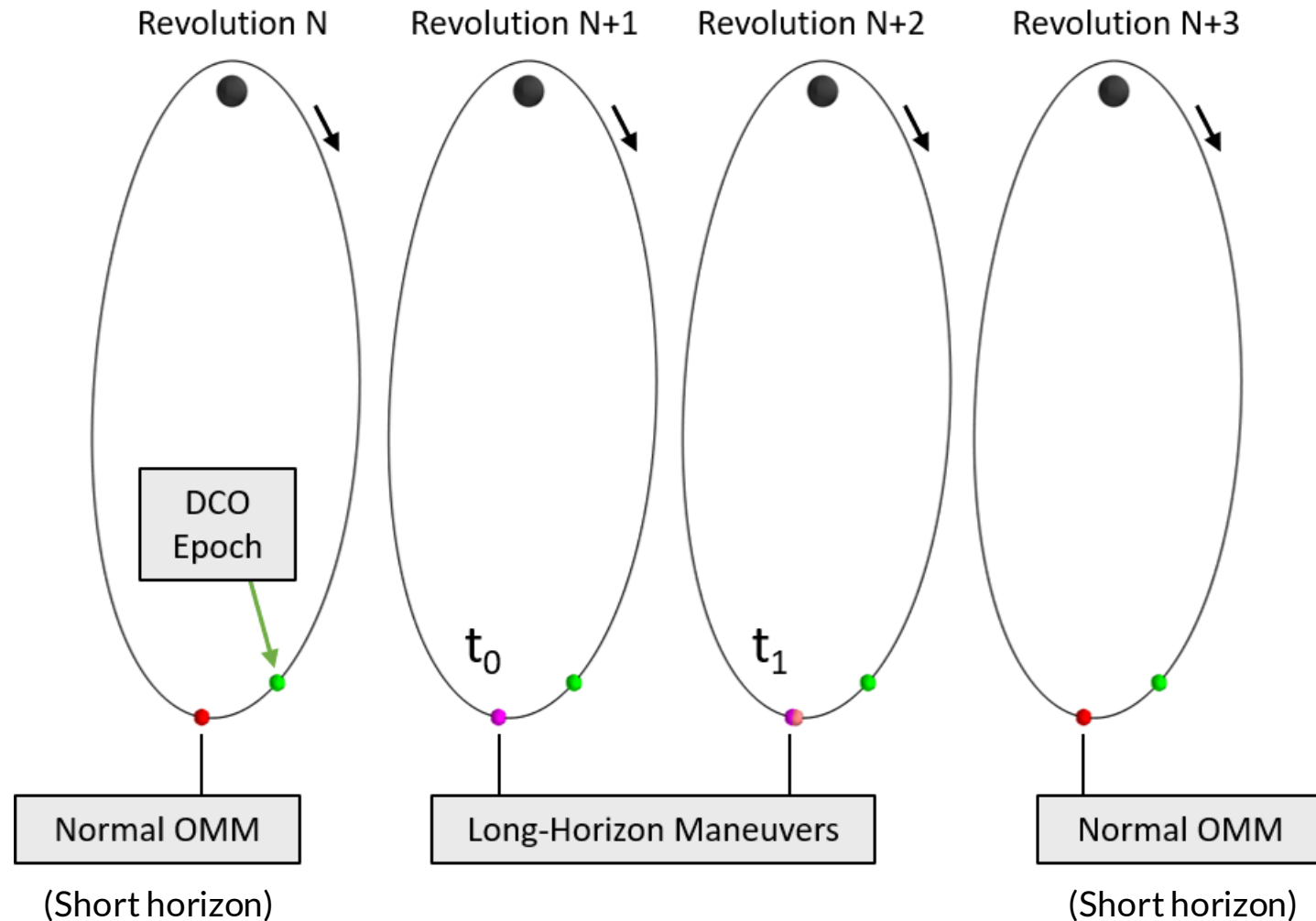
Stationkeeping

Stationkeeping Overview

- Short and long horizon maneuvers simulated in Monte Carlo analysis with simulated orbit determination
- Short horizon
 - Small maneuver ~once per revolution
 - Maneuver not executed if $<$ fixed execution error of 3 cm/s
 - X-axis crossing algorithm
 - Target v_x to match reference at perilune ~6.5 revolutions later
 - Studied extensively in literature
 - Safe and fuel efficient
 - Drifts away from the reference over the course of months-years
- Long horizon
 - Larger maneuver(s) required periodically to stay close to the reference
 - No consensus yet on how to solve this
 - One strategy considered here: pair of maneuvers, 1 revolution apart, located at subsequent apolunes

Long Horizon Stationkeeping

- Long horizon method spliced into short horizon method
- Long horizon correction consists of a pair of maneuvers at subsequent apolunes



Short & Long-Horizon SK Results

Navigation simulated with 8 hr/day DSN tracking, for 1 year

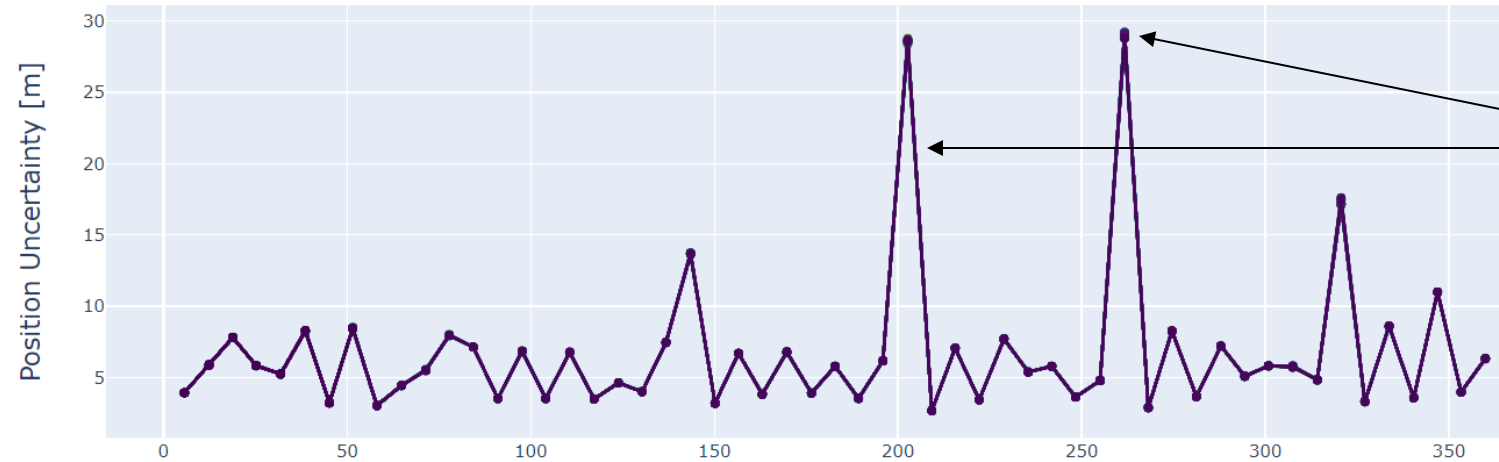
Gateway Config	Mean Annual ΔV [m/s]
PPE	4.43 ± 0.58
PPE+HALO	2.42 ± 0.51

Takeaway: High area-to-mass configuration (PPE only) has higher ΔV , for the given reference orbit

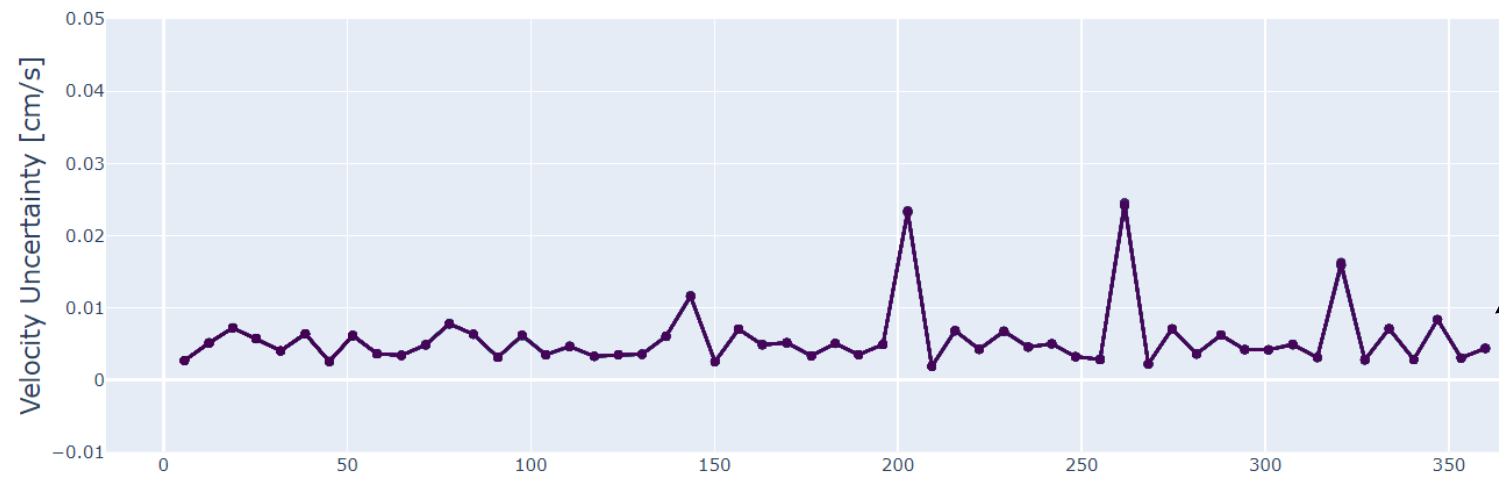
Batch Filter State Uncertainty



State uncertainty (1-sigma) each orbit with 8 hours/day DSN tracking



Larger errors following larger SK maneuvers



100 independent trials shown. All have very similar state uncertainty because they follow nearly the same path.

Elapsed Days

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Navigation Trades

Navigation Trades

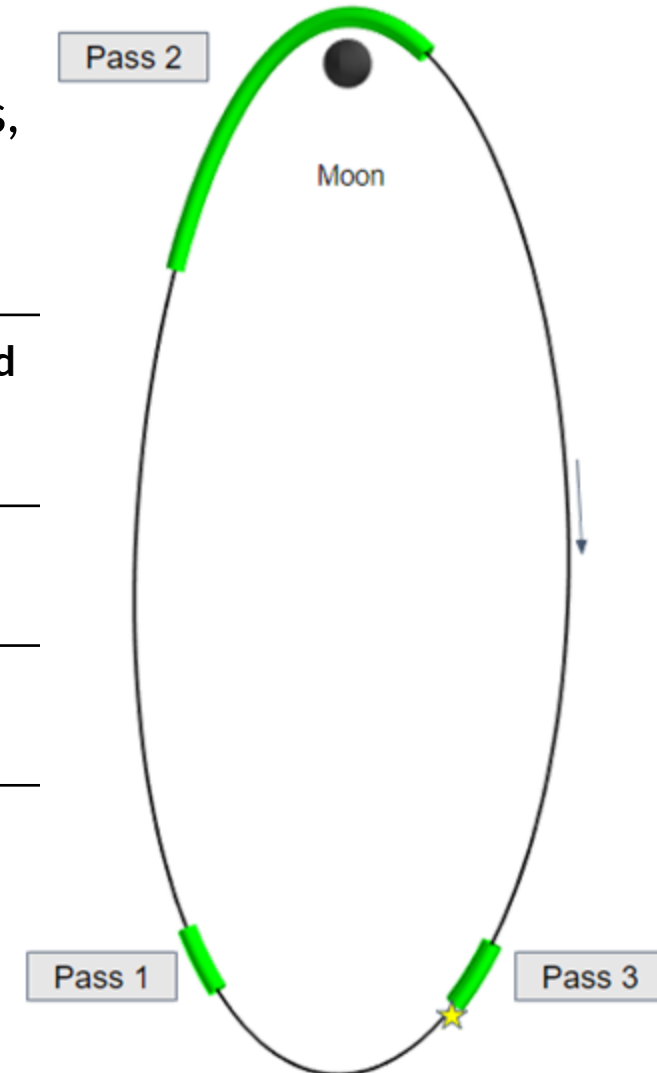
- Preliminary trades presented to understand the relationship between nav solution quality and each of the following:
 - Tracking cadence
 - Filter type
 - Measurement noise
 - Measurement type

Filter Type & Tracking Pass Phasing



Monte Carlo of 100 trials, each 1 year long, with short-horizon SK maneuvers,
OD with batch filter in GMAT

Case	All		Converged Only		
	Filter Convergence	Mean 1 σ Covariance [km, cm/s]	Mean 1 σ Covariance [km, cm/s]	Mean State Error [km, cm/s]	State Error Standard Deviation [km, cm/s]
Pass 3 only	65%	125.74, 200.144	8.819, 5.5	10.094, 6.80	219.24, 48.03
Passes 1 & 3	90%	0.1058, 0.07119	0.0809, 0.06409	0.0604, 0.04446	0.0670, 0.03865
Passes 1, 2, & 3	99%	0.0186, 0.01149	0.0185, 0.01148	0.0150, 9.435×10^{-3}	0.0153, 9.117×10^{-3}

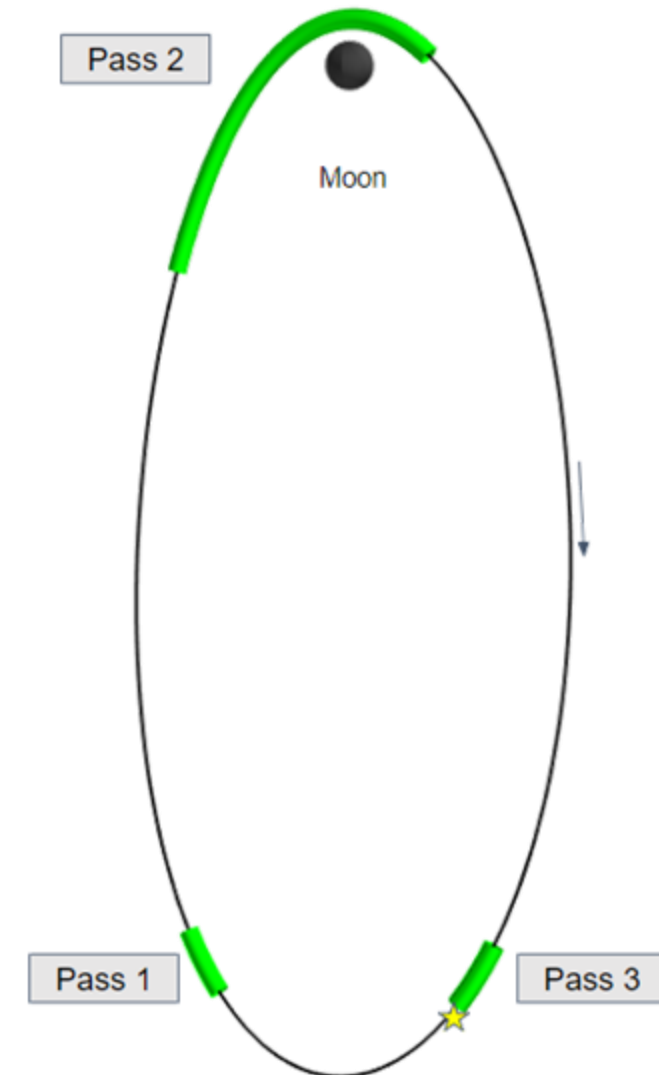


Filter Type & Tracking Pass Phasing



Comparison of OD solutions for 1 orbit

Case	1 σ uncertainty, GMAT Batch	1 σ uncertainty, Monte U-D Factorized Covariance	1 σ uncertainty, Monte SRIF
Pass 3 only	5.641 km, 12.0 cm/s (did not converge)	1.836 km, 1.75 cm/s	1.836 km, 1.75 cm/s
Pass 1 & 3	0.306 km, 0.351 cm/s	0.040 km, 0.083 cm/s	0.040 km, 0.083 cm/s
Pass 1, 2, & 3 (nominal)	0.016 km, 0.009 cm/s	0.025 km, 0.016 cm/s	0.025 km, 0.016 cm/s

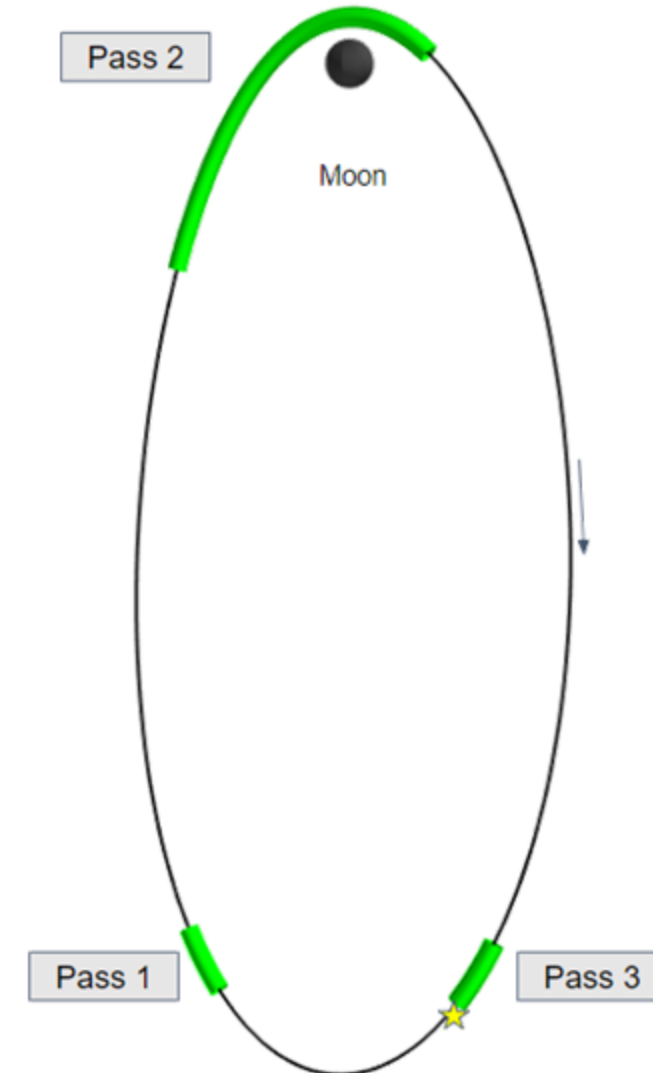


Measurement Noise



Comparison of OD solutions for 1 orbit, using Pass 1, 2, & 3
Monte UD Factorized Covariance

Measurement noise (3σ)	Apolune Position Uncertainty [km]	Apolune Velocity Uncertainty [cm/s]
3 m, 1 mm/s (nominal)	2.49×10^{-2}	1.60×10^{-2}
10 m, 10 mm/s	3.39×10^{-2}	2.06×10^{-2}
15 m, 25 mm/s	3.92×10^{-2}	2.38×10^{-2}

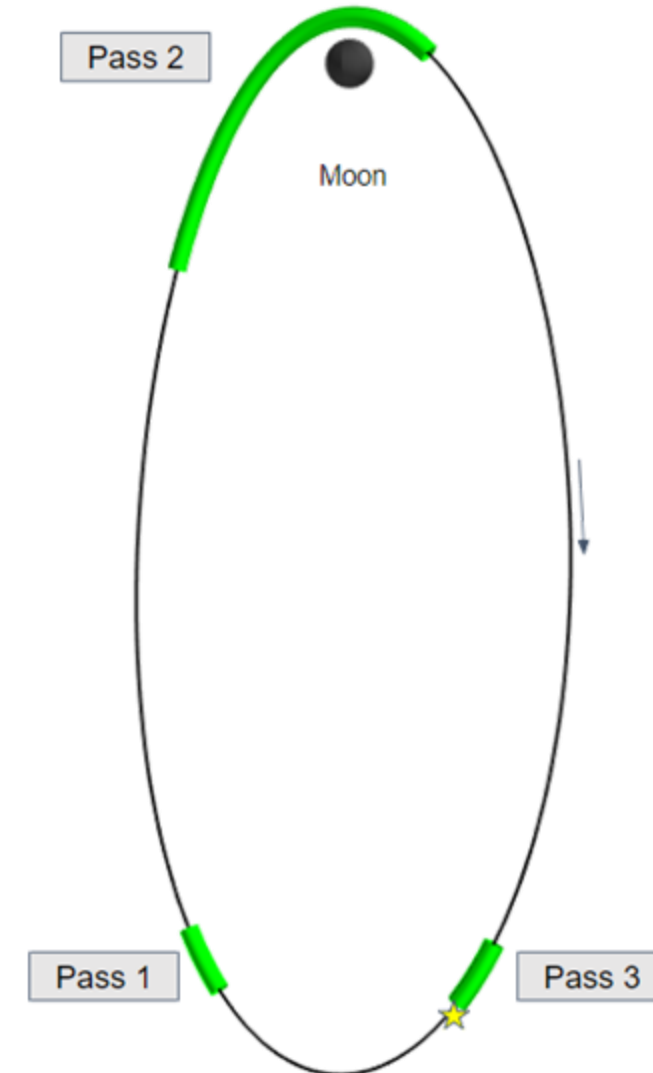


Measurement Type



Comparison of OD solutions for 1 orbit, using Pass 1, 2, & 3
Monte UD Factorized Covariance

Measurement type	Apolune Position Uncertainty [km]	Apolune Velocity Uncertainty [cm/s]
Range only	1.91×10^{-2}	1.32×10^{-2}
Range-rate only	6.60×10^{-2}	3.56×10^{-2}
Range + range-rate (nominal)	2.49×10^{-2}	1.60×10^{-2}



Conclusions

- Presented preliminary trades on:
 - NRHO insertion cleanup, incoming from a BLT
 - Ground contact cadence
 - Measurement noise
 - Measurement type
 - Phasing of observations in NRHO
- Statistical analysis of NRHO stationkeeping and navigation
- Work ongoing to refine these analyses

Acknowledgements



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Thank you to Goddard Space Flight Center for
creating the open-source GMAT



Thank you

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Additional resources available at

<https://advancedspace.com/blt/>

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