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Ballistic Lunar Transfers to Near Rectilinear Halo Orbit: Operational Considerations

Nathan L. Parrish, Ethan W. Kayser, Matthew J. Bolliger, Michael R. Thompson, Jeffrey S. Parker, Bradley W. Cheetham, Diane C. Davis, Daniel J. Sweeney

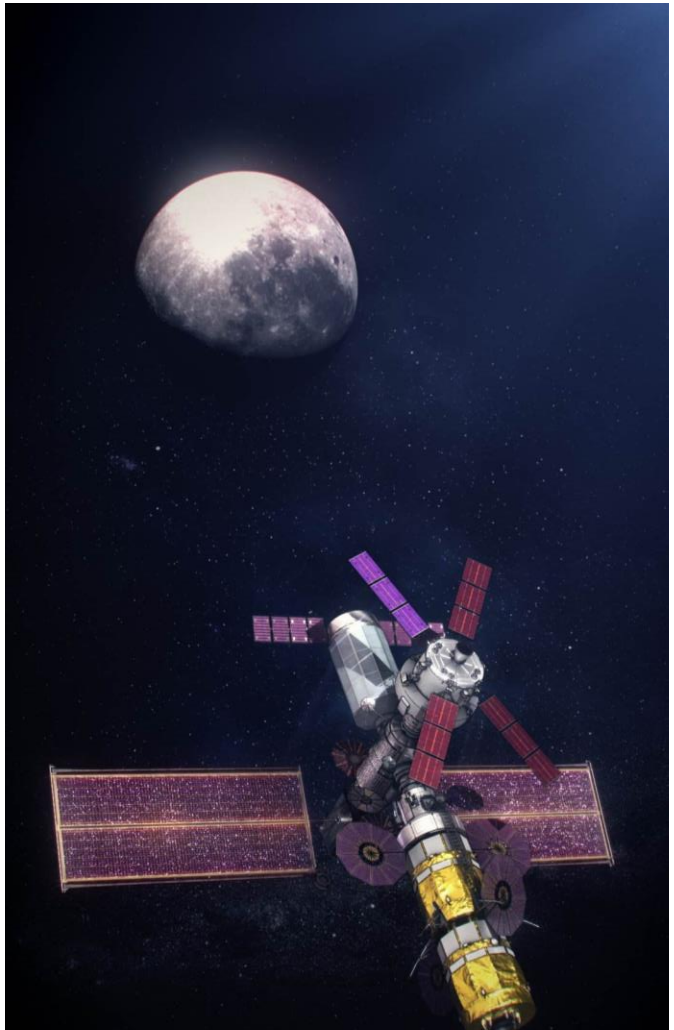
2100 Central Avenue, Suite 102
Boulder, CO 80301
720-545-9191

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 ~3,500 km
  - Apolune radius of ~71,000 km

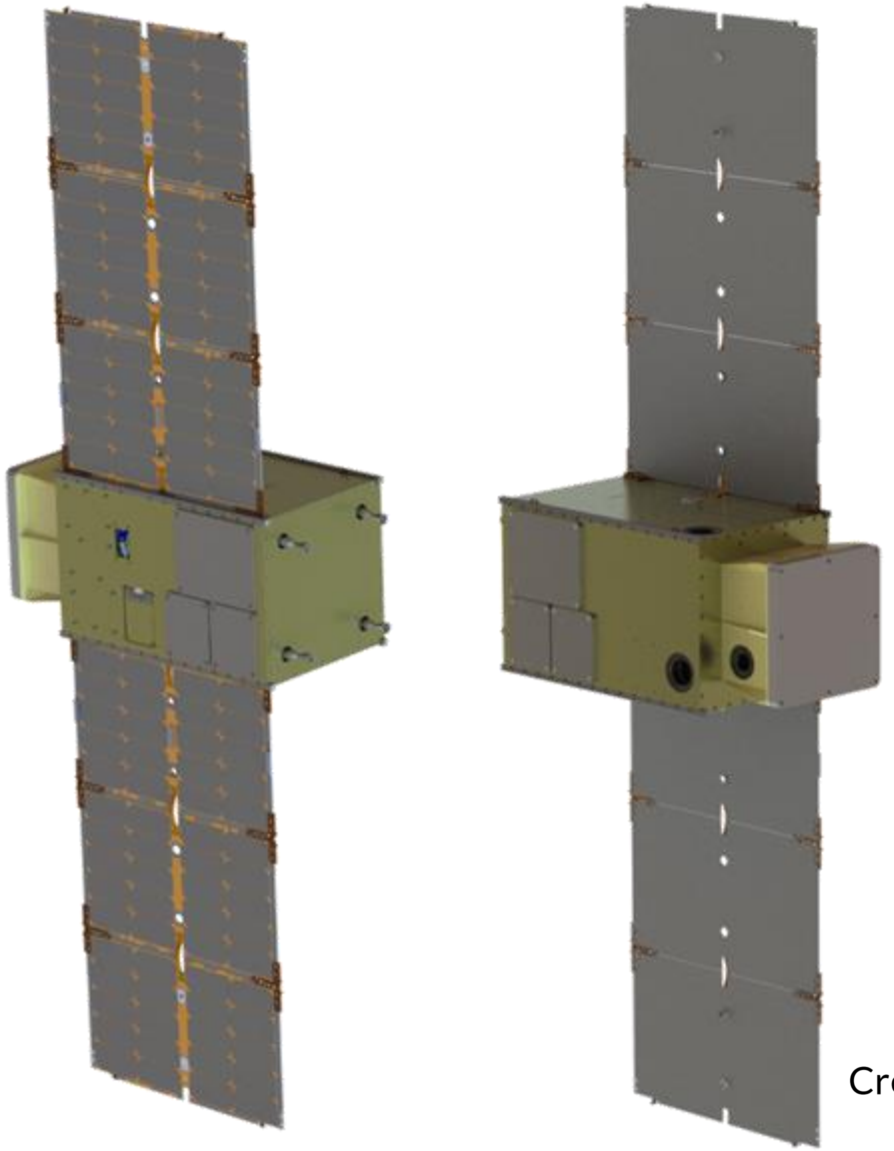

Credit: NASA

[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

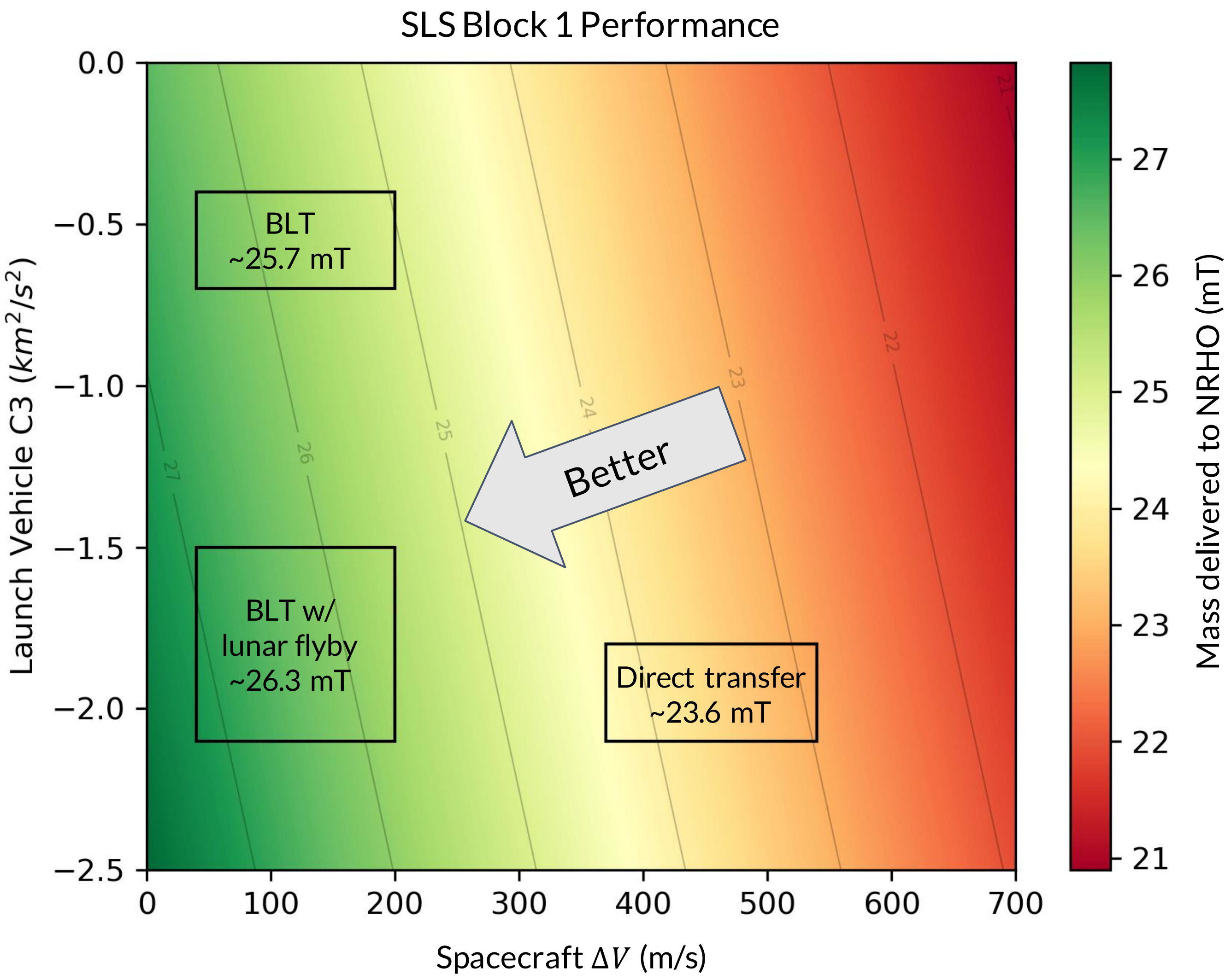


Credit: Tyvak

Why Ballistic Lunar Transfer (BLT)?

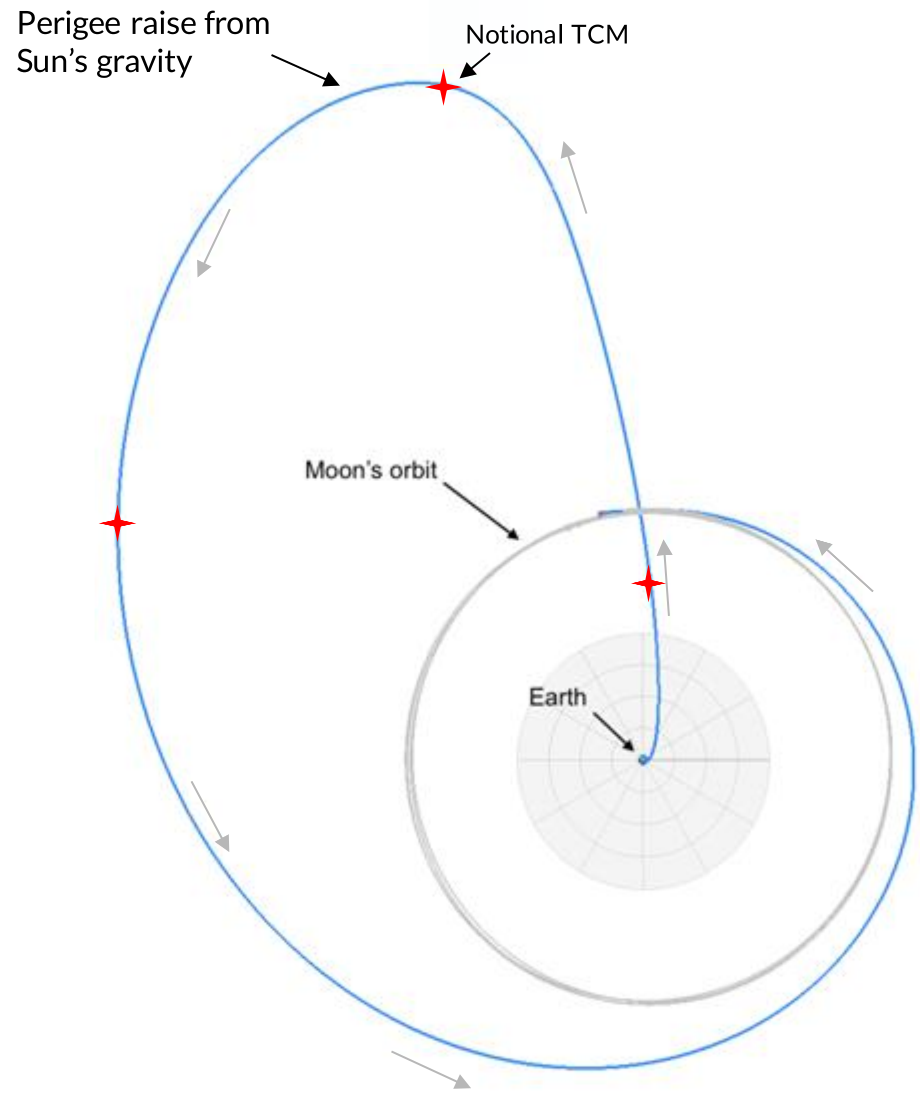
- Assume spacecraft Isp = 300 s
- Benefits:
  - Reduced spacecraft ΔV
  - Reduced operational cadence (more time between maneuvers)
  - Increased launch window
  - Secondary payloads to anywhere in cislunar space
- Trade-offs:
  - Increased time of flight (12-20 weeks)
  - Greater maximum distance from Earth can challenge comms
  - Increased operations duration
  - Potentially higher C_3

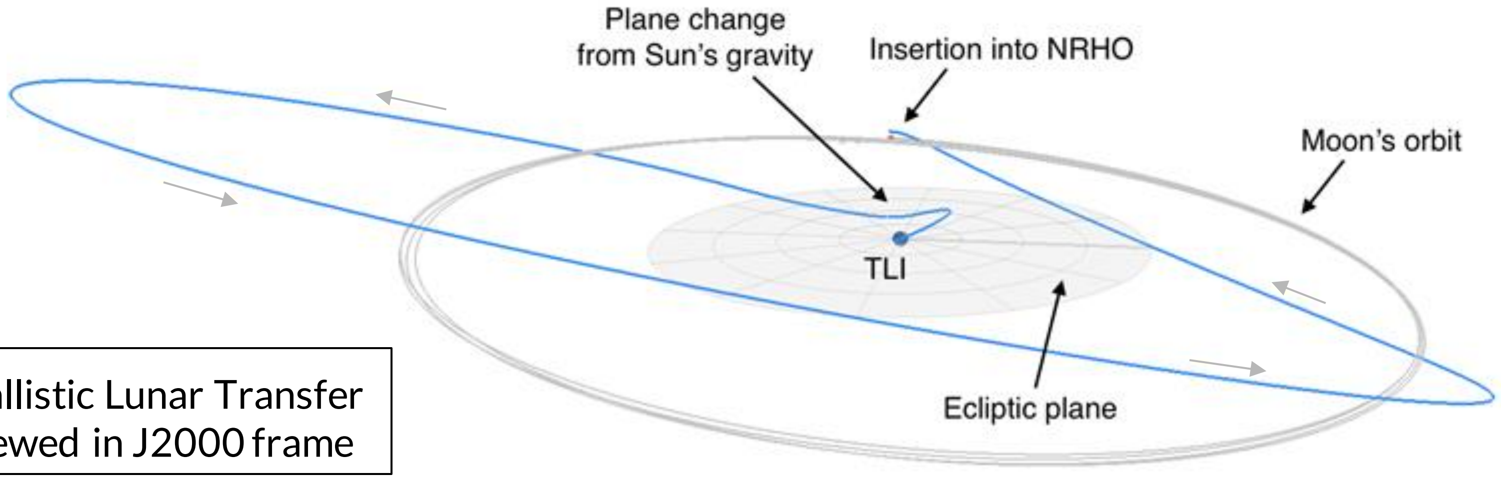
Bottom line:
BLT increases mass delivered to NRHO



Background - BLTs

- Sun's gravity causes plane change and perigee raise, taking the spacecraft from TLI to NRHO for "free"
- Deterministic ΔV opens up launch period and permits rendezvous with target
- Transfer relies on dynamics of four-body problem (Earth, Sun, Moon, spacecraft)

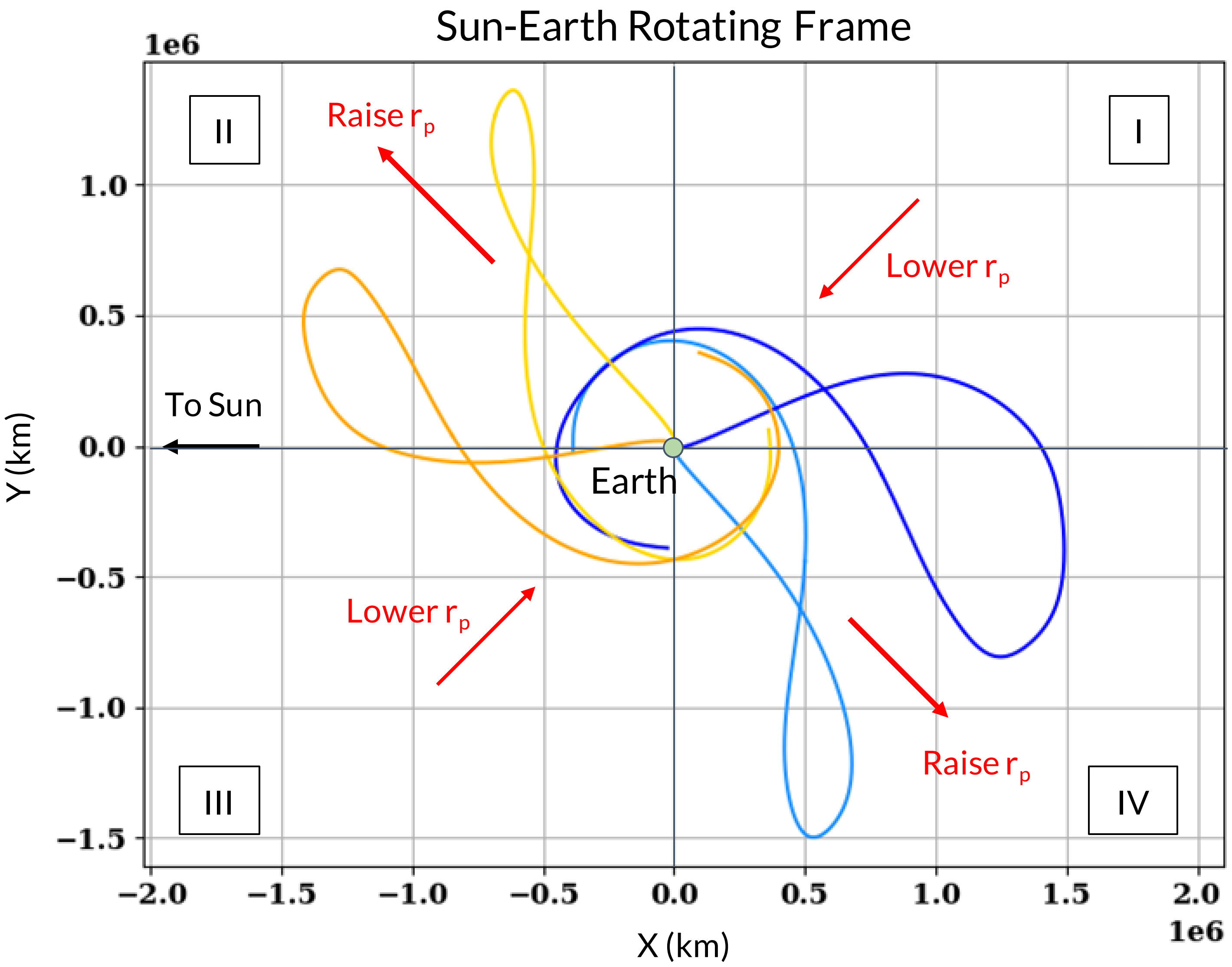




Ballistic Lunar Transfer viewed in J2000 frame

Background - BLTs

- Sun's gravity perturbation affects the radius of perigee
- Effect determined by which quadrant apogee is in:
  - Quadrants II or IV raise perigee
  - Quadrants I or III lower perigee



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: BLTs with realistic OD and maneuver execution errors
  - Parrish et al., “Near Rectilinear Halo Orbit Determination with Simulated DSN Observations”, Thursday at 11:30am.
- Resources available at www.advancedspace.com/blt

What questions are we trying to answer?

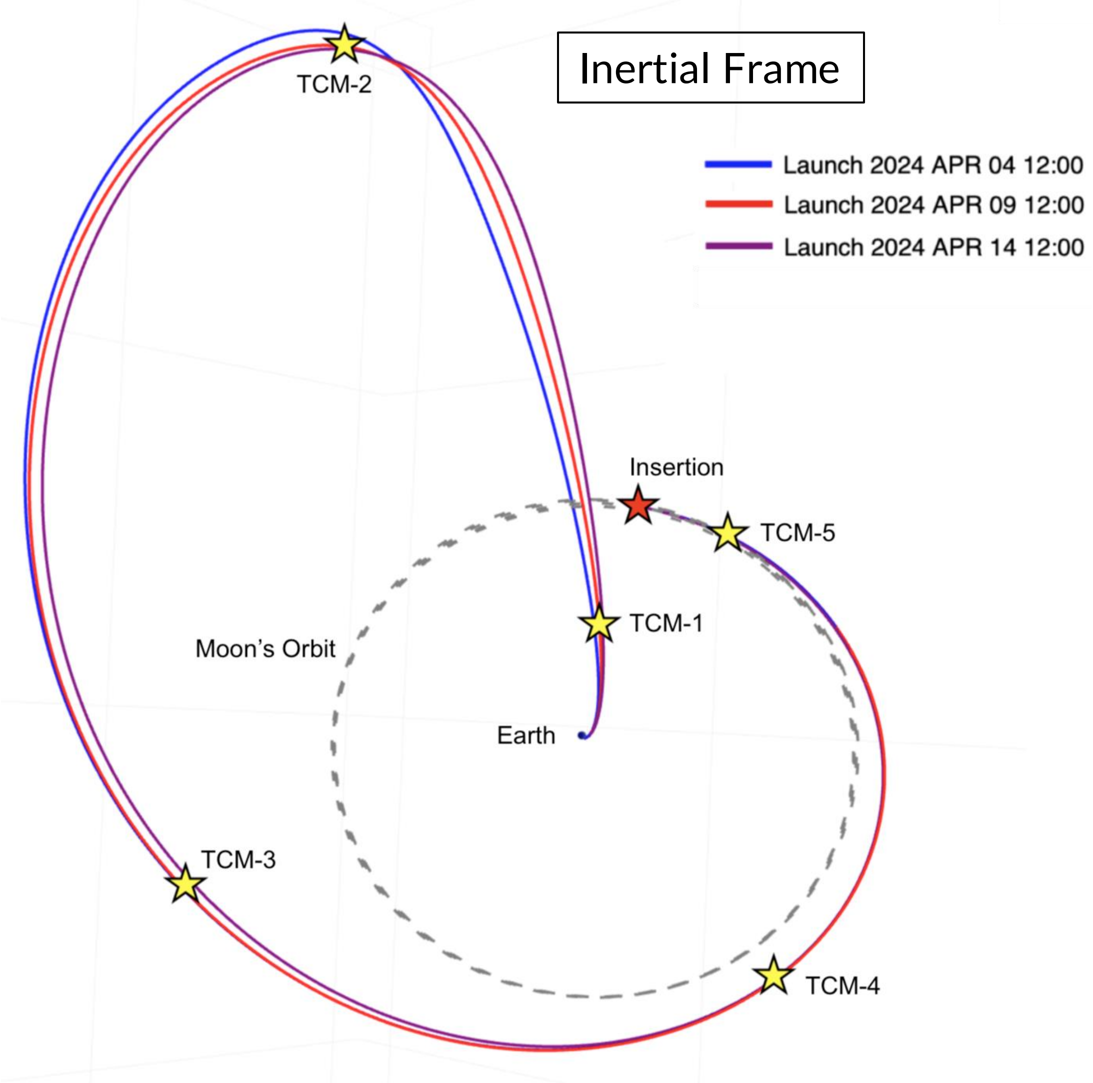
- What are the navigation accuracy requirements for BLTs to NRHOs?
- How much ΔV should be set aside for statistical cleanup maneuvers?
- How many TCMs (trajectory correction maneuvers) are required?
- What are the contributors to the statistical ΔV?
- What are the contributors to the NRHO insertion accuracy?
- How do you practically navigate a spacecraft on a BLT to an NRHO?

Dynamics and Assumptions

- Simulation engine: Copernicus (design), Monte (navigation)
- Force model:
  - Sun & Earth point masses, states from DE430
  - Moon 16x16 (filter) or 32x32 (truth) gravity field, GRGM660PRIM model
  - 14,000 kg spacecraft
  - SRP Area: 23 m^2, CR: 2.0, spherical model
  - Impulsive maneuvers
- Launch not considered — start in parking orbit at Earth
  - 100 km circular, 28° inclination
  - Node orientation optimized
- Maneuvers:
  - Trans Lunar Injection (TLI): Velocity direction
  - Up to 5 Trajectory Correction Maneuvers (TCMs) – 1 deterministic, others statistical clean-up
  - NRHO Insertion Maneuver (NIM)
- Error sources:
  - Launch vehicle injection error
  - Orbit determination error
  - Maneuver execution error
  - Dynamics mis-modeling

Nominal BLTs Considered

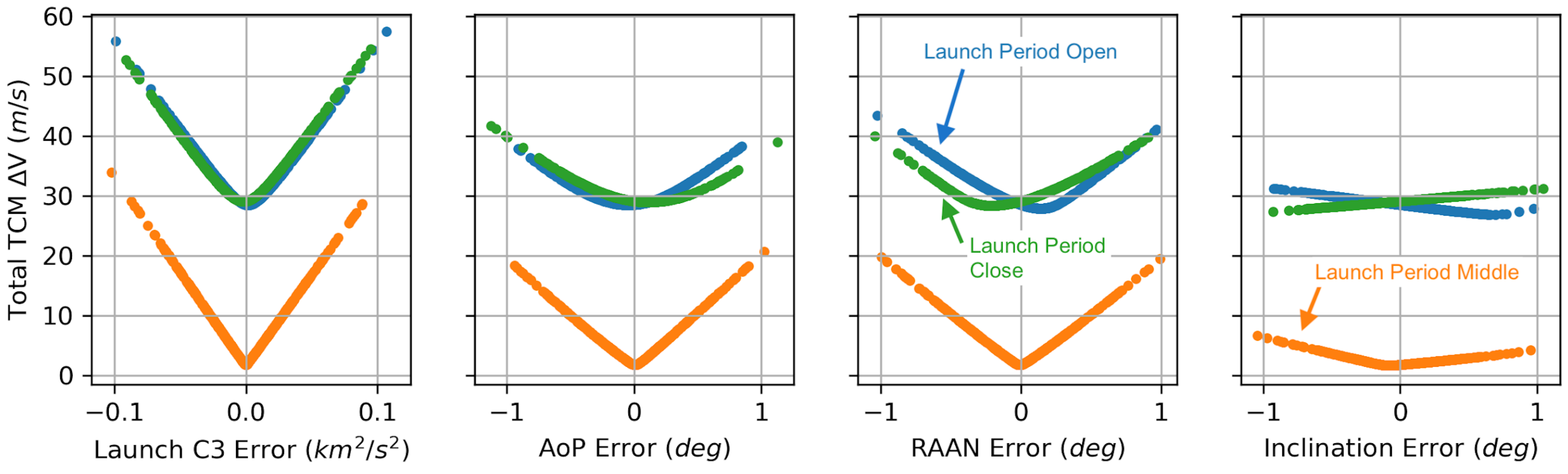
Example 10-day Launch Period (duration determined by ΔV requirement)	Open	Middle	Close
Deterministic TCM-2 ΔV	25.4 m/s	1.6 m/s	25.2 m/s
Nominal Insertion ΔV	15.8 m/s	15.8 m/s	15.9 m/s
Nominal Total ΔV	41.2 m/s	17.4 m/s	41.1 m/s
TLI Epoch	April 4, 2024	April 9, 2024	April 14, 2024
Time of flight	111.6 days	106.6 days	101.3 days



Launch Injection Error

Launch Injection Error

- Launch vehicle never delivers the spacecraft to the exact injection state desired
- What TCM ΔV is required to correct for the launch errors?



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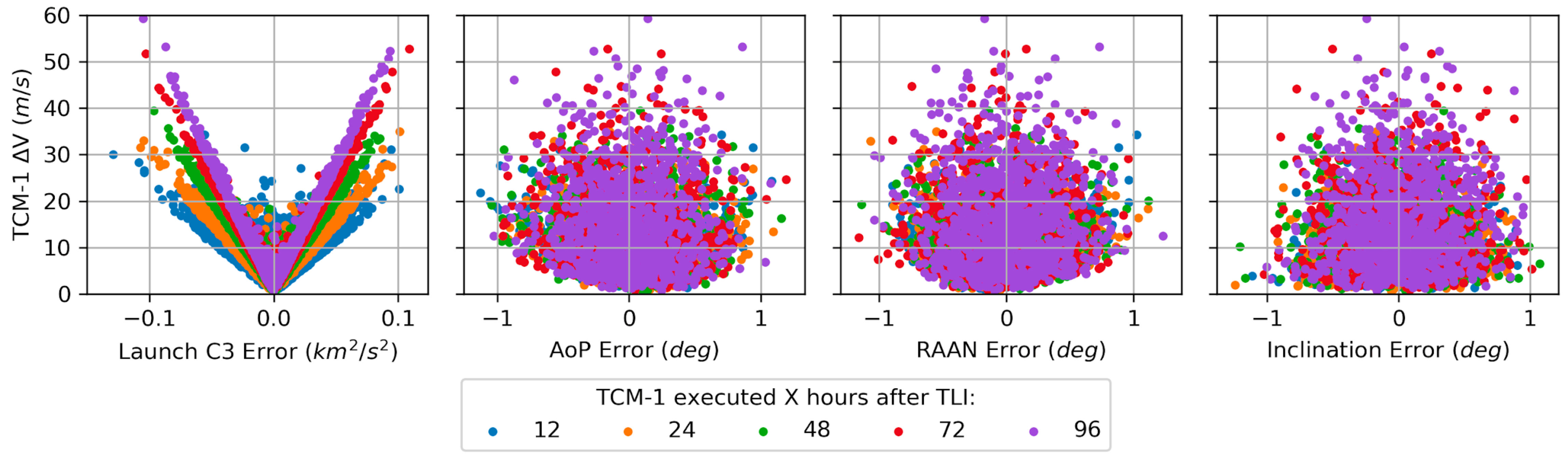


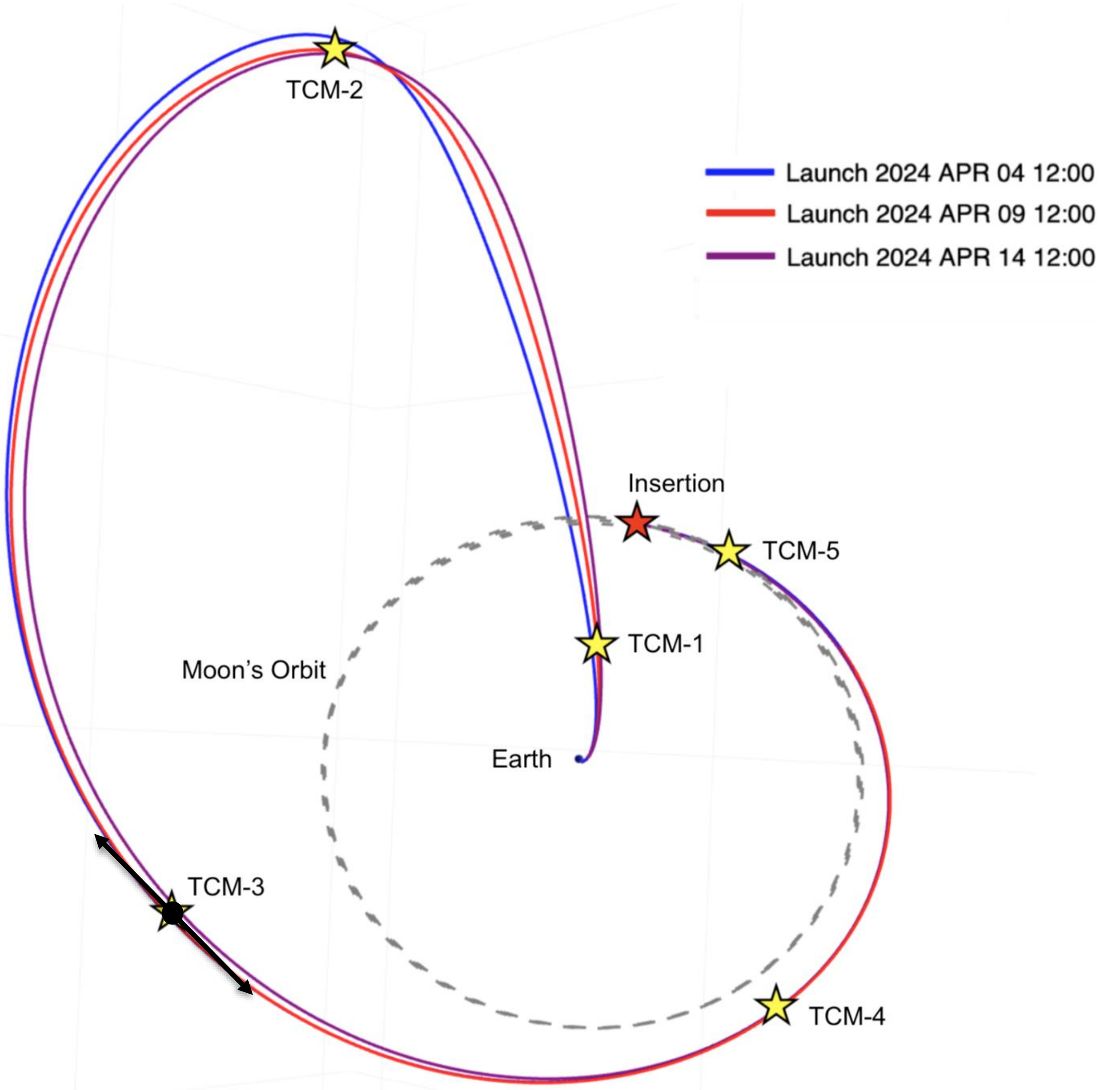
Navigation Requirements

Navigation Requirements Analysis

- Errors modeled:
  - Launch injection
  - Navigation error (maneuver designed based on flawed state estimate)
  - Maneuver execution error (flawed nominal design executed with error)

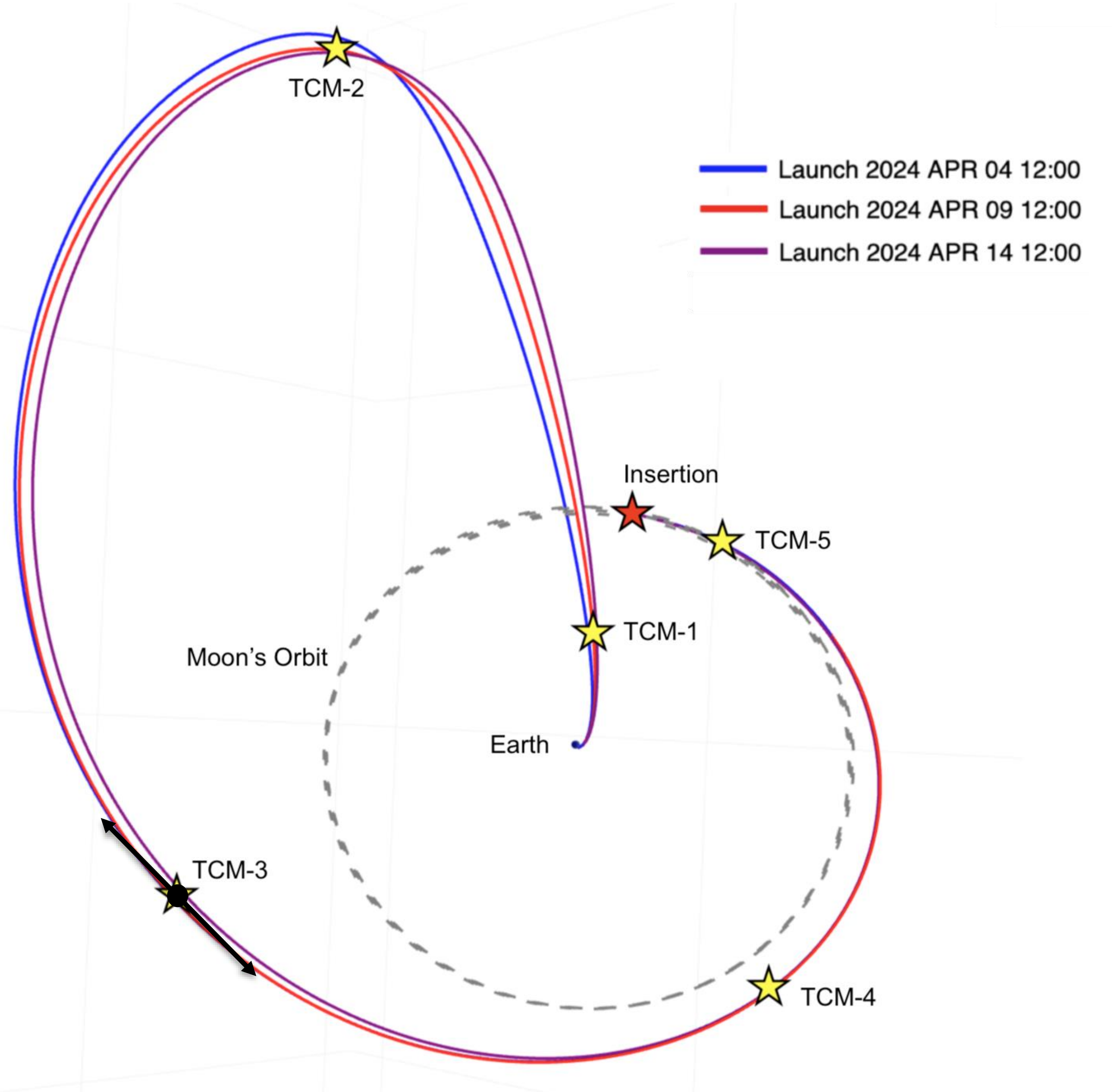
- Multiple Monte Carlo analyses run to answer these questions, for the open, middle, and close of 10-day launch period:
  - How many TCMs?
  - Where should TCMs be placed to minimize DV99 (99^{th} % ΔV)

Nav Requirements: TCM Placement



- TCM-1: as soon after launch as you can get a decent OD solution
- TCM-2: deterministic & stochastic components
  - Deterministic to expand launch period
  - Stochastic to clean up errors
- TCM-3: clean-up errors from deterministic TCM-2
- TCM-4: clean-up before insertion
- TCM-5: clean-up before insertion

Nav Requirements: TCM Placement

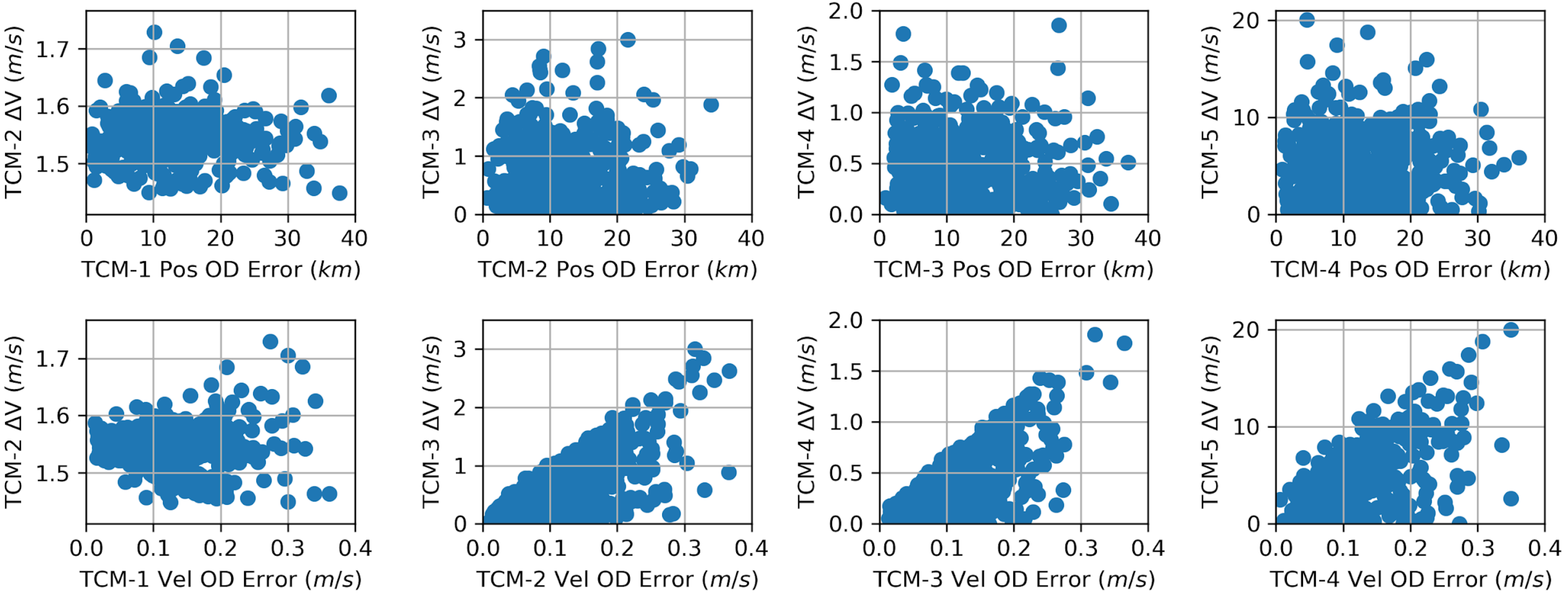


Results:

- Open and close of launch period:
  - TCM-2 is 25 m/s deterministic
  - TCM-3 should be soon after TCM-2 to clean up the deterministic burn
- Middle of launch period:
  - TCM-2 is 2 m/s deterministic
  - TCM-3 should be spaced between TCM-2 and TCM-4

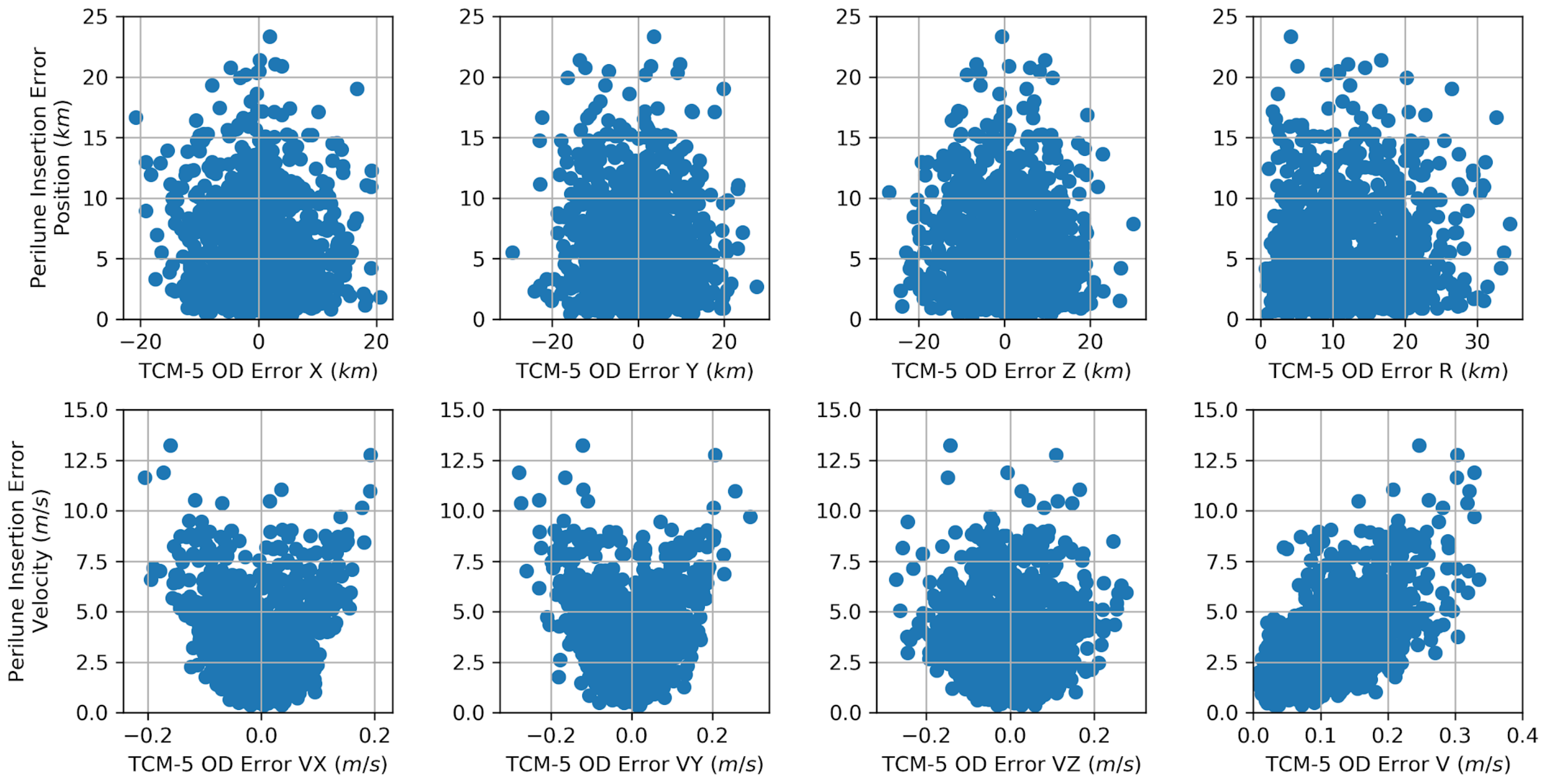
Nav Requirements: OD Uncertainty

Error from TCM-(*i*-1) determines the correction at TCM-(*i*)

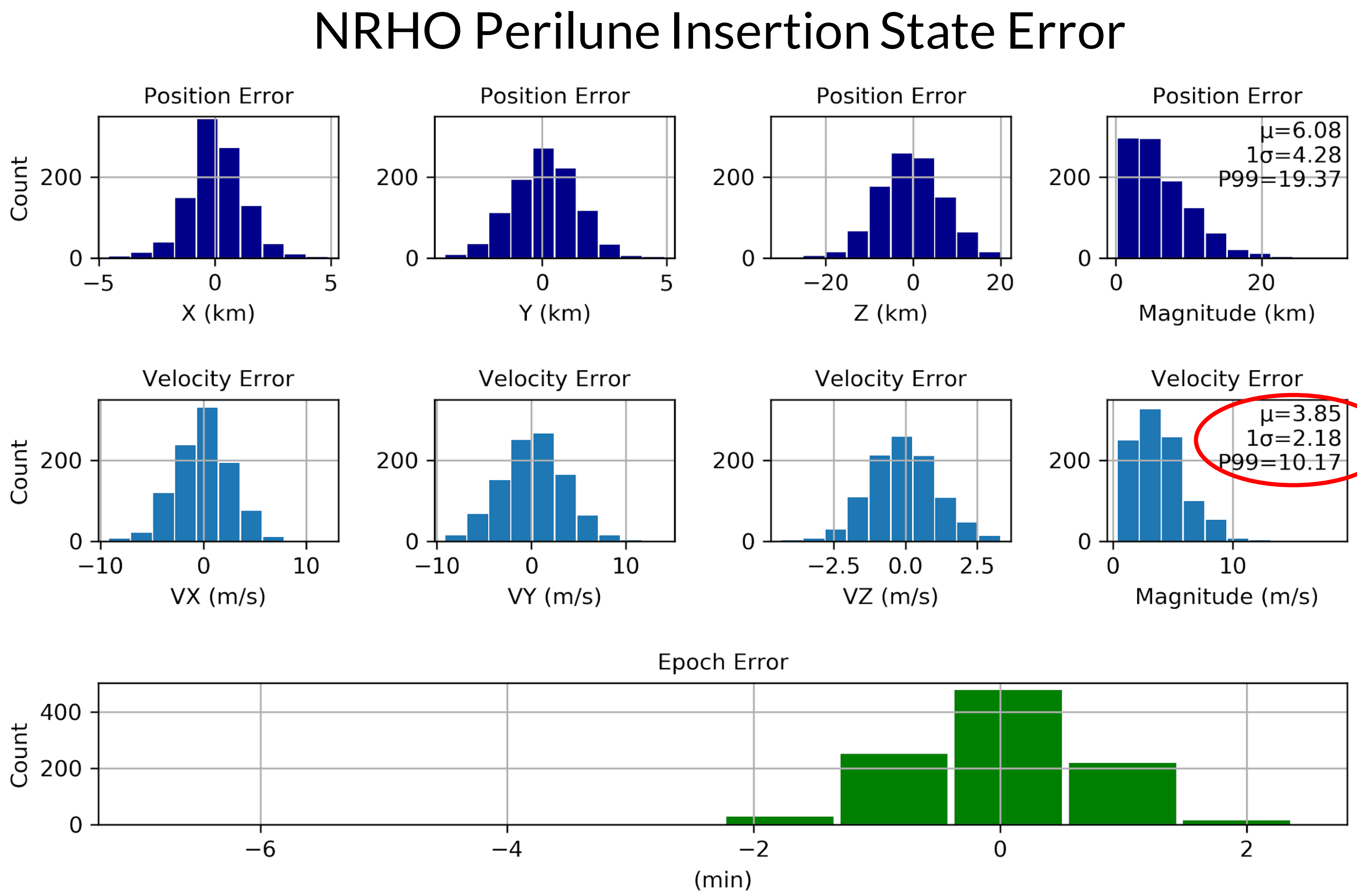


Nav Requirements: OD Uncertainty

Error from TCM-5 determines the error at NRHO insertion



Nav Requirements: OD Uncertainty



High OD error

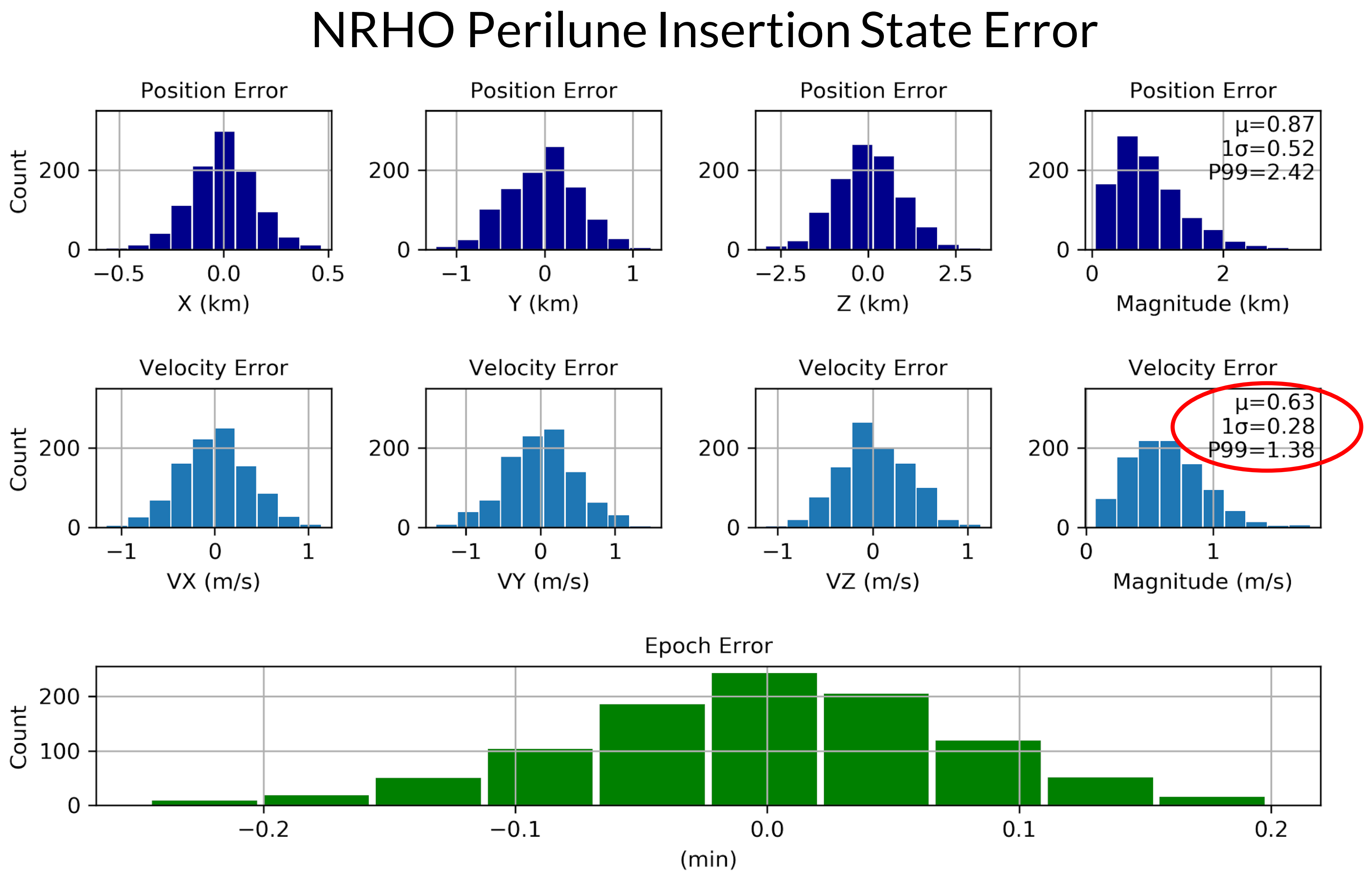
R: 3 km, 3 cm/s

T: 30 km, 30 cm/s

N: 30 km, 30 cm/s

Nav Requirements: OD Uncertainty

Low OD error
R: 0.3 km, 0.3 cm/s
T: 3 km, 3 cm/s
N: 3 km, 3 cm/s

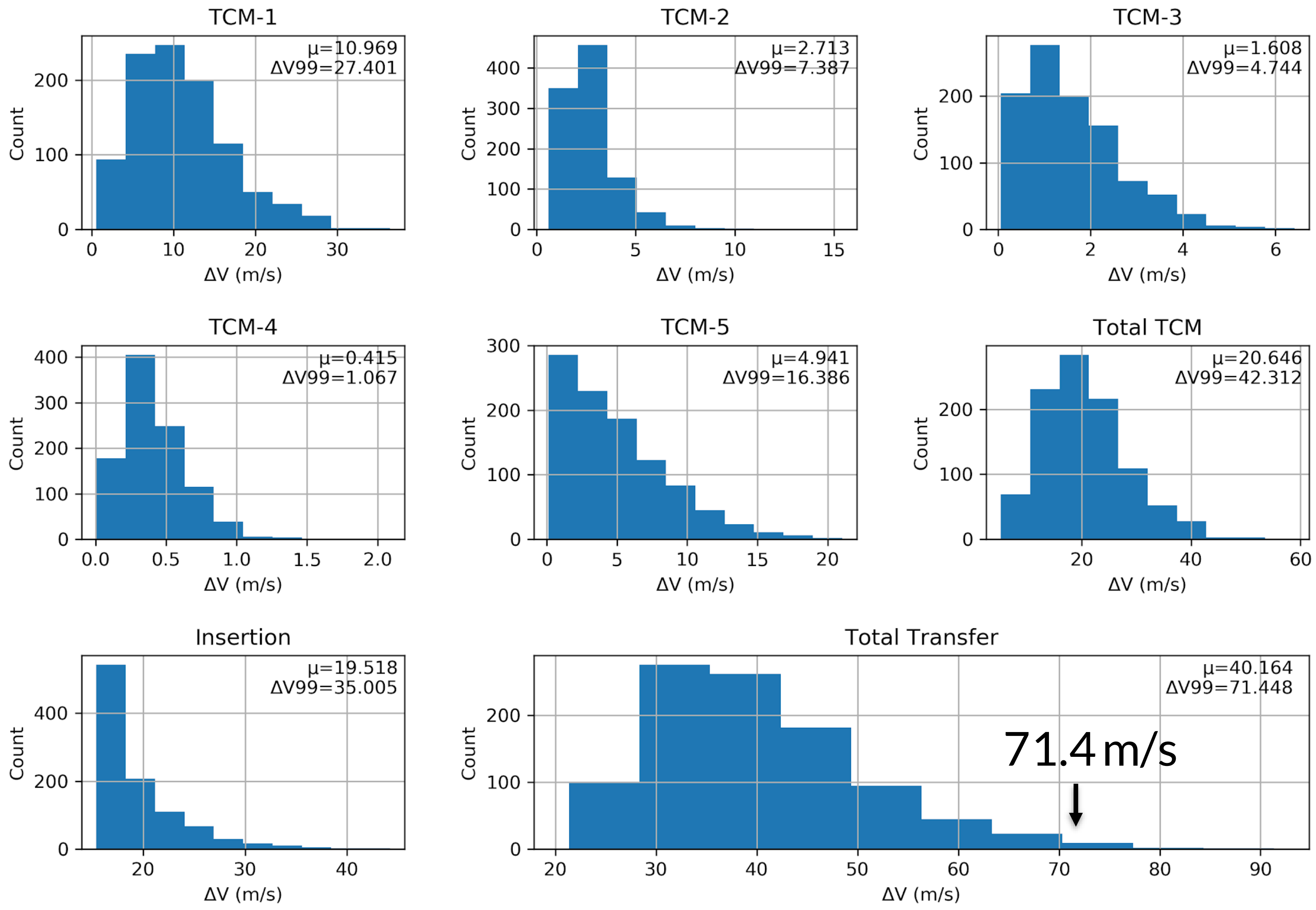


Nav Requirements: OD Uncertainty

High OD error
R: 3 km, 3 cm/s
T: 30 km, 30 cm/s
N: 30 km, 30 cm/s

ΔV breakdown:
- Launch cleanup: 28 m/s
- Deterministic TCMs + Insertion: 18 m/s
- Statistical TCMs + Insertion: 25 m/s

ΔV distribution for each maneuver



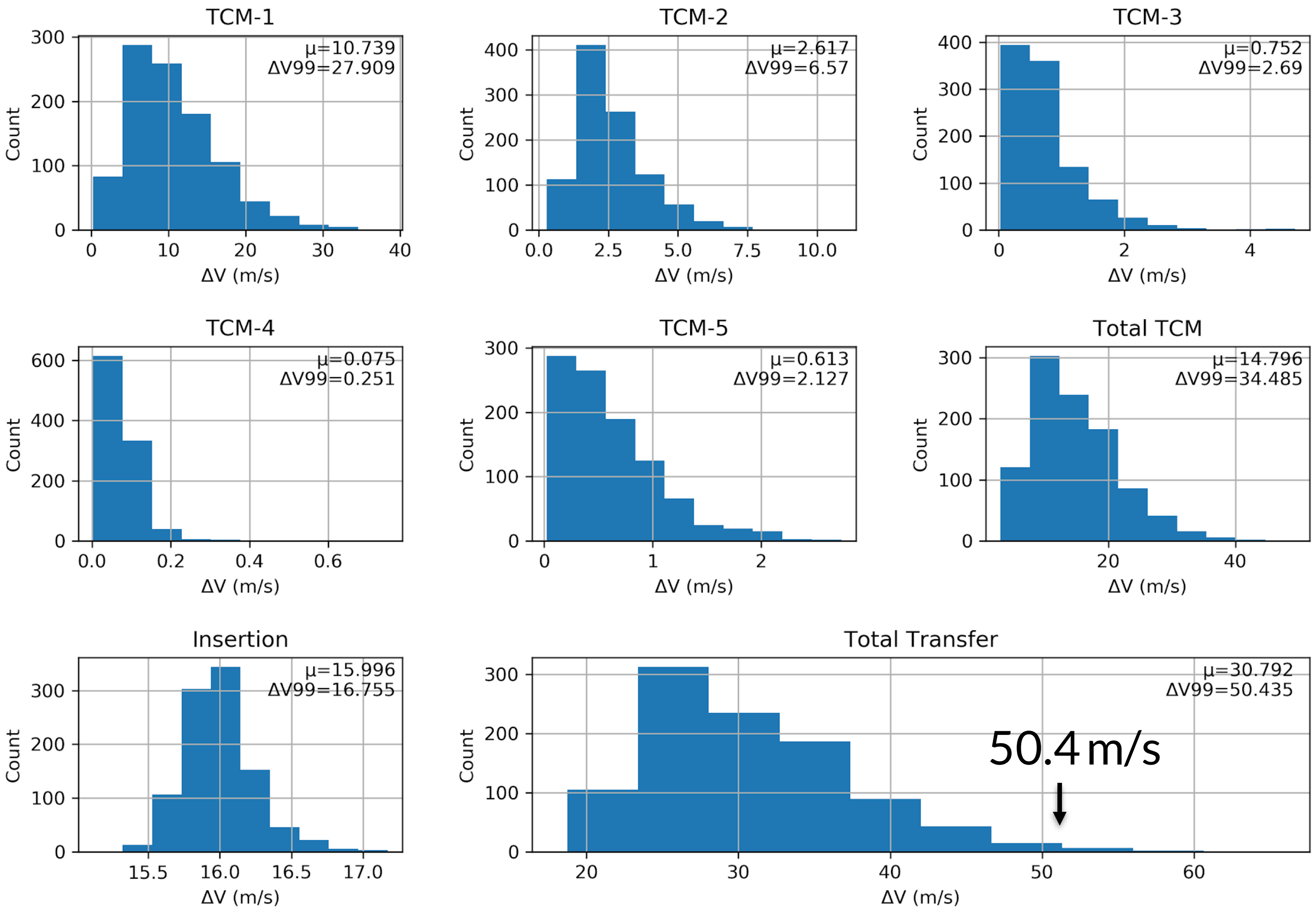
Nav Requirements: OD Uncertainty

Low OD error
R: 0.3 km, 0.3 cm/s
T: 3 km, 3 cm/s
N: 3 km, 3 cm/s

ΔV breakdown:

- Launch cleanup: 28 m/s
- Deterministic TCMs + Insertion: 18 m/s
- Statistical TCMs + Insertion: 14 m/s

ΔV distribution for each maneuver

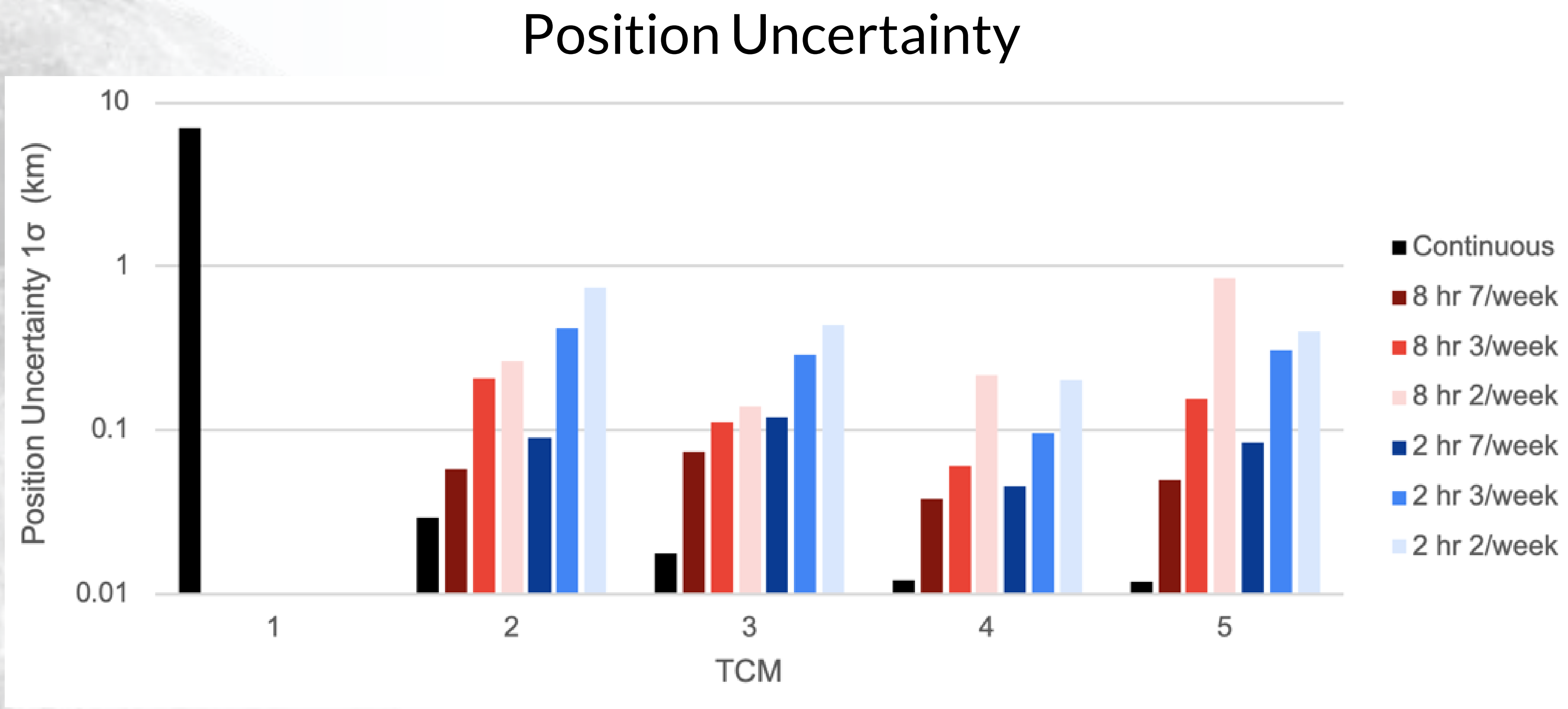


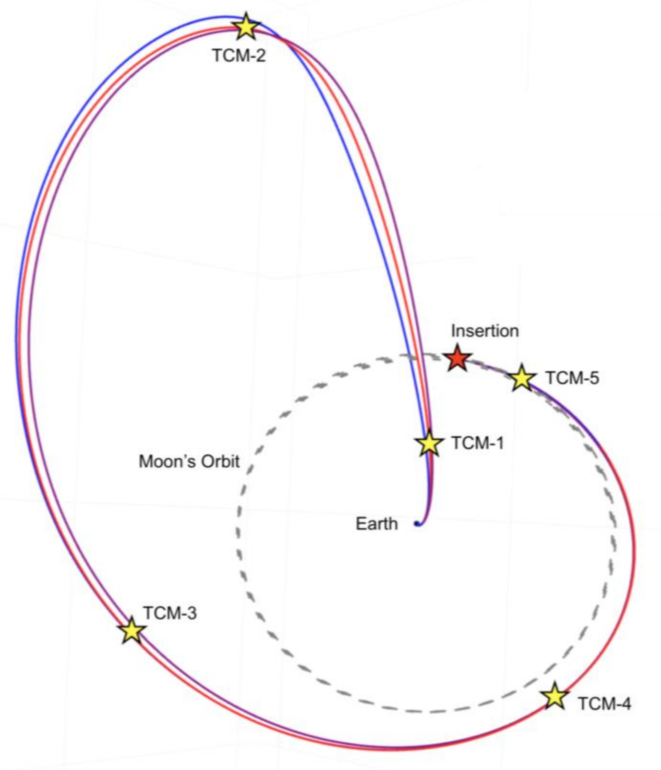
BLT Navigation Analysis

Simulated OD: Setup

- Models:
  - Truth: SPK file generated by Copernicus
  - Filter: Monte U-D factorized covariance
  - Dynamical errors introduced from lunar gravity field and SRP
- Simulated observations
  - Noisy observations generated by Monte based on the truth SPK
  - Observation generation does not model any spacecraft dynamics – states simply queried from SPK file
  - Measurement noise based on published numbers and post-processing of real ARTEMIS data
- Analysis performed
  - Covariance study of various tracking schedules for each leg of transfer
  - Monte Carlo analysis with randomly sampled errors for various tracking schedules for each leg of transfer

Covariance Analysis: Tracking Frequency





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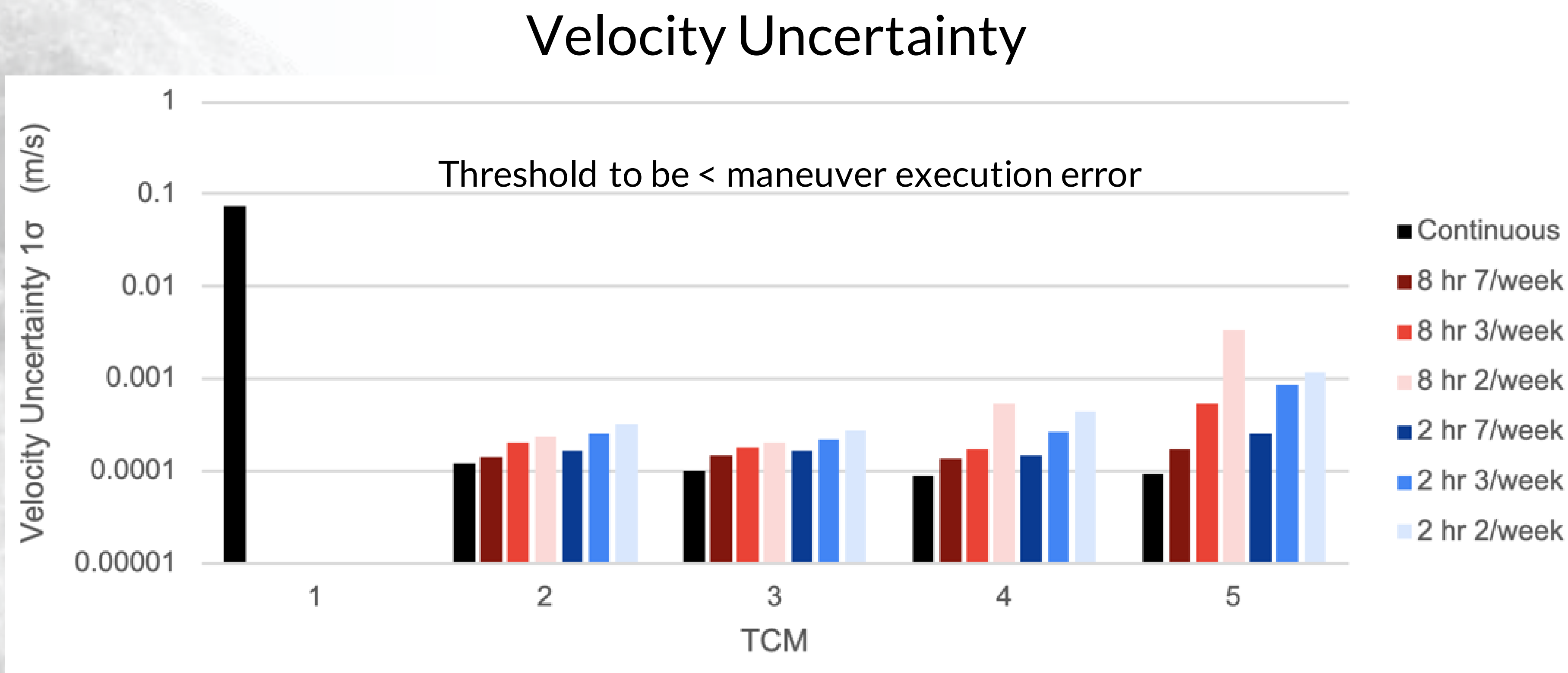
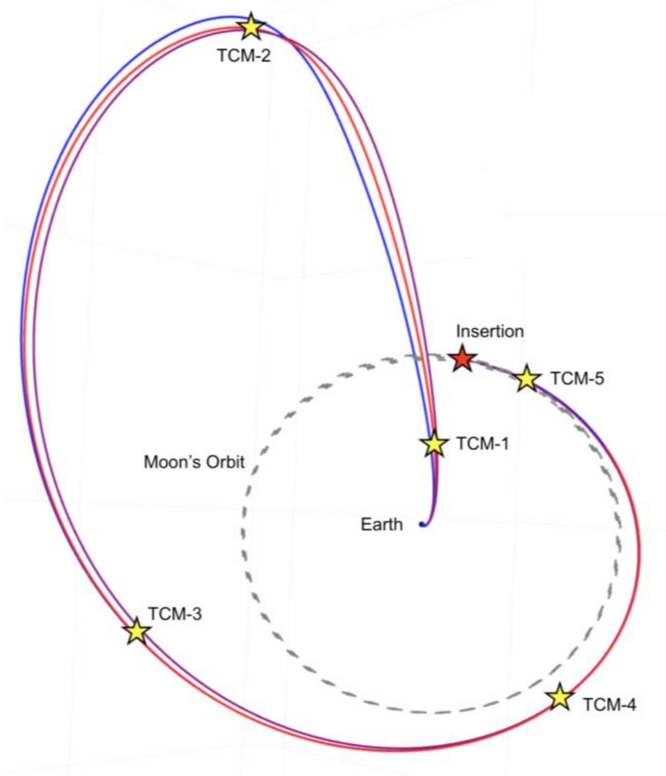
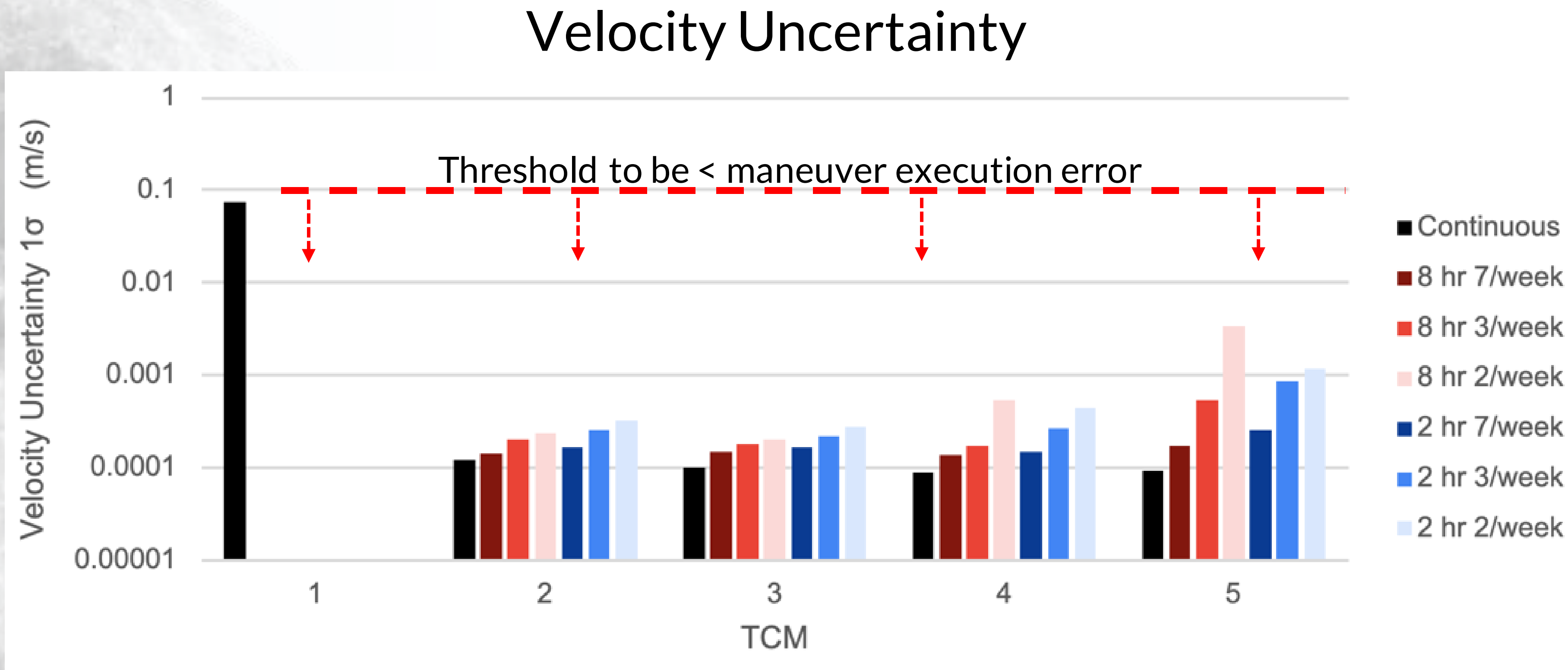
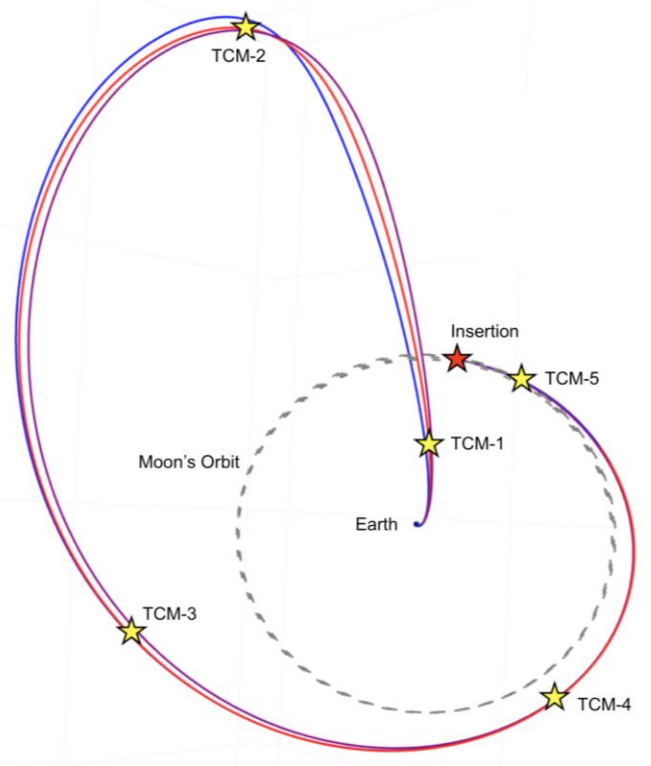




Covariance Analysis: Tracking Frequency





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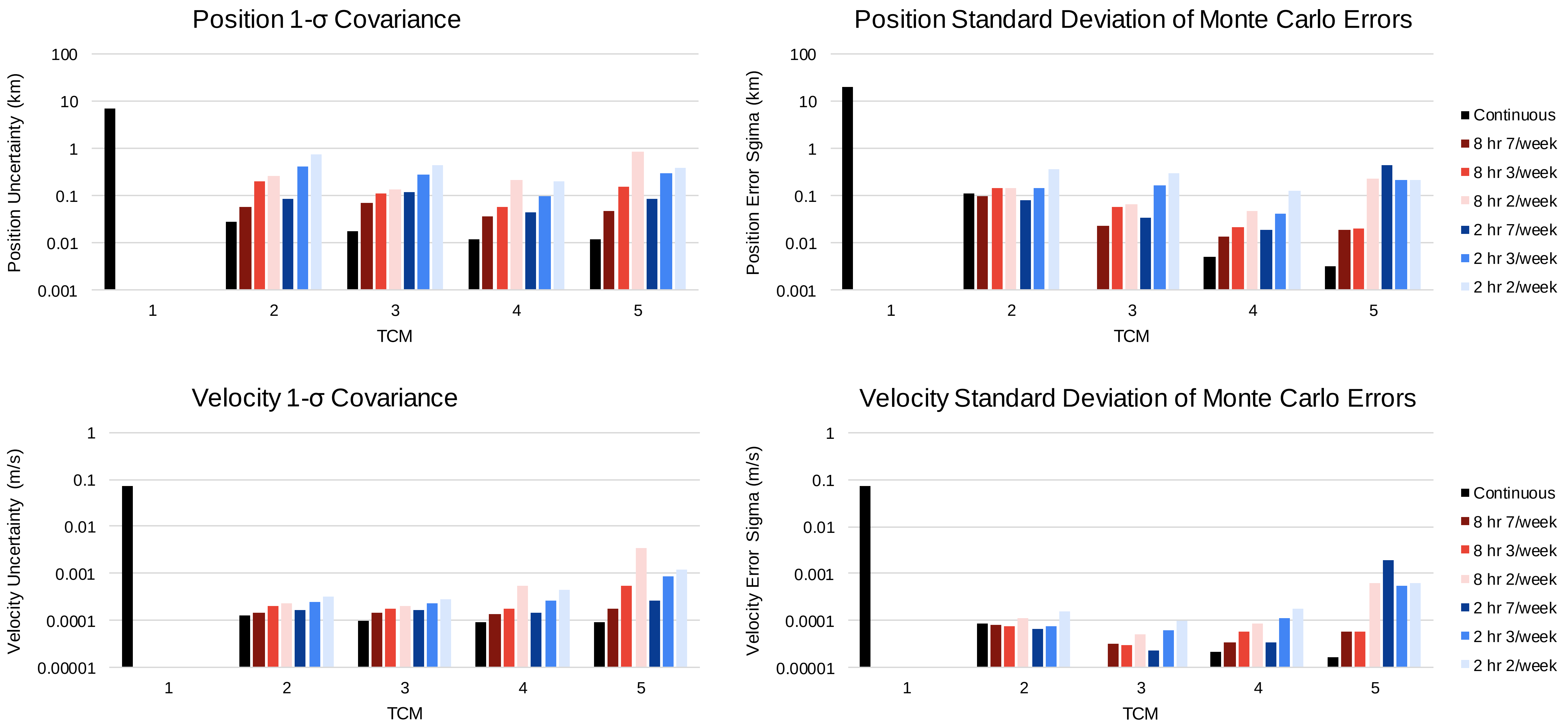
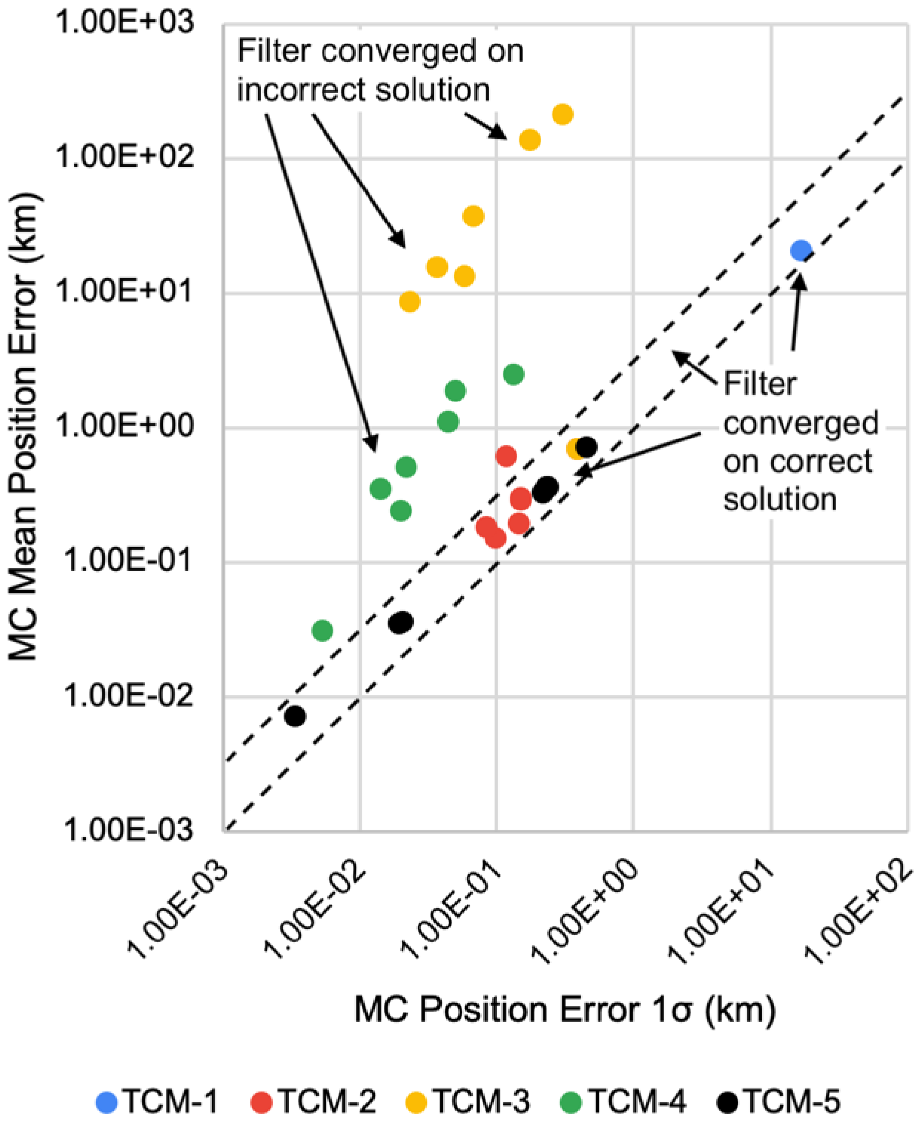


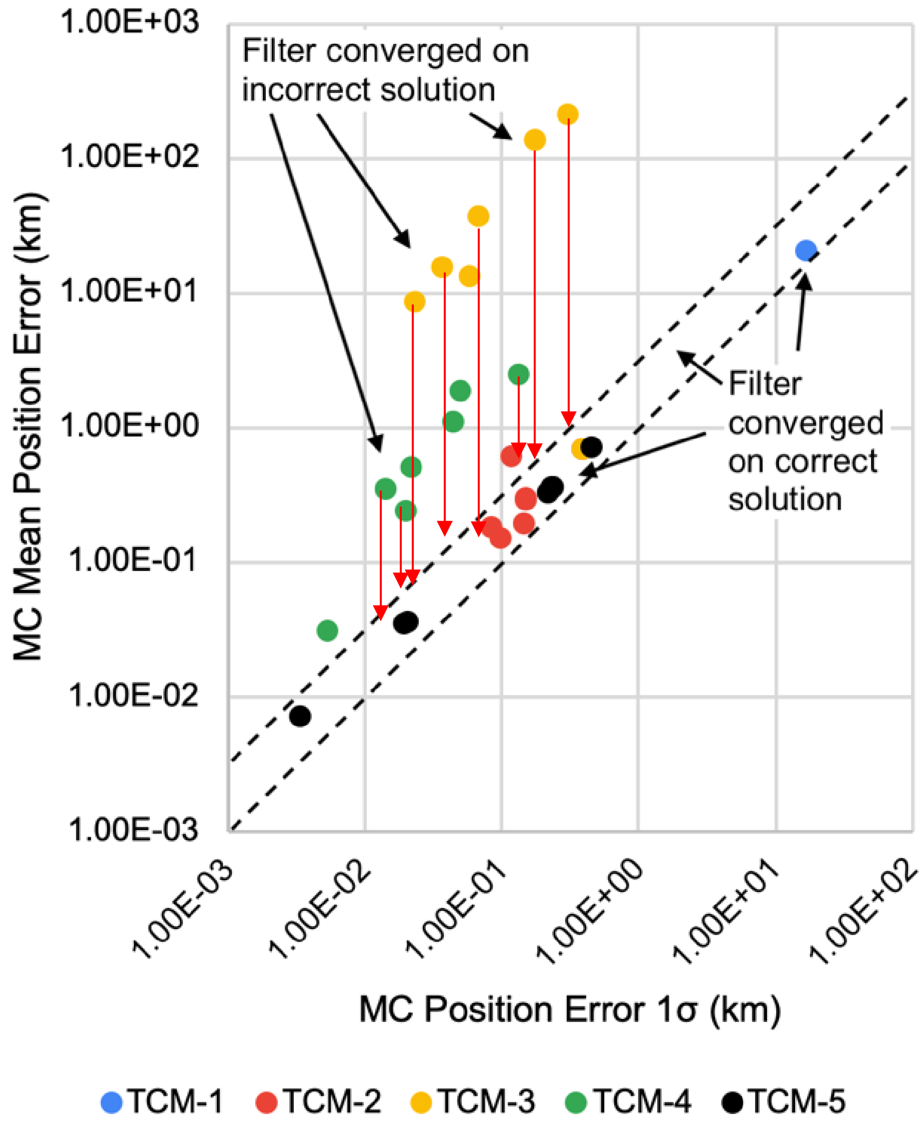
Simulated OD: Results

- Initial implementation contained a bug which made it appear that the filter was converging on the wrong solution



Simulated OD: Results

- Initial implementation contained a bug which made it appear that the filter was converging on the wrong solution
- Fixed now, leading to reliable results
- Correction will be published



Conclusions

Presented analysis on:

- Launch injection errors
- Navigation accuracy requirements
- Number and placement of trajectory correction maneuvers
- Contributors to statistical ΔV
- Contributors to NRHO insertion accuracy
- Preliminary study of BLT navigation

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Thank you

Contact:
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parrish@advanced-space.com

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