The Lunar SLALOM: Sustained Low-Altitude Lunar Orbital Mission

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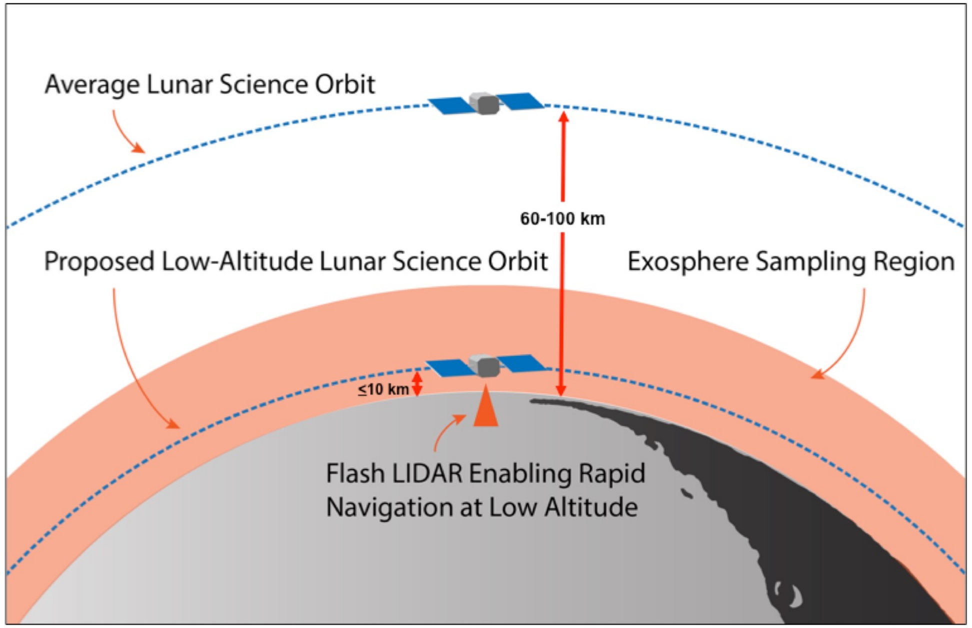
Delivering innovation to orbit

Agenda

- SLALOM Introduction
- Mission Design
- Stationkeeping Design
- Navigation System
- Flight Software
- Path Forward

SLALOM: Introduction

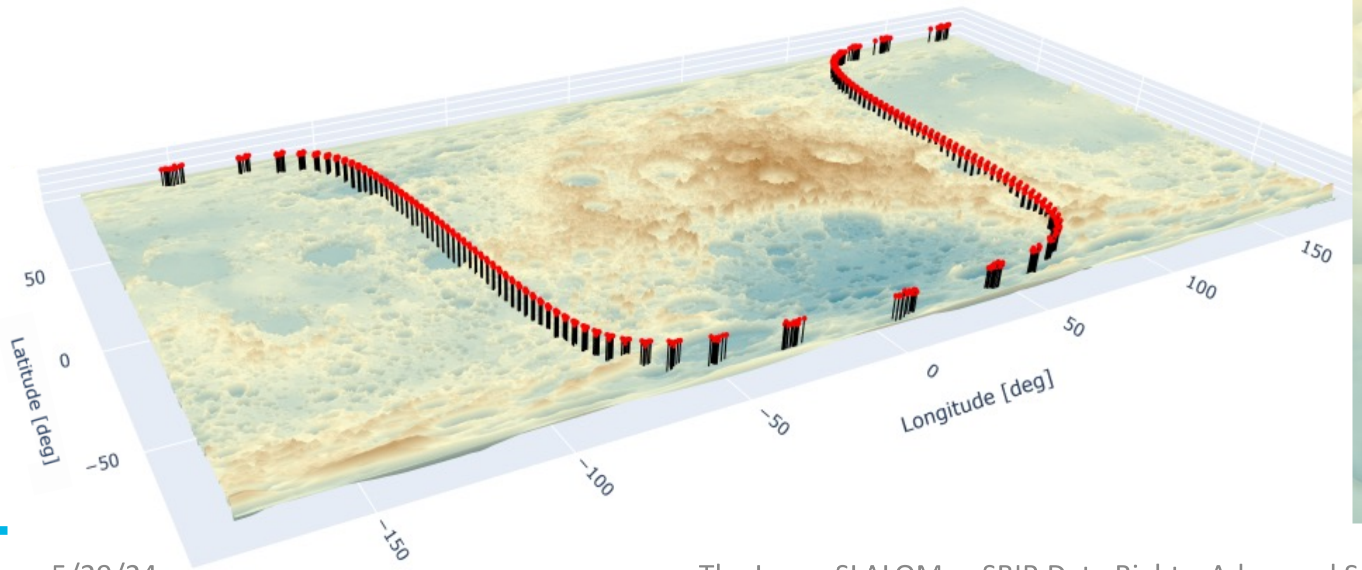
- Sustained Low-Altitude Lunar Orbital Mission (SLALOM)
- SLALOM answers the question: **How does a mission achieve a *sustained* average altitude below 10 km?**
- Answer: Autopilot with ALPINE (Autonomous Maneuver Location Processor using Integrated Navigation Estimate)
  - This is an autonomous navigation system that is embedded on a spacecraft.
  - Processes LIDAR / RADAR / OpNav data onboard
  - Generates maneuver designs
  - Satisfies robustness requirements to ensure that the spacecraft remains within the corridor.
  - Built and tested on flight software.

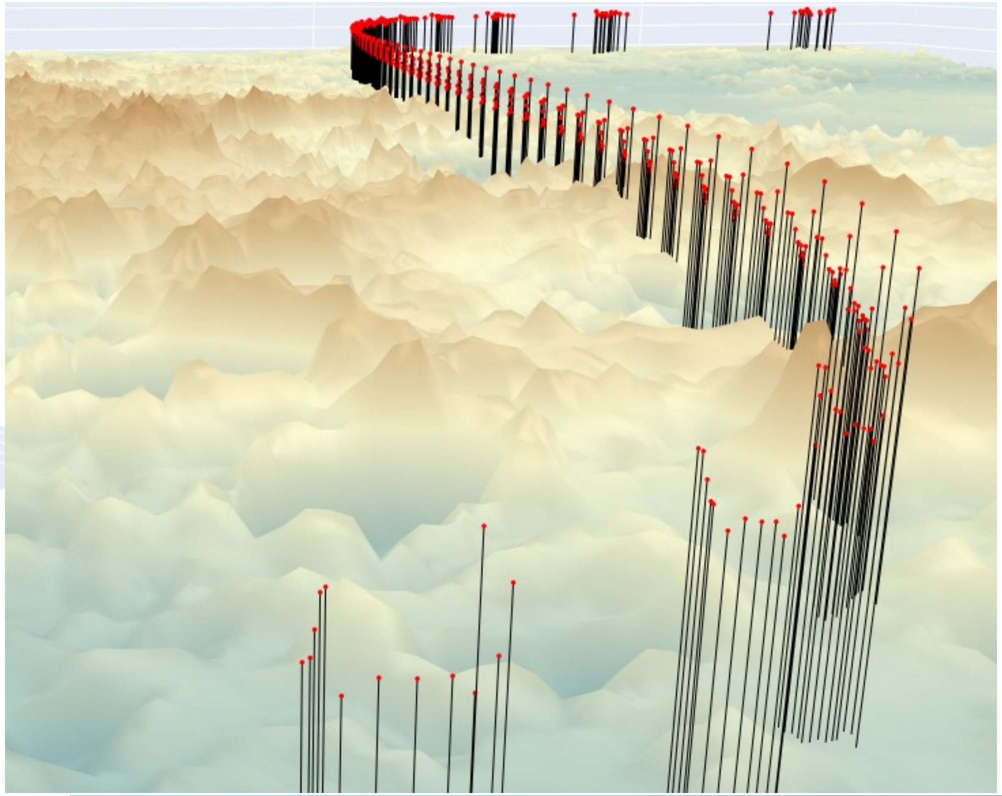


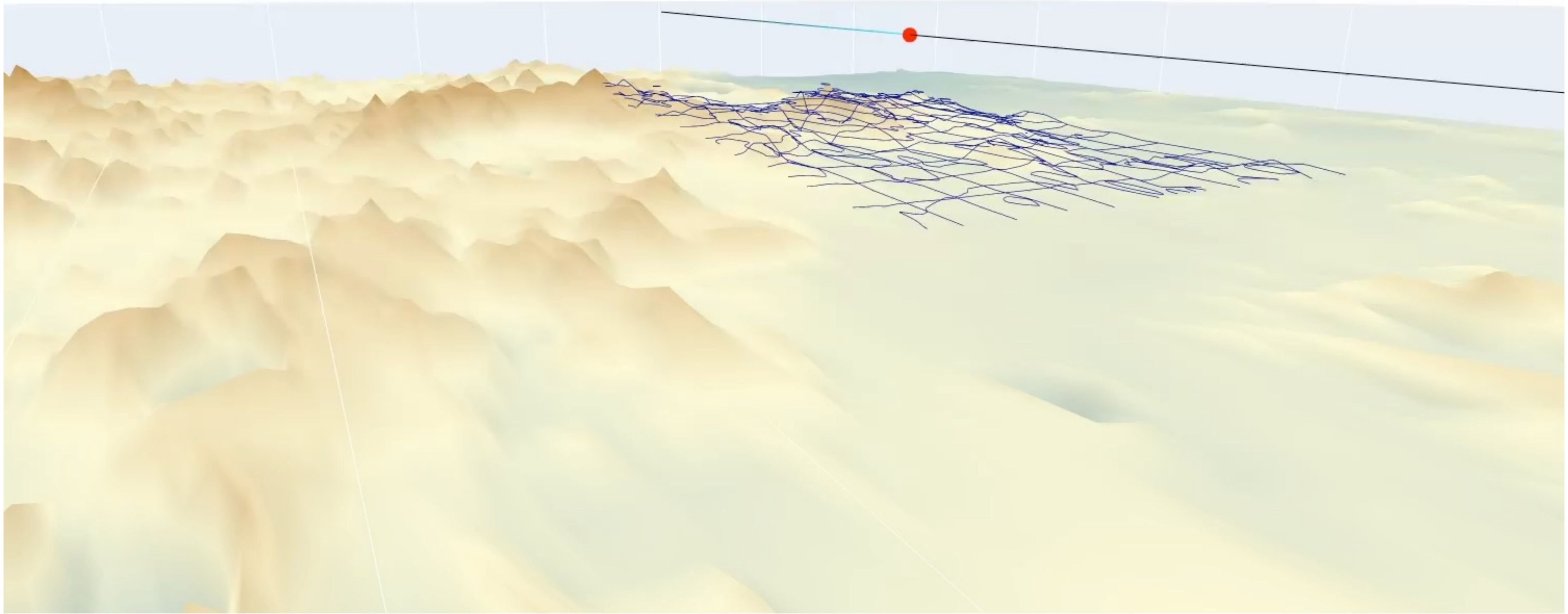
GRAIL: 55 km average: monthly maneuvers.
GRAIL: 23 km average: weekly maneuvers.
SLALOM: 6-10 km average: daily maneuvers.

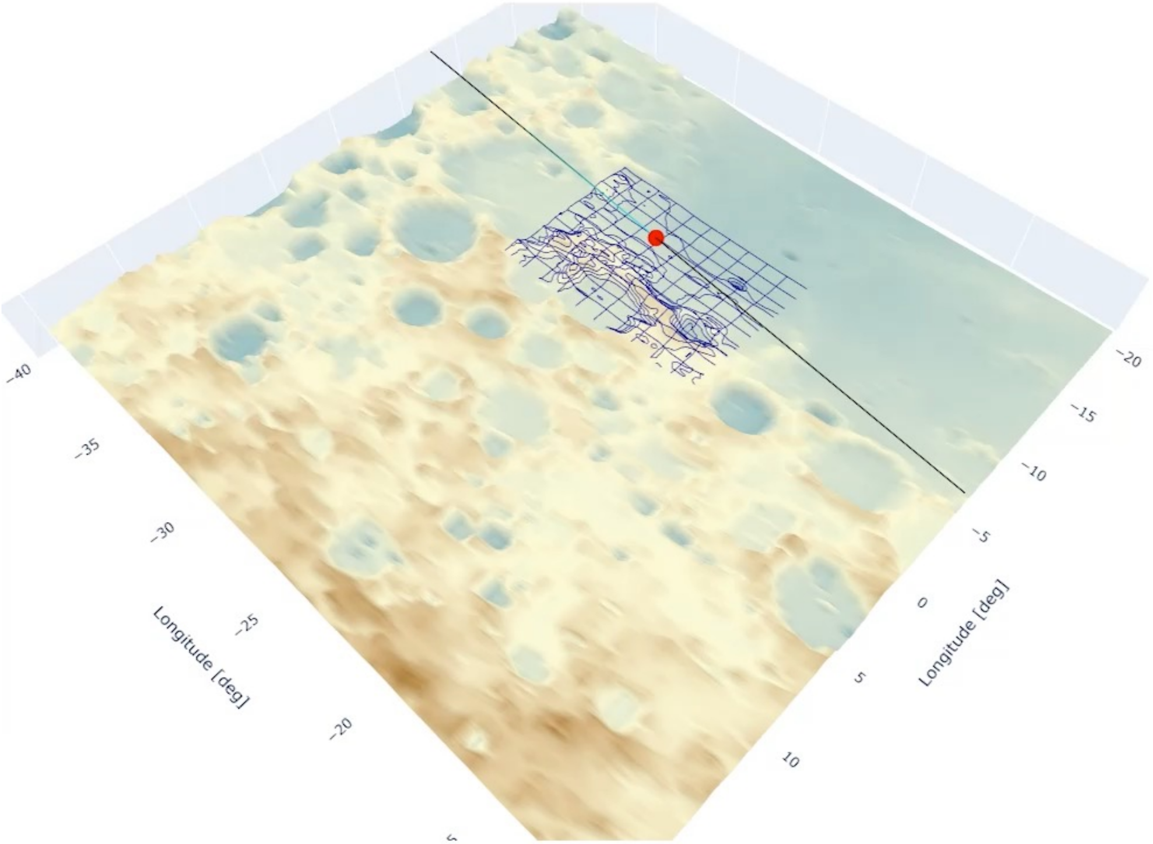
Reference Mission Design

- Low-energy ballistic lunar transfer (BLT) from Earth to the Moon
- Lunar orbit insertion: targeting ~4 hour lunar orbit
- Tests in a 100 km x 2330 km orbit
- Reduction down to 5 km x 7 km orbit
- SLALOM ALPINE Ops








−40
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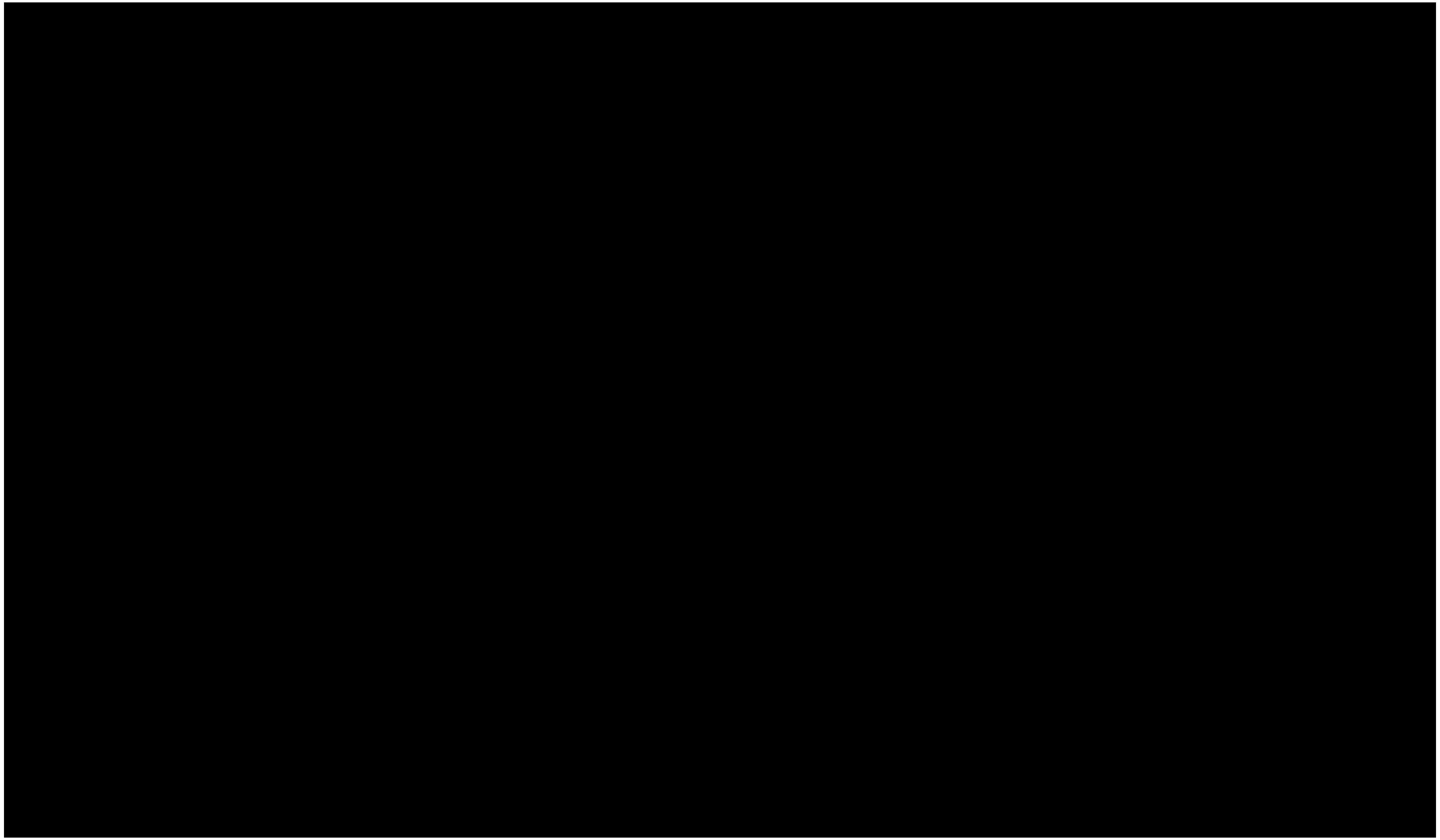
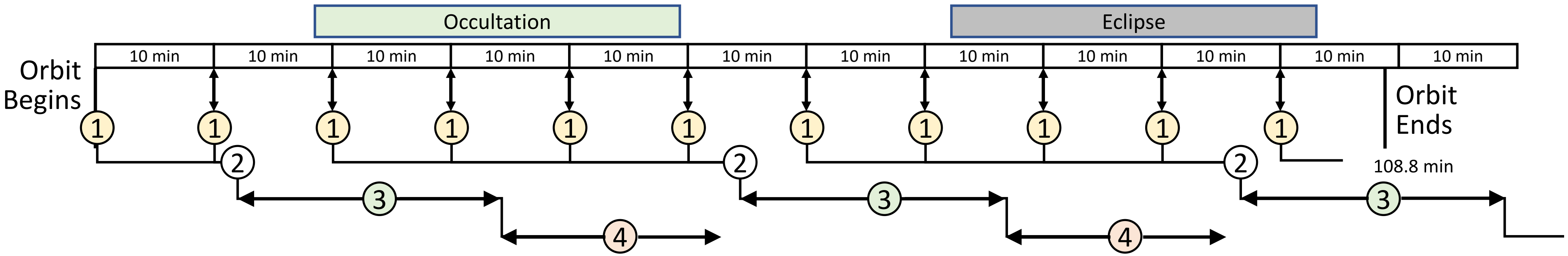


SLALOM Concept of Operations

SLALOM ConOps: Orbit in the Life



1 Collect Observation. The plan shown has a cadence of once every 10 minutes, including collecting raw data and post-processing into an accumulated *pose.*
More can be collected via parallel processing

2 Measurement pre-processor issue check: sanity checks, pre-filter editing, pre-processor maneuver checks. Lambert check.

2M When a maneuver is executed, perform sanity checks, maneuver size and expectations check.
ALPINE adds maneuver to the filter state.

3 Process batch of measurements, iterate, produce the best state estimate and associated uncertainty. Produce 7-hour predict. Identify corridor violations.
Robustness/Issue checks. Compare filters for consistency; evaluate special filters for faults; identify any errors; respond as needed.

4 Update maneuver designs, including all nominal and backup maneuvers for next 7 hours.

Note: Occultation and Eclipse shown with approximate maximum durations for reference. They may occur in any part of the orbit, possibly overlapping, and may be shorter or absent.

SLALOM’s Innovation, Algorithms

- A low-altitude mission provides an opportunity to use LIDAR; LIDAR enables SLALOM. Optical Navigation is also excellent, but must be built for very low altitudes.
  - Navigation *poses*

- Autonomous processing of observations, orbit determination, maneuver design, contingencies.
  - Observation validation
  - Multiple simultaneous orbit determination filters
  - Frequent trajectory predicts
  - Frequent maneuver designs
  - Safety is paramount: Emergency maneuver always prepared

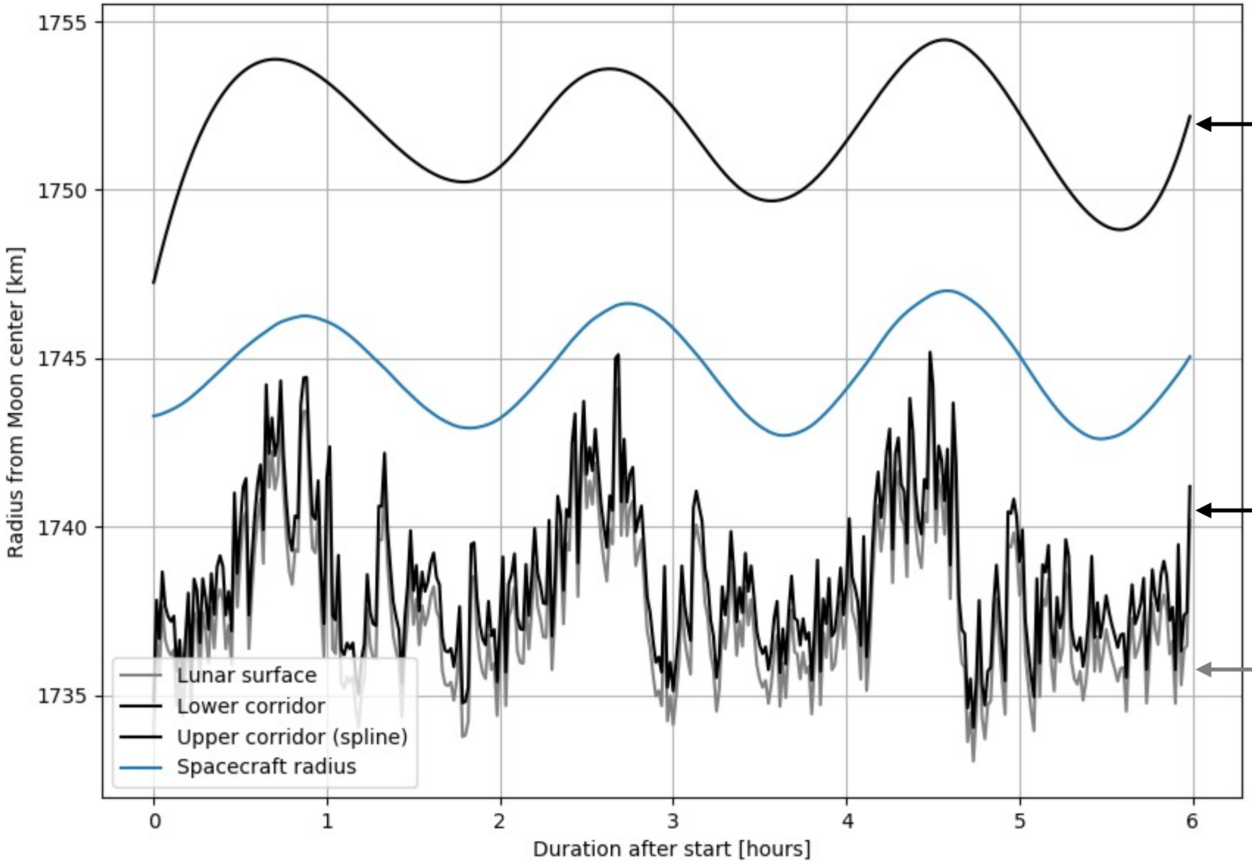
- Computational efficiency
  - Neural network model of gravitational potential of lunar gravity field.
  - Differential corrector for maneuver designs.
  - Memory efficient topography queries.

SLALOM Stationkeeping Strategy

- Goal: remain within altitude corridor.

Challenges:

- **Dynamics**: orbital elements change over time.
- **Topography**: lunar surface is not very uniform.

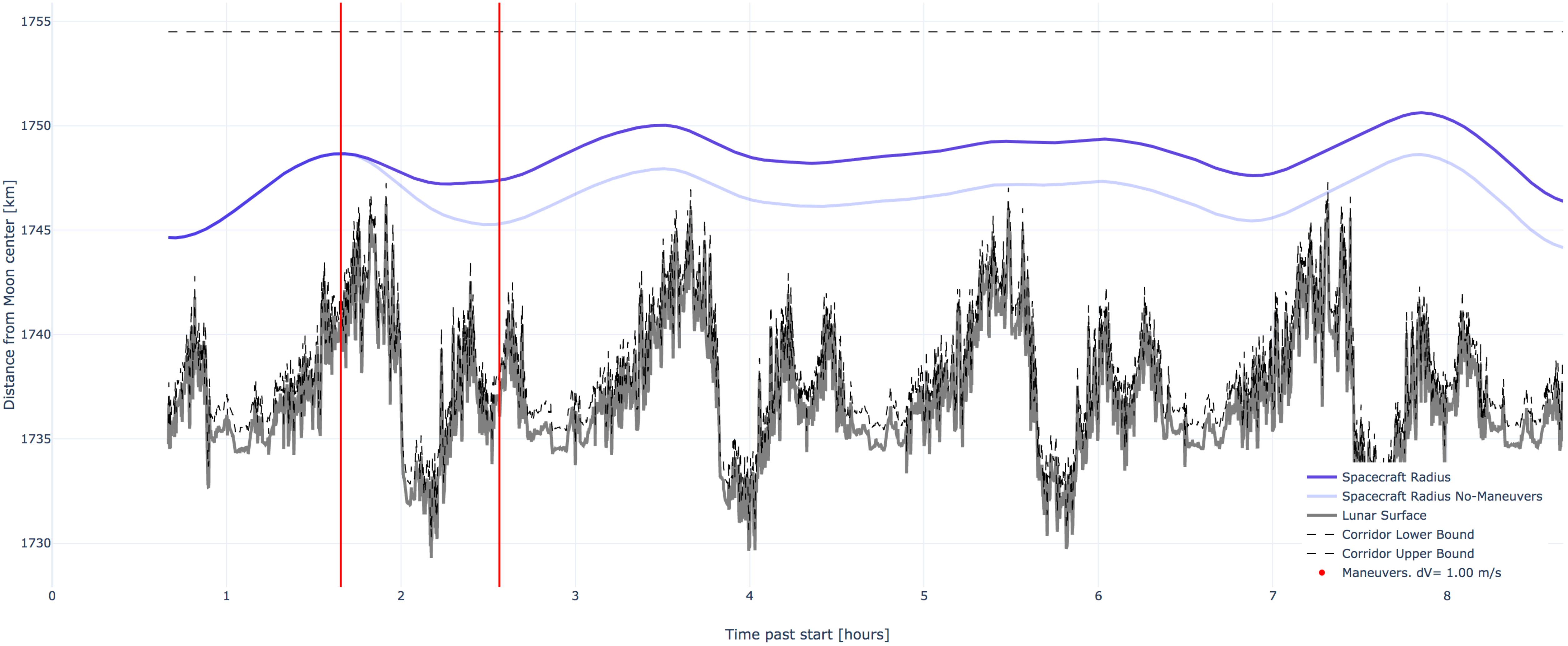


Example upper corridor boundary

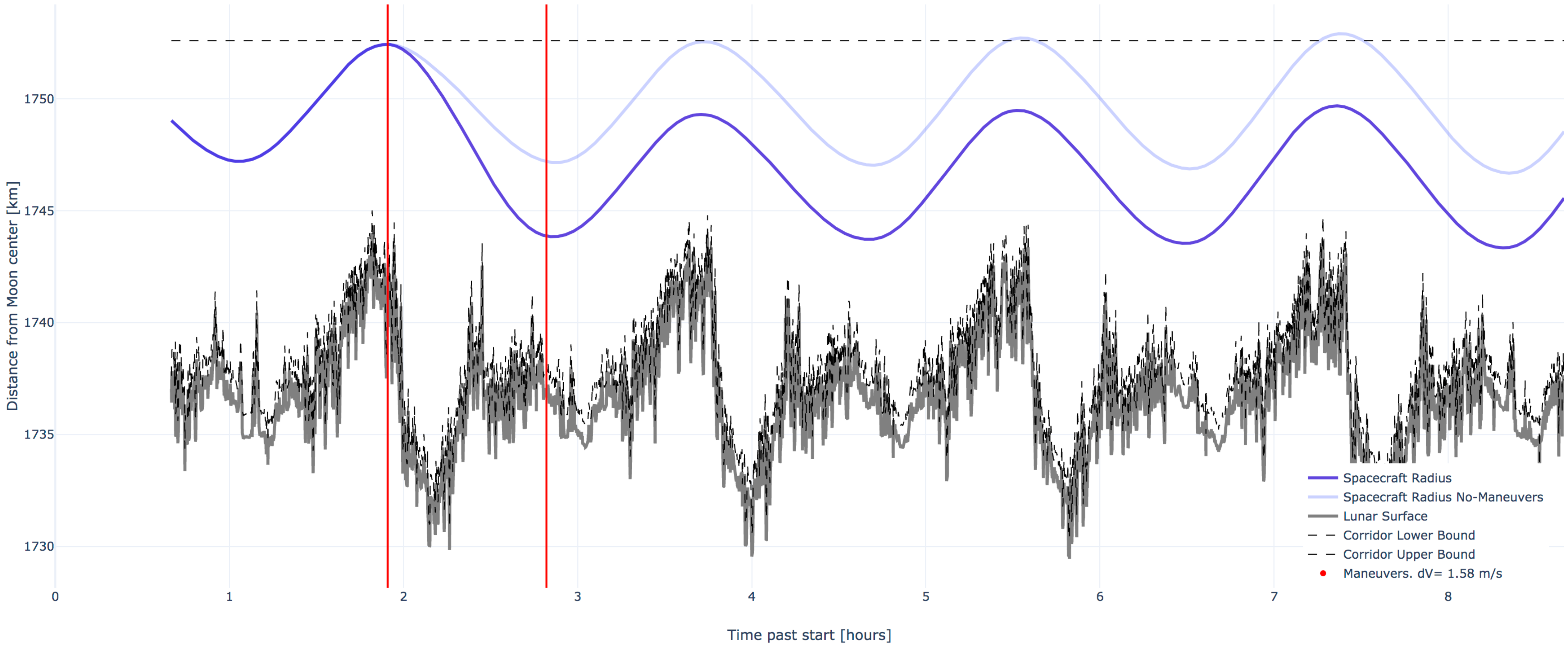
Lower corridor boundary

Lunar surface

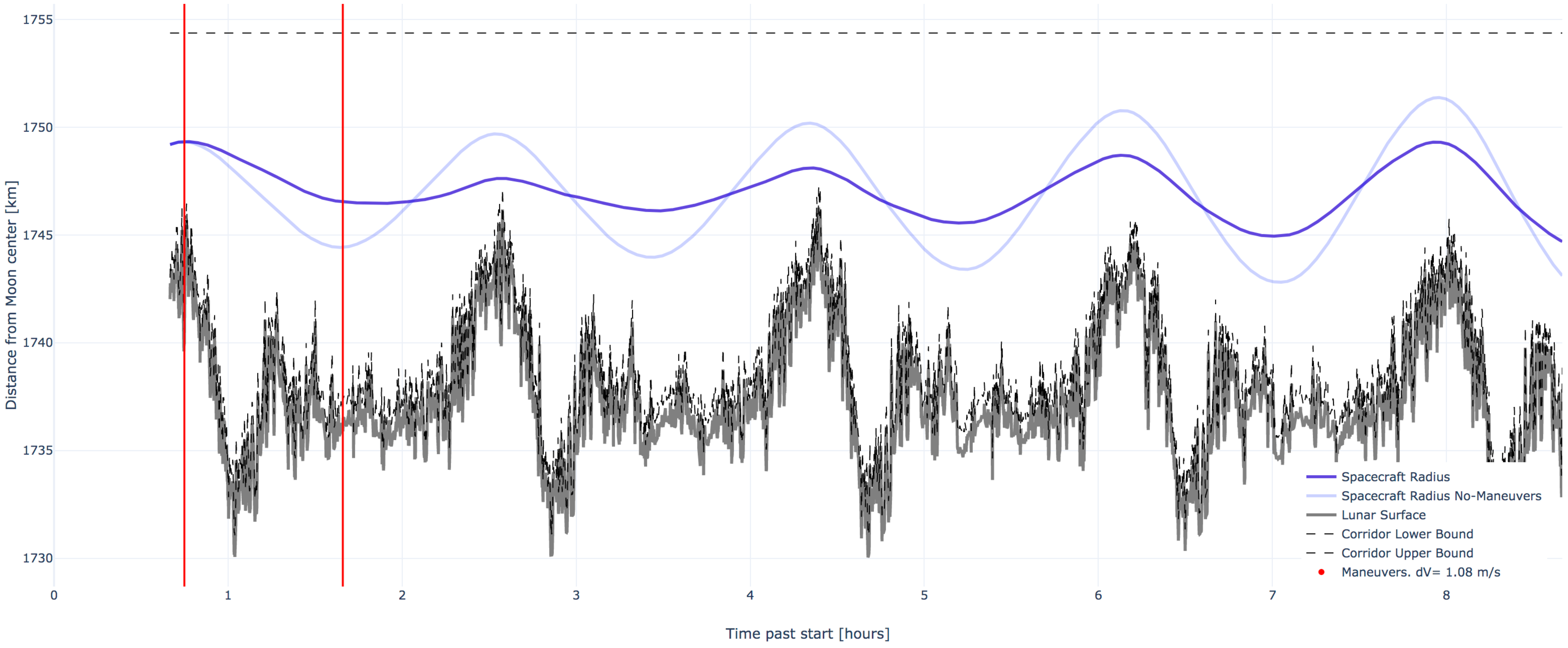
Lower Corridor Violation Response



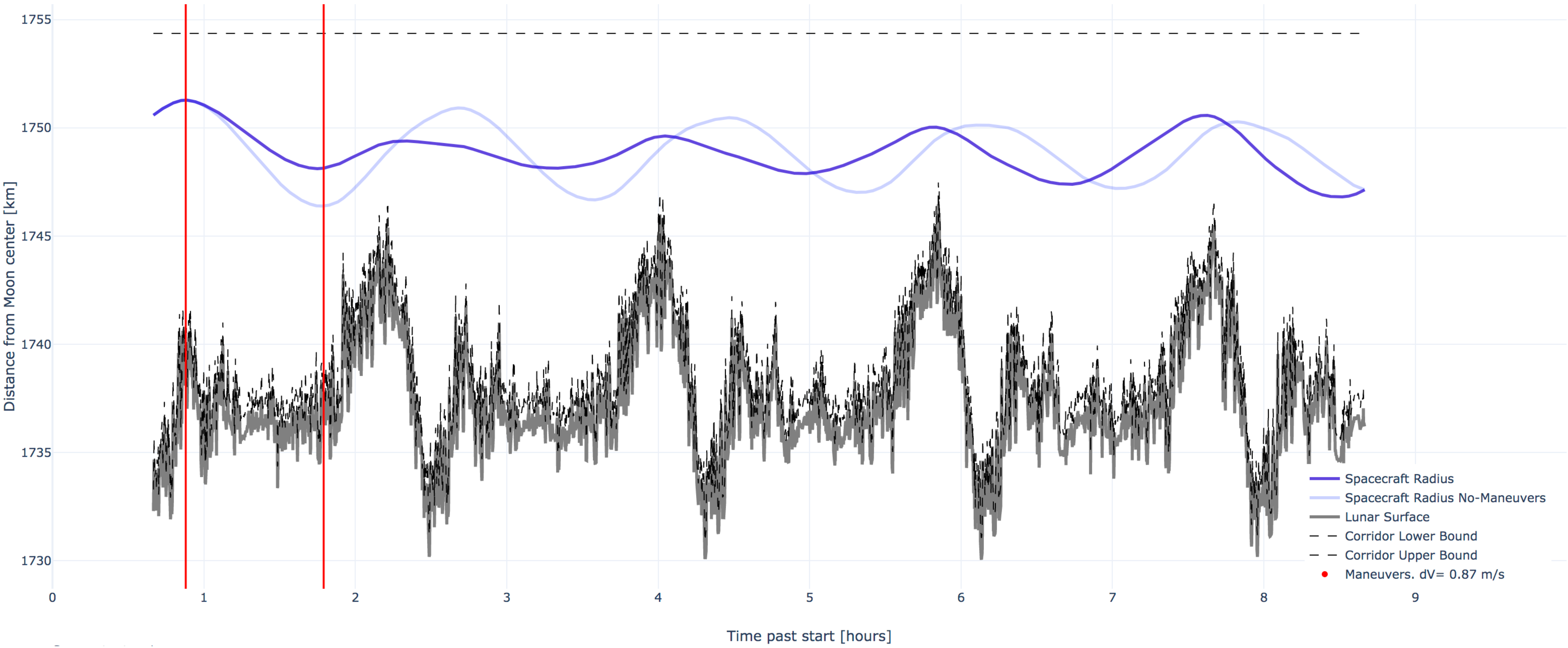
Upper Corridor Violation Response



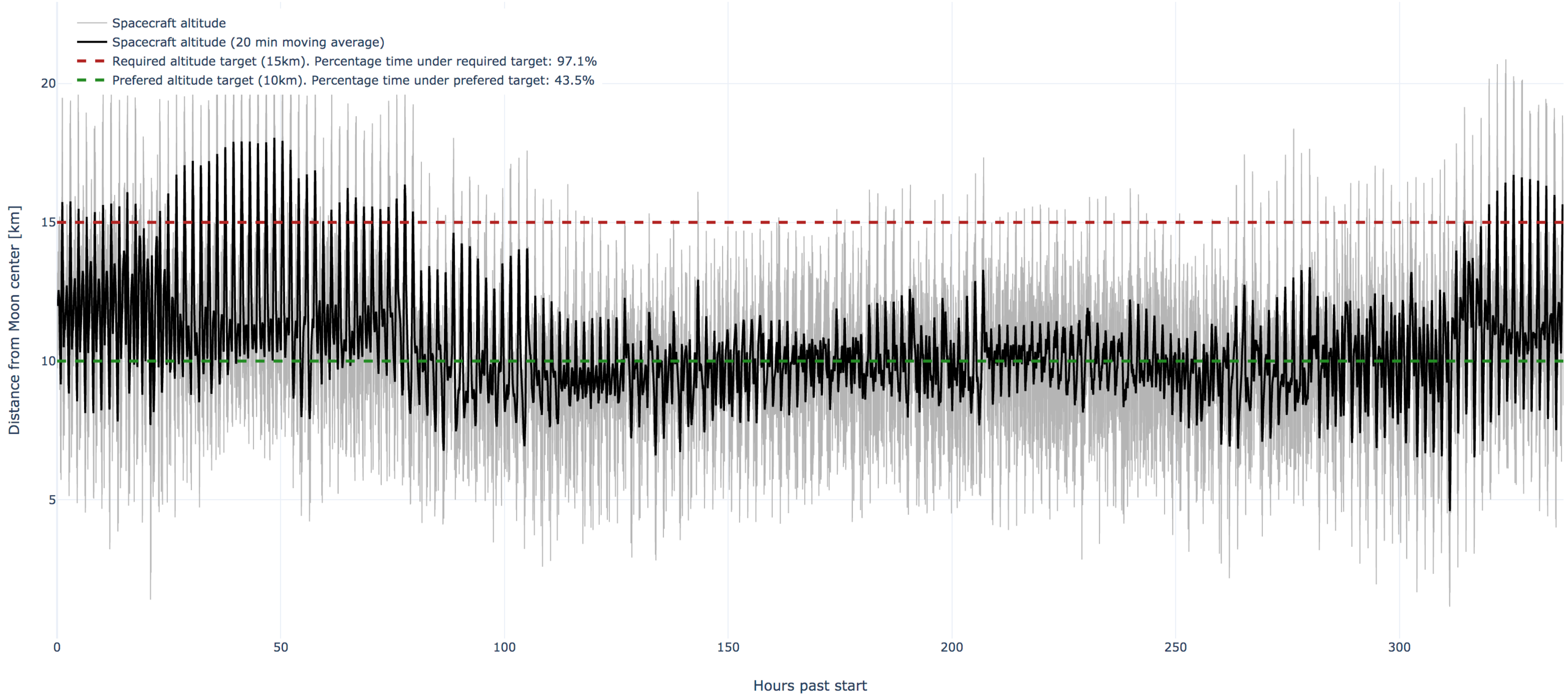
Eccentricity Correction



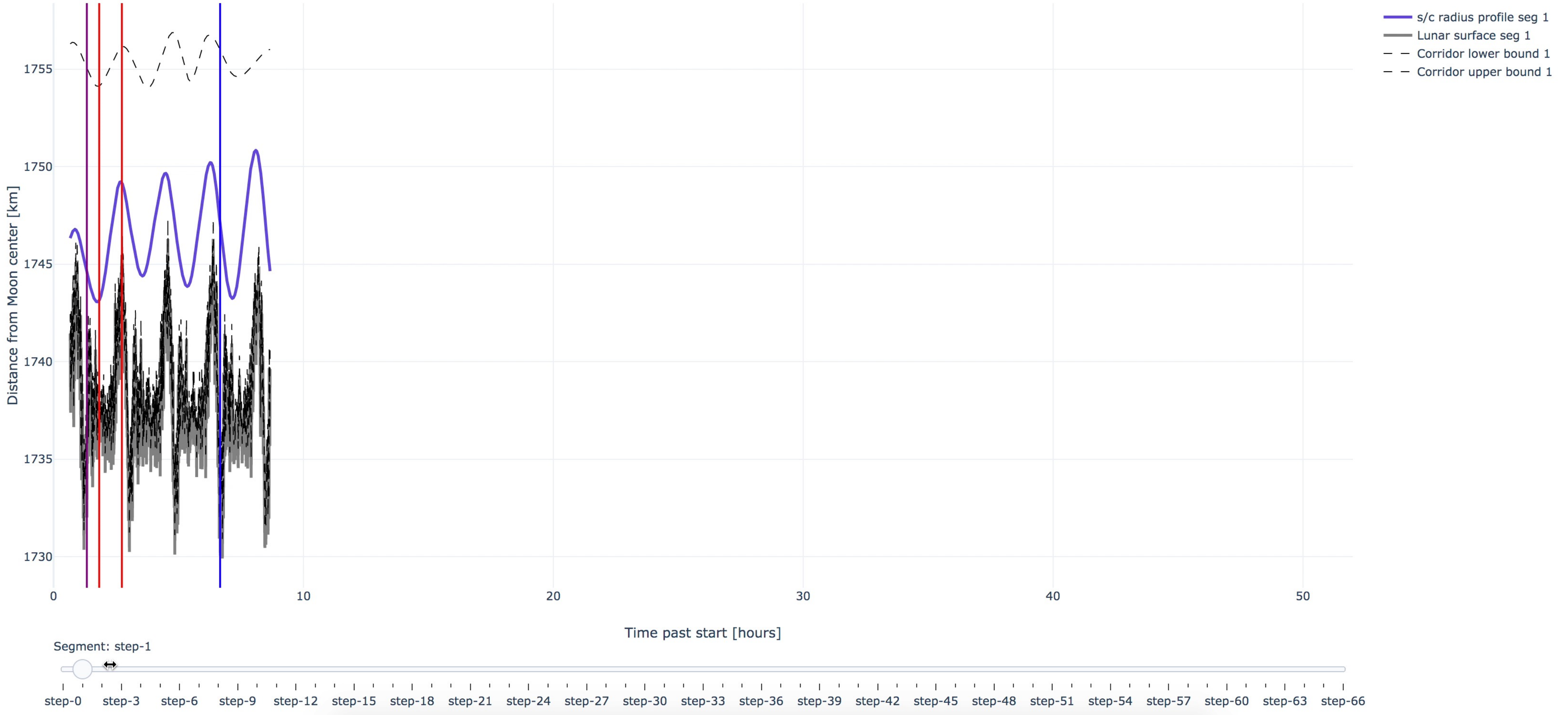
Argument of Periapse Correction



Performance Over a Week



SLALOM Stationkeeping

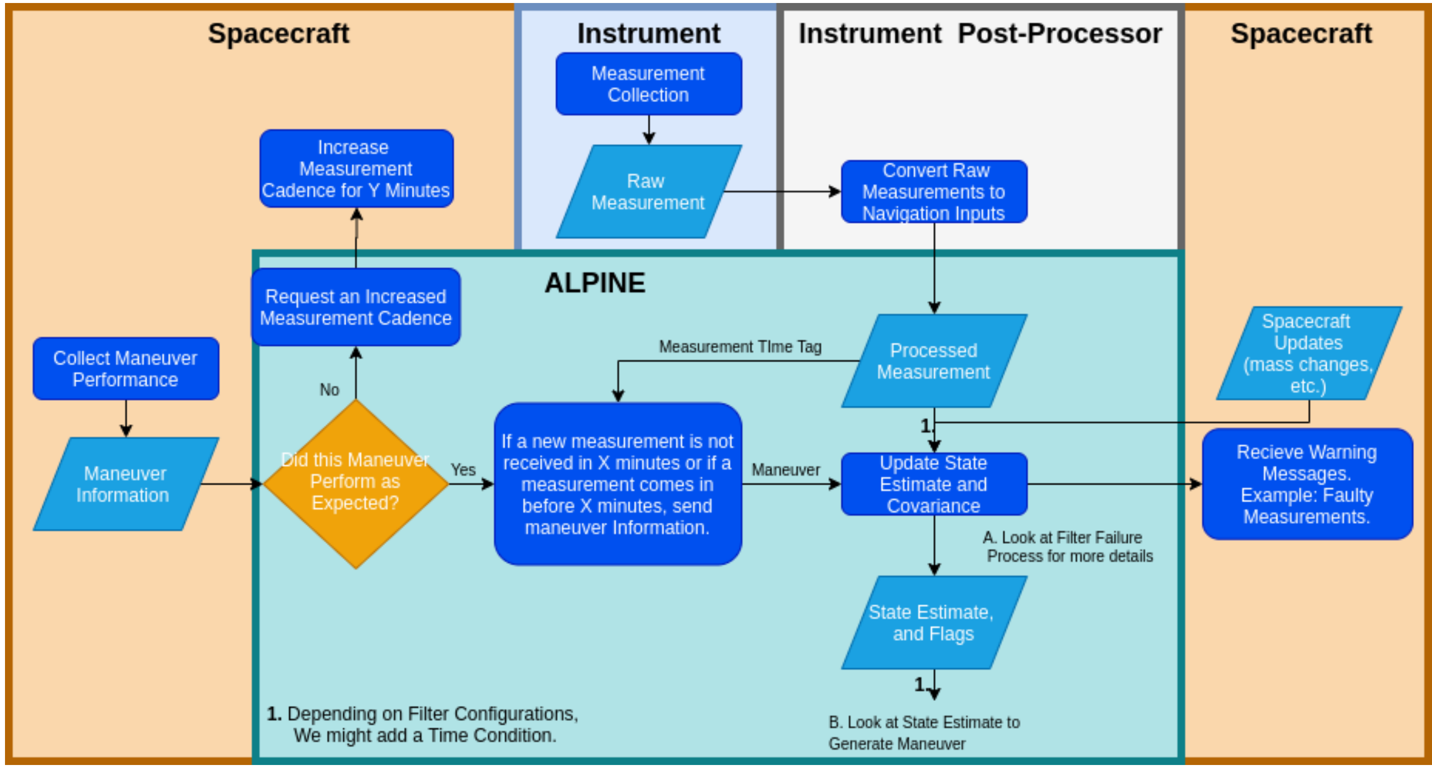


SLALOM's Delta-V Budget

Item	ΔV	Resulting Orbit
Lunar Transfer Trajectory Correction Maneuvers (TCMs)	30.0 m/s (TBD)	
Lunar Orbit Insertion (LOI)	392.8 m/s 39.3 m/s Finite Burn Losses (TBD)	100 km x 2331 km 4 hour orbit
Drop Apoapse to 500 km	205.6 m/s 20.6 m/s Finite Burn Losses (TBD)	100 km x 500 km
Drop Periapse to 5 km	20.6 m/s	5 km x 500 km
Drop Apoapse to 100 km	79.2 m/s 4.0 m/s Finite Burn Losses (TBD)	5 km x 100 km
Drop Apoapse to 25 km	17.3 m/s 0.5 m/s Finite Burn Losses (TBD)	5 km x 25 km
Drop Apoapse to 10 km	3.6 m/s	5 km x 10 km
DV99 Navigation during Orbit Reduction	20.0 m/s (TBD)	
StationKeeping for 2 months, assuming 5 m/s per day	305.0 m/s	5 km x 7 km
Pop-up Allocation x2 apo raises and x2 apo lowers	68.0 m/s	5 km x 25 km
Margin	200.0 m/s	
Total	**1406.5 m/s**	

SLALOM's Navigation

- Two Inputs
  - Observations
  - Maneuver estimates
- Processing Observations
  - The raw image is transformed into a position coordinate.
- Processing Maneuvers
  - Maneuver performance is compared to expected performance.
    - If it differs, ALPINE increases the observation cadence.



SLALOM’s Navigation

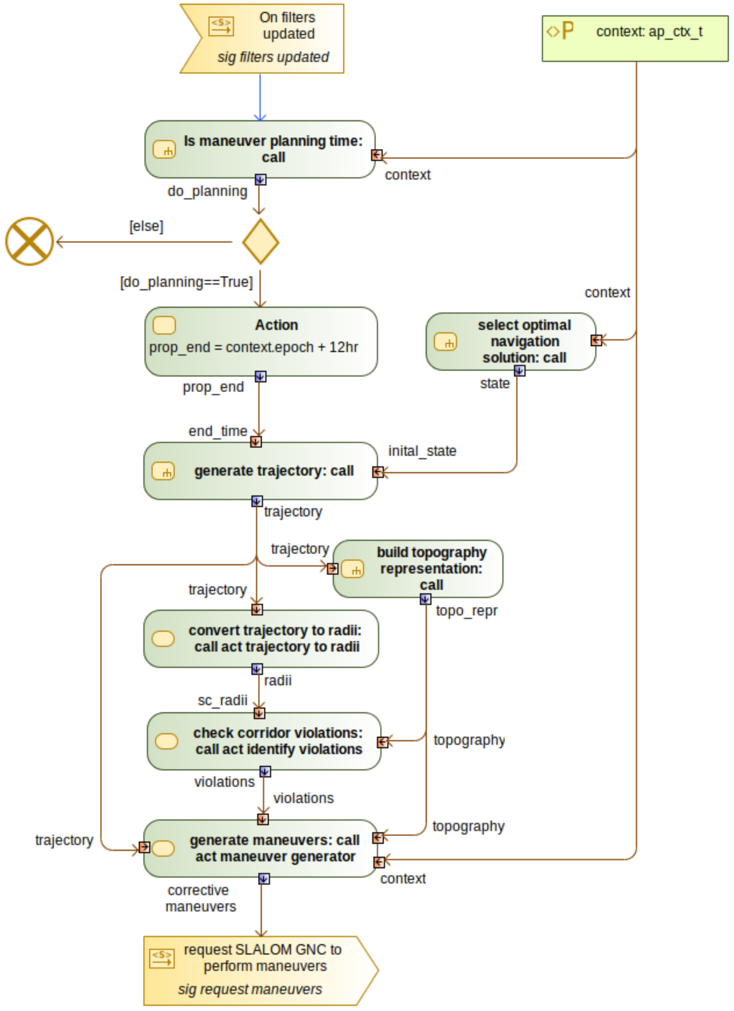
- SLALOM’s navigation ConOps are different than conventional NAV
  - Optical *poses* have substantial information content.
  - Very infrequent data
  - Known, imperfect dynamical model

- Filter Setup
  - A primary filter
  - A backup filter
  - Issue Trackers

- Primary filter tuned to trust measurements.
- Backup filter is a more conservative primary filter → adds fault tolerance.
- Issue Trackers detect issues with the primary filter → added robustness.

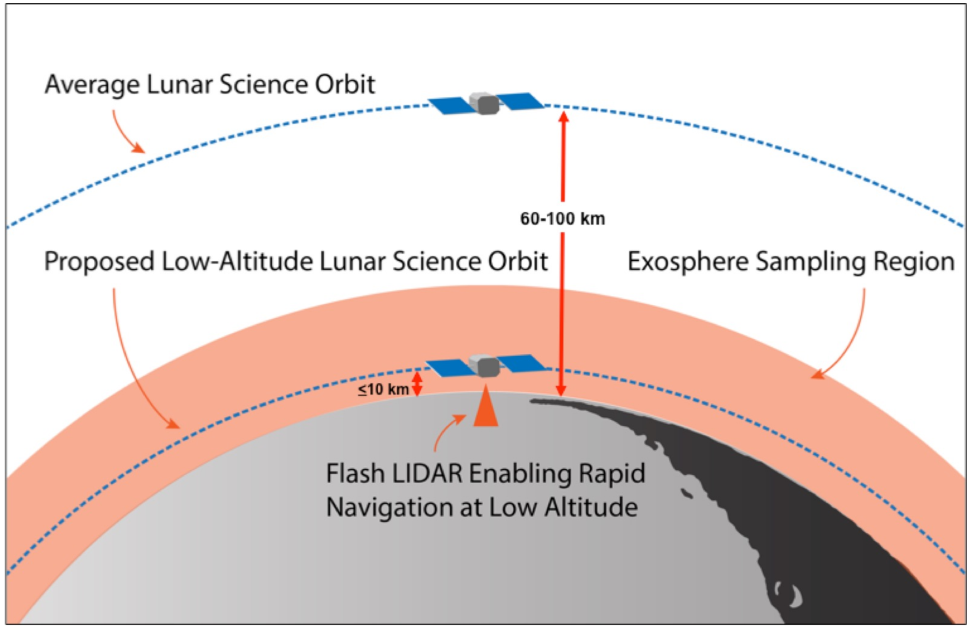
SLALOM’s Software (ALPINE)

- Software Design & Architecture
  - Model based approach
  - FSW & platform independent
- Implementation
  - Instantiated within a cFS host application
- Testing and Development
  - Test driven development
  - Continuous automated testing during development activities
  - Hardware test-bed



SLALOM's Next Steps

- Further refining the stationkeeping
- Monte Carlos of navigation simulations
- Complete software build-out
- Testbed simulations
- Add in capability to fly over specific observation targets
  - Resource mapping
  - Site surveys
  - High resolution imagery



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