Efficient Station-keeping of Very Low Lunar Orbits

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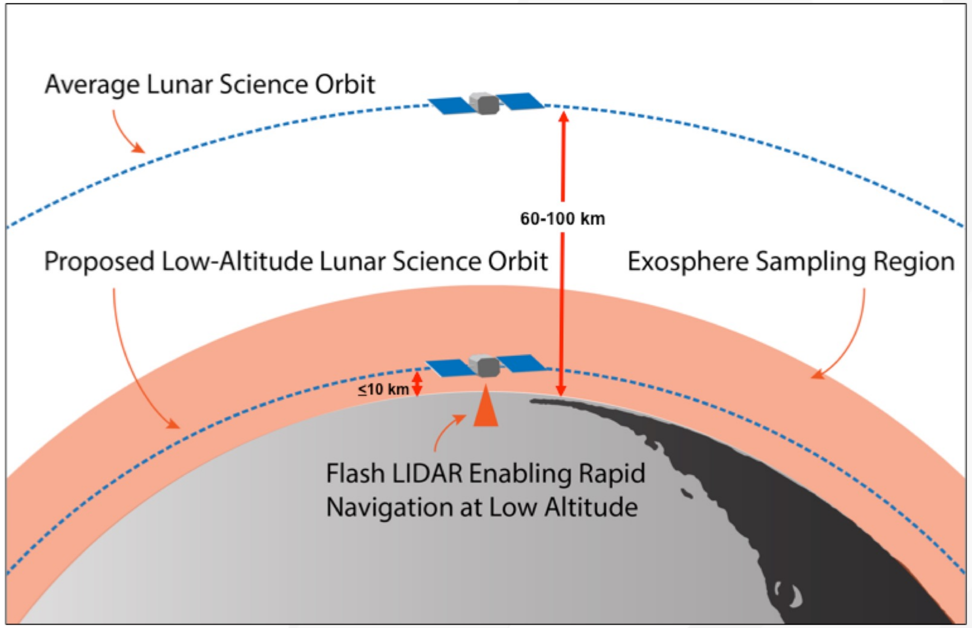
and Bradley Cheetham

SLALOM: Introduction

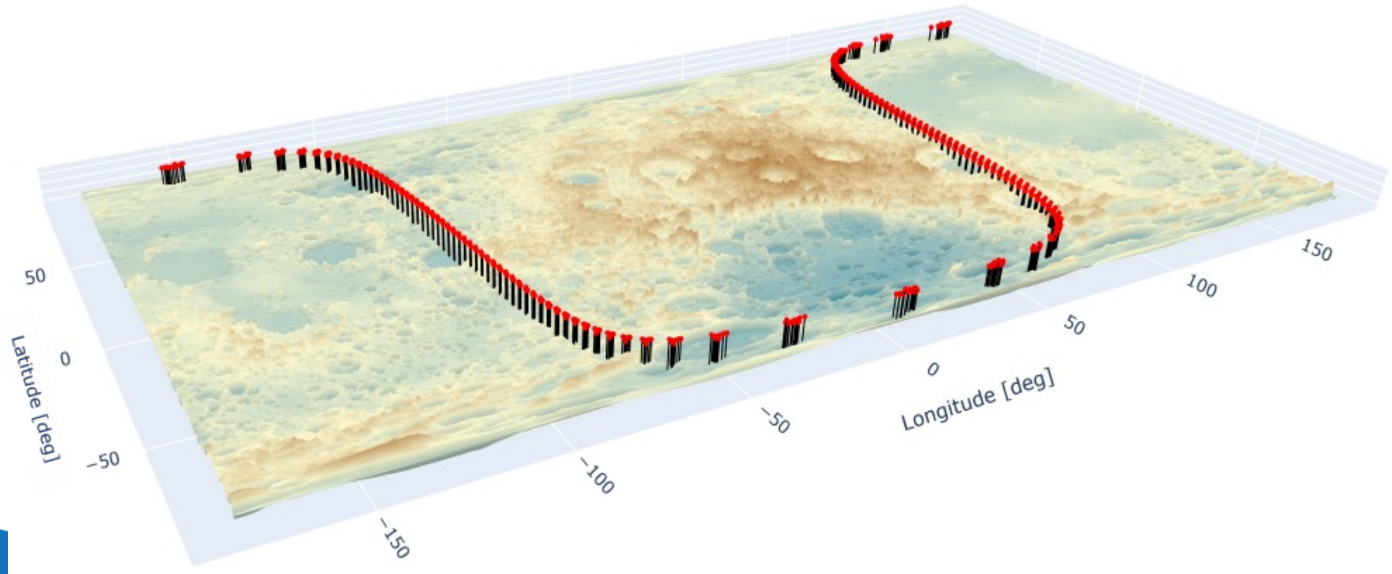
- Sustained Low-Altitude Lunar Orbital Mission (SLALOM)
- SLALOM answers the question: **How does a mission achieve a *sustained* average altitude below 10 km?**
- Answer: ALPINE (Autonomous Maneuver Location Processor using Integrated Navigation Estimate)
  - This is an autonomous navigation system that is embedded on a spacecraft.
  - Processes onboard observations, produces OD products
  - Generates maneuver designs
  - Satisfies robustness requirements to ensure that the spacecraft remains within the corridor.

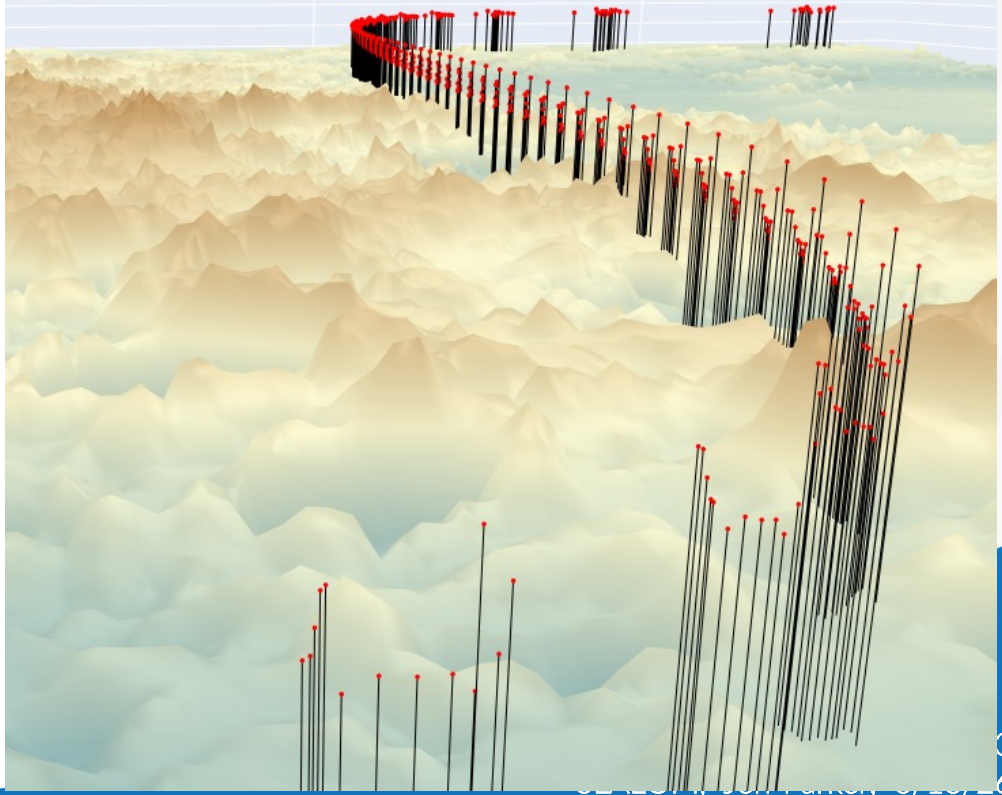


GRAIL: 55 km average: monthly maneuvers.
GRAIL: 23 km average: weekly maneuvers.
SLALOM: 6-10 km average: daily maneuvers.

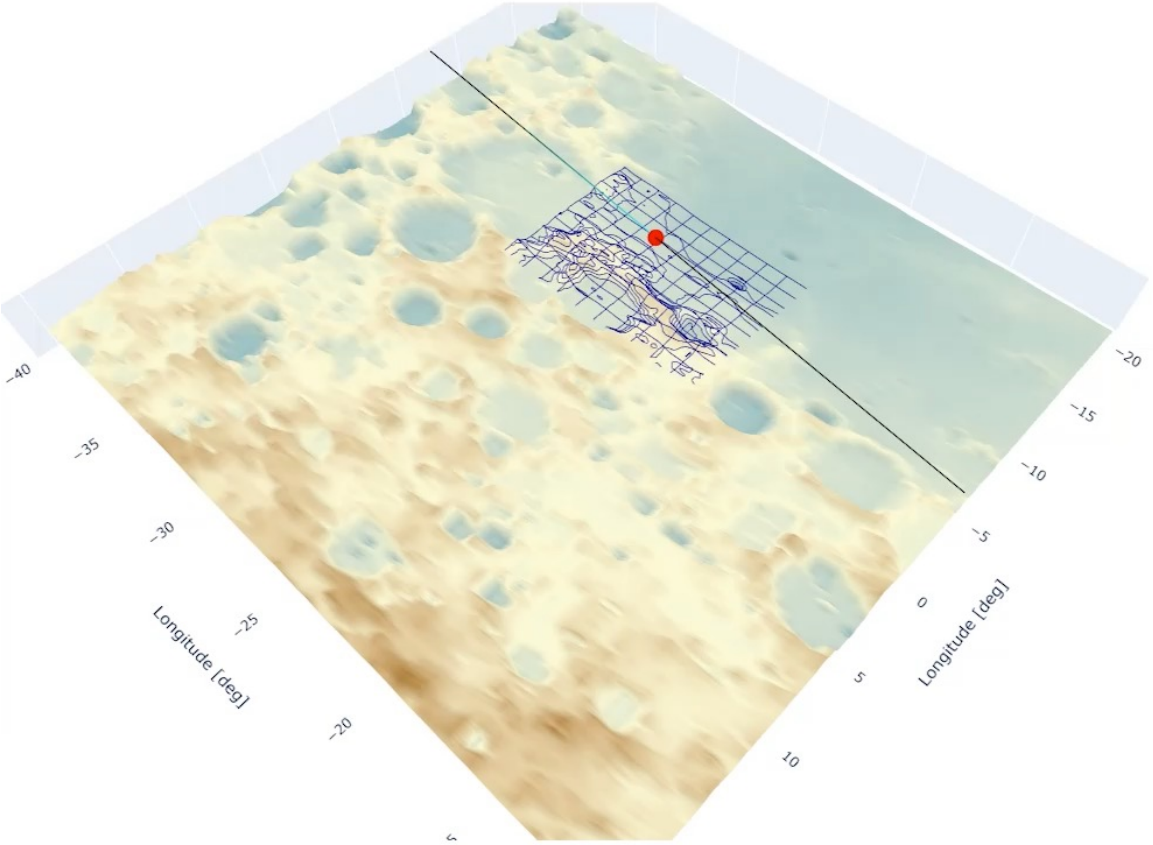
Reference Mission Design

- ✦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 15 km orbit
- ✦SLALOM ALPINE Ops





Low-Altitude Orbiting



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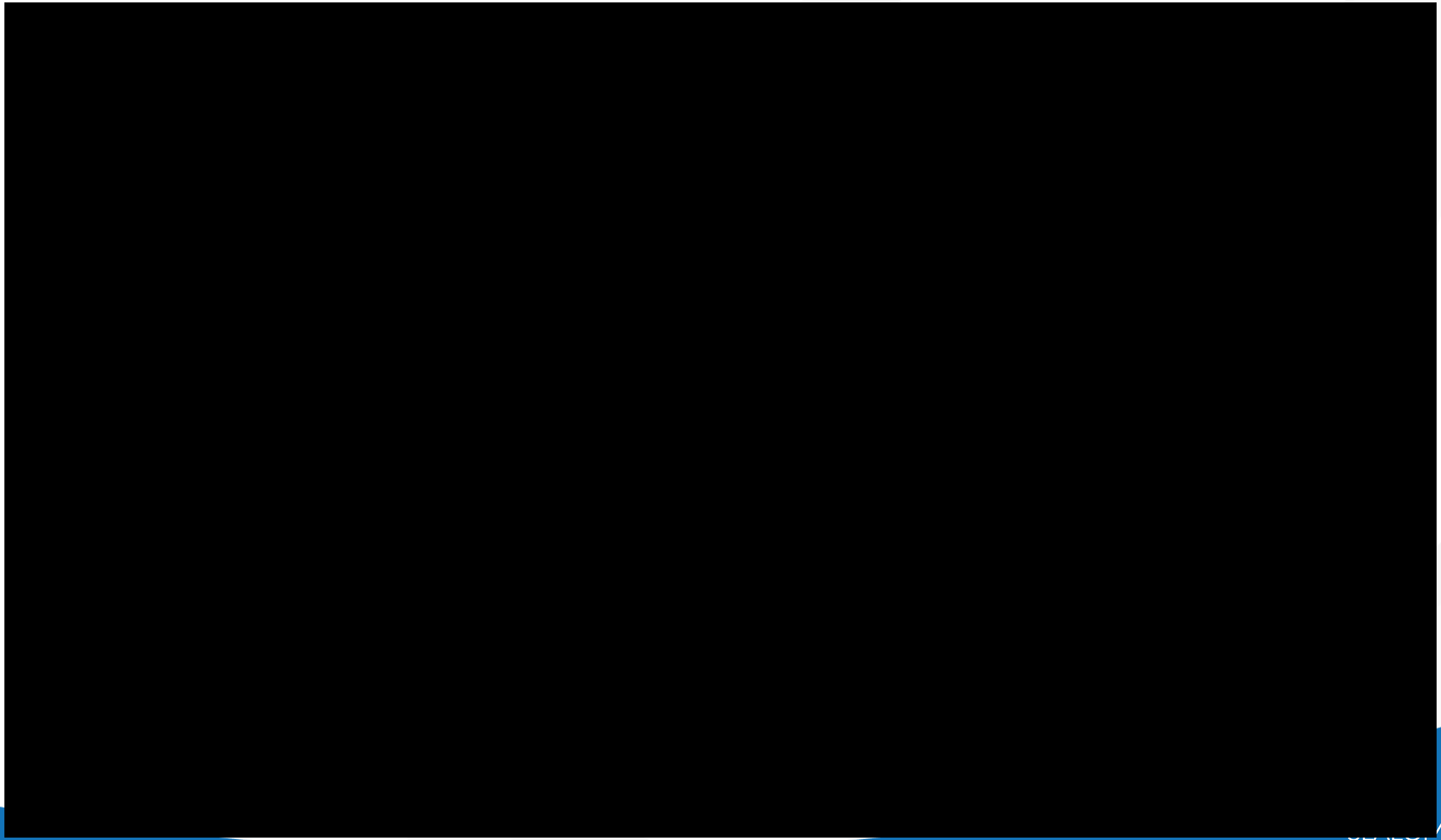


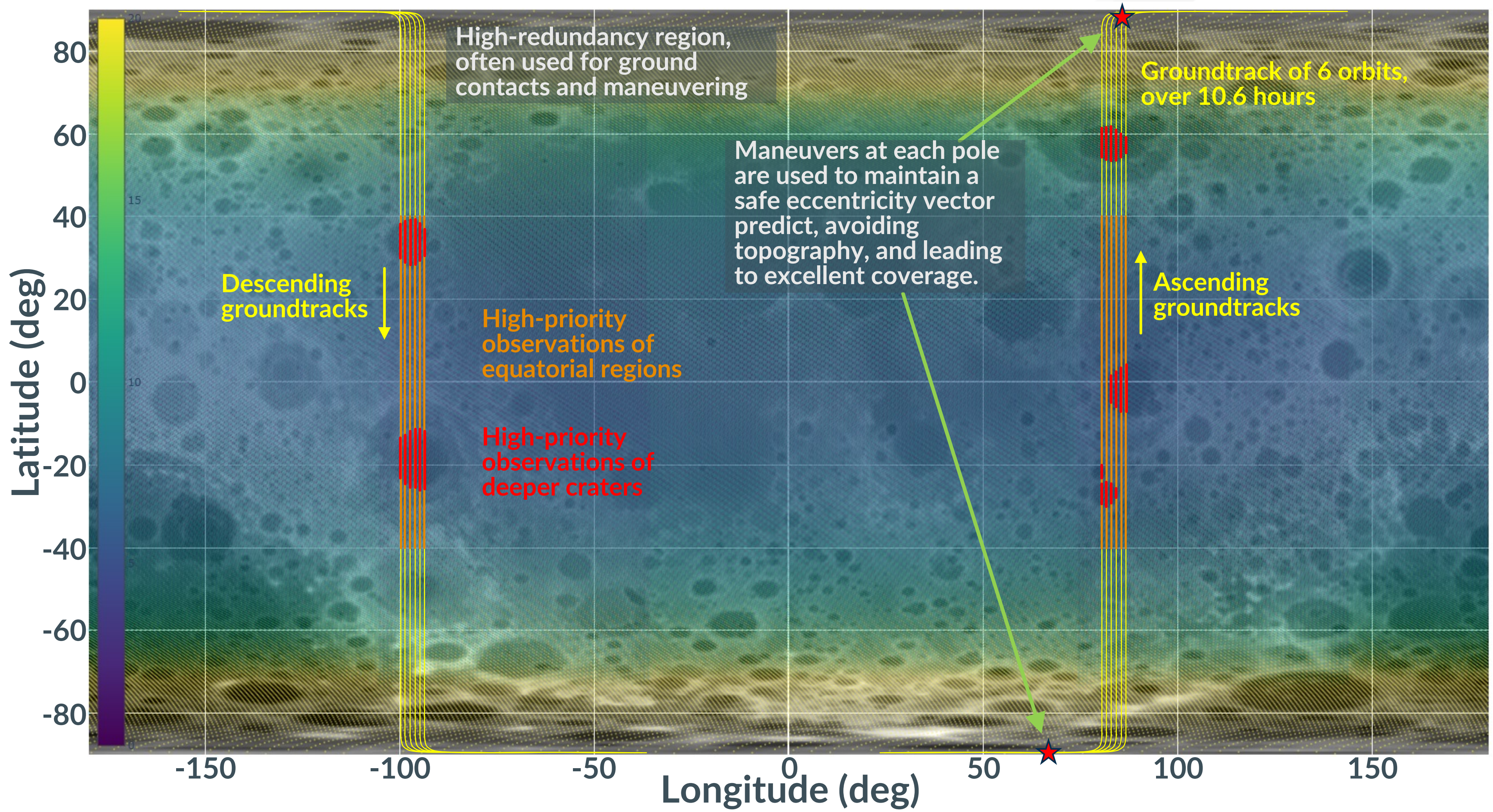
Numerous Applications

- Objectives include: Mapping the entire surface of the Moon; mapping both poles; remaining very low over the surface to measure one lunar environment feature or another; etc.

- **Assertion 1:** At least one spacecraft must have an inclination near 90 deg to reach and map both poles.
- **Assertion 2:** Observations must be made at very low altitude to achieve the resolution or vertical height objectives of the mission.

- If in a very low-altitude lunar orbit, then the spacecraft traverses 360 revs in a month.
  - At the equator, each successive ascending node will be ~30 km from the previous one
  - Observations near the equator – and observations of deeper craters – are high priority observations and cannot be skipped.
  - Polar observations are common and often redundant – good locations to execute maneuvers and maintenance activities.

Concept of Operations



One orbit: 108 min, polar

360.125 orbits per month: each equatorial crossing is 1 deg away from the last. 8-month groundtrack repeat cycle.

The entire surface is covered in 8 months twice (once ascending and once descending).

The poles are covered 360 times more than the equator since every orbit passes over them. The coverage improves from equator toward the poles.

The equatorial regions and deeper craters are thus the highest priority observations.

Ground contacts and maneuvering activities are performed where coverage is excellent.

The system is capable of small adjustments every polar passage, though only a few are expected.

Safe autonomy: responds to any corridor violation with multiple contingency opportunities, ensuring spacecraft safety and successful lunar coverage.

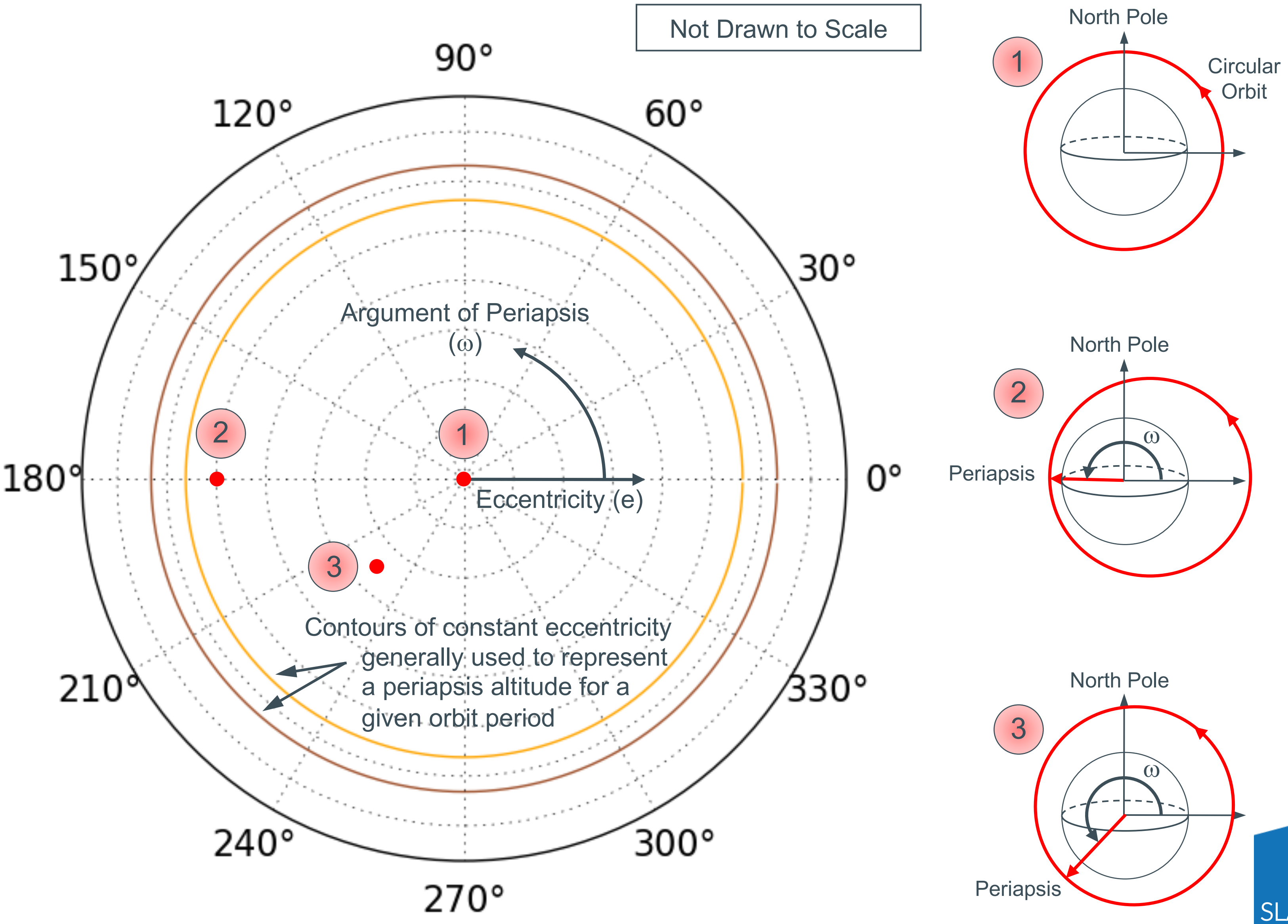
How do we guide the spacecraft?

- First of all, we cannot count on ground contacts for navigation. Too slow and if any are missed we have to raise the orbit.

- Autonomous navigation.
  - Radiometric data will always exist and be processed.
  - Optical is always available. Cameras are low SWAP. Modern systems have flown very capable hardware, such as GPUs to rapidly process optical data.
  - Numerous optical algorithms at our disposal: some of which have already flown.

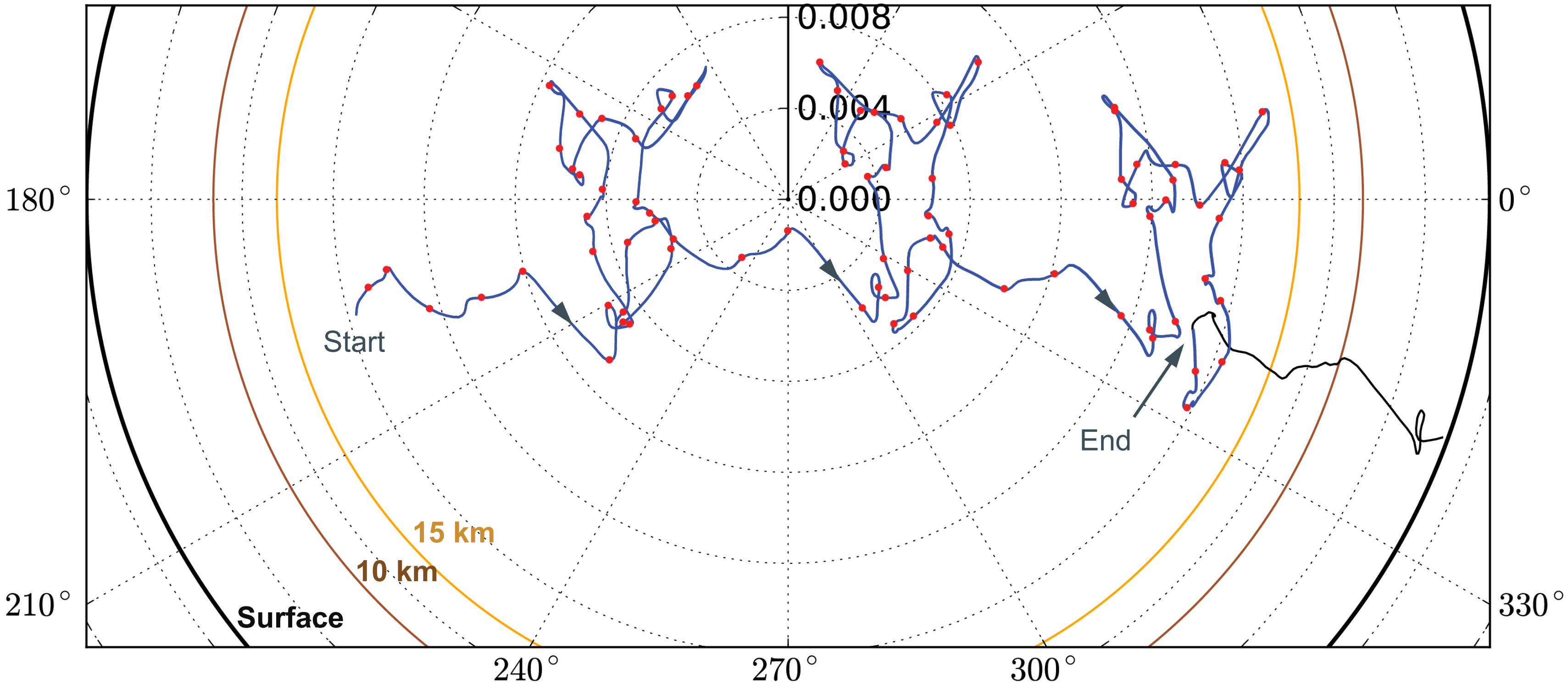
- Maneuvering. How do we stay safe very low?
  - Stand on the shoulder of giants. Let's take the GRAIL approach and take the next leap forward.

Introduction to Eccentricity Vector Space



e-ω Plot for Primary GRAIL Science Phase

- Primary GRAIL Science Phase = 82 days
  - March 8th to May 29th, 2012
  - 3 lunar sidereal months (3 x 27.3 days) = 3 Mapping Cycles
- Mean orbit altitude = 55 km
  - No orbit maintenance maneuvers – orbit evolves from elliptical, to near-circular, back to elliptical



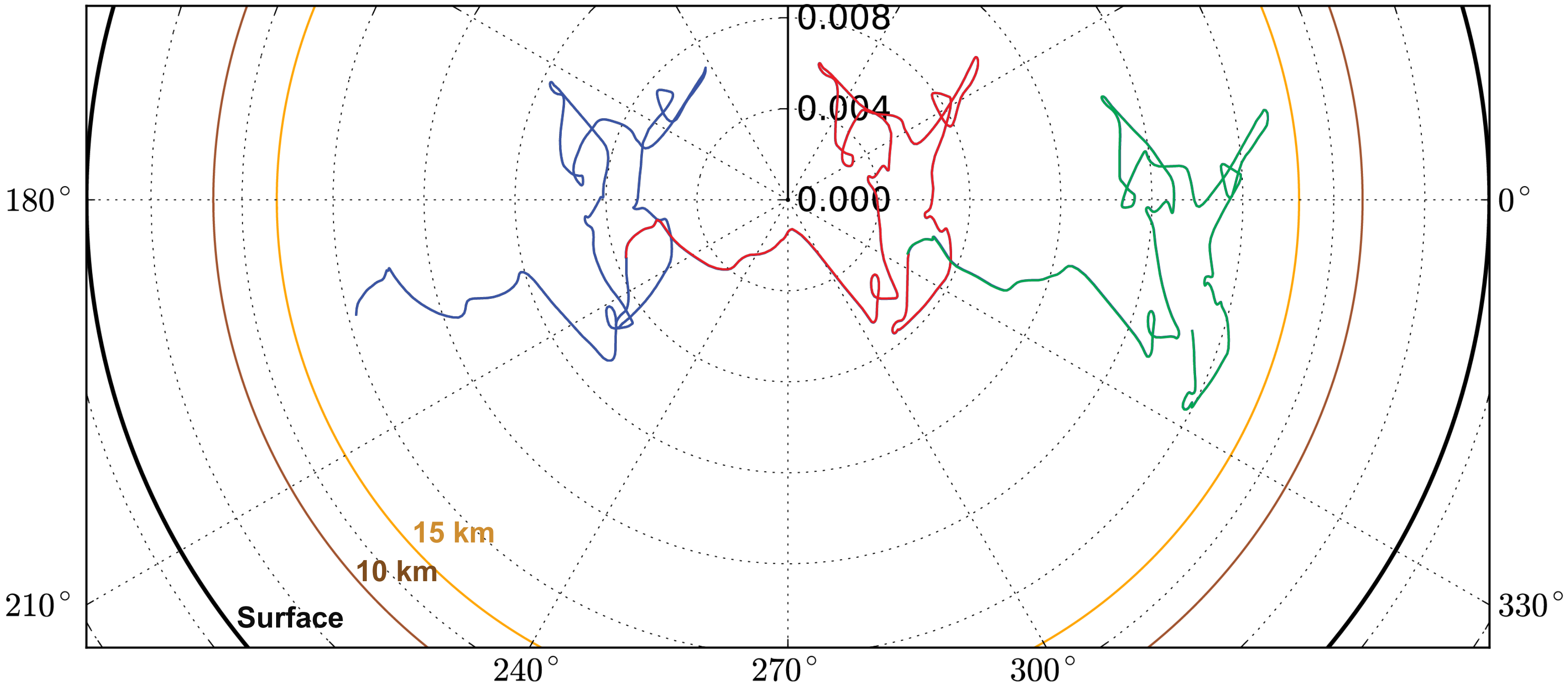
Lunar gravity field = LP150Q (150x150)

Managing the e-ω Evolution

- Adding Maneuvers
  - To minimize the maximum altitude variation and potentially lower the mean orbit altitude

Consider the case of performing a maneuver after each Mapping Cycle (27.3 days)

Centering the e-ω evolution minimizes the maximum altitude variation



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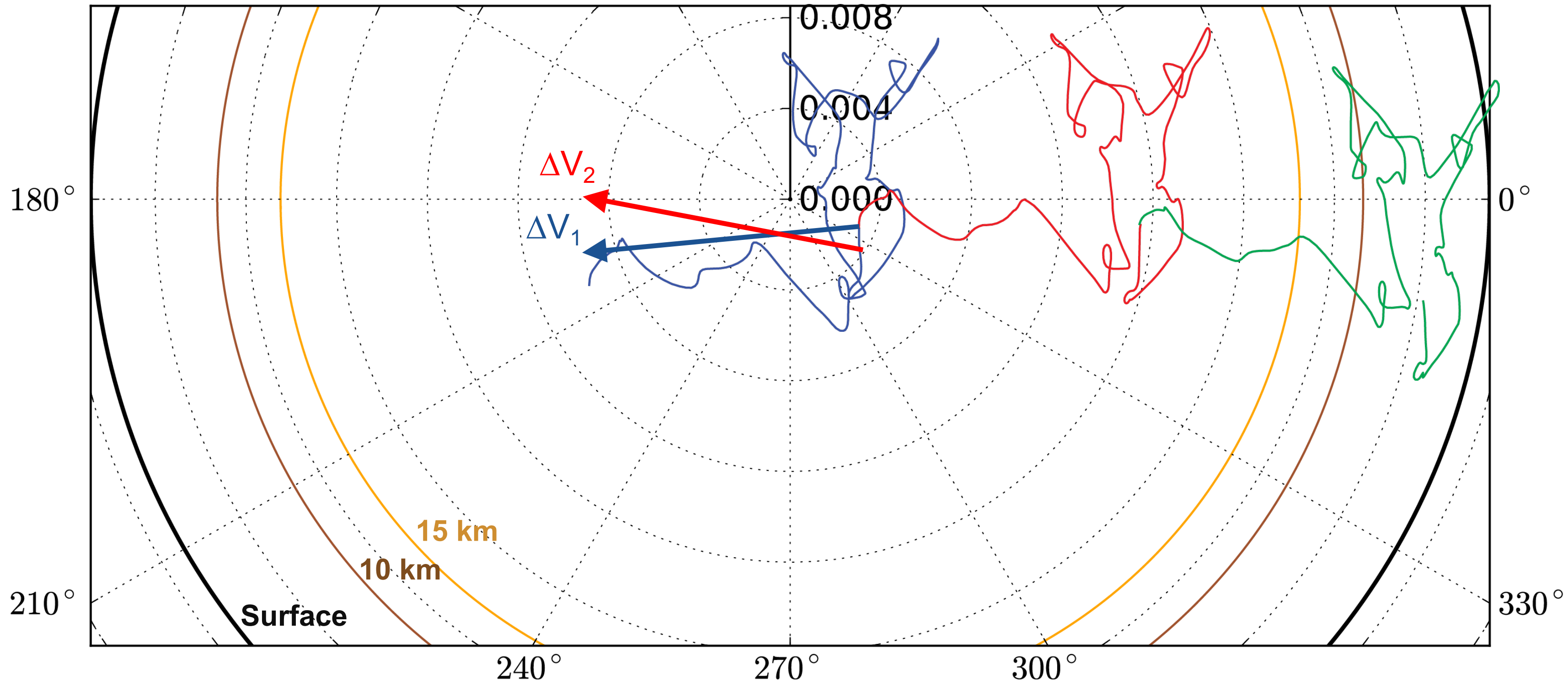

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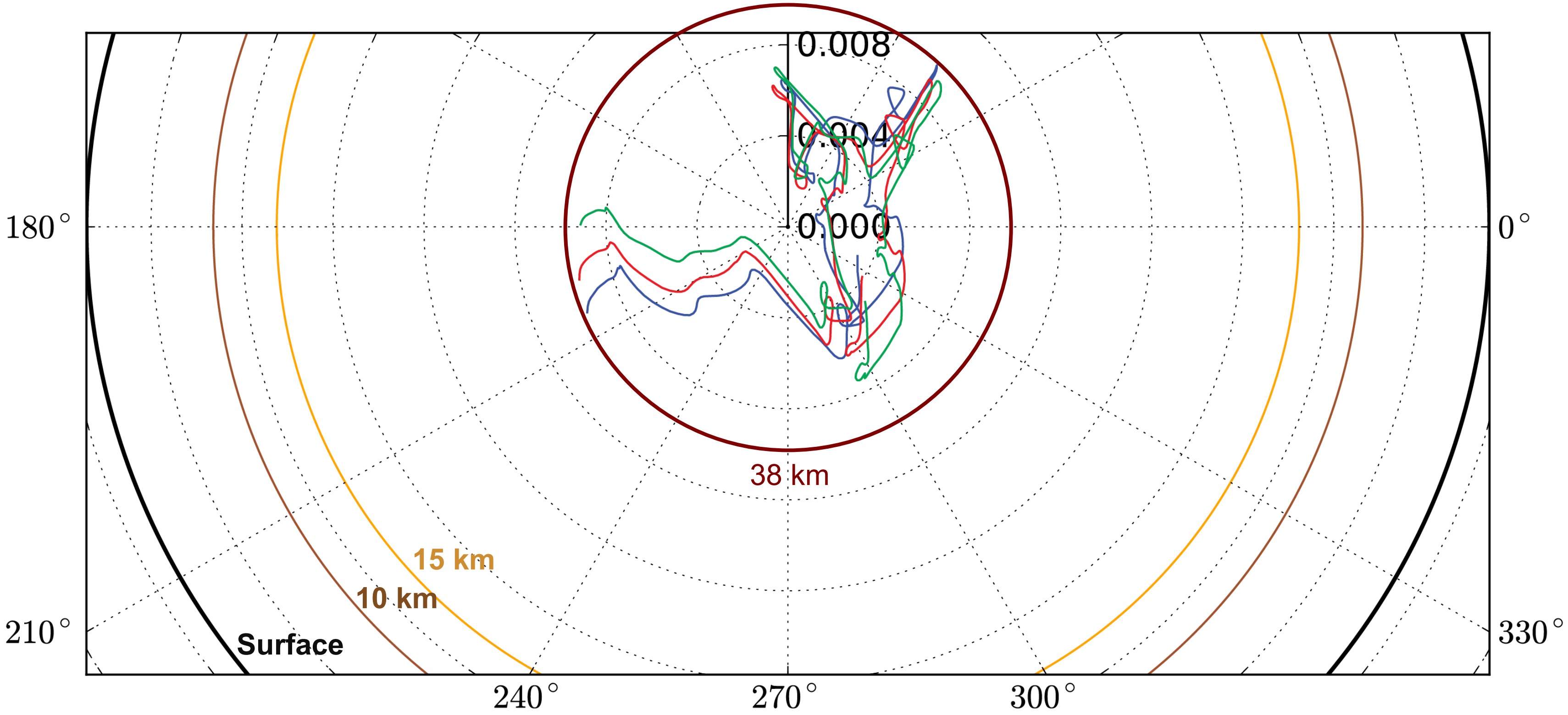

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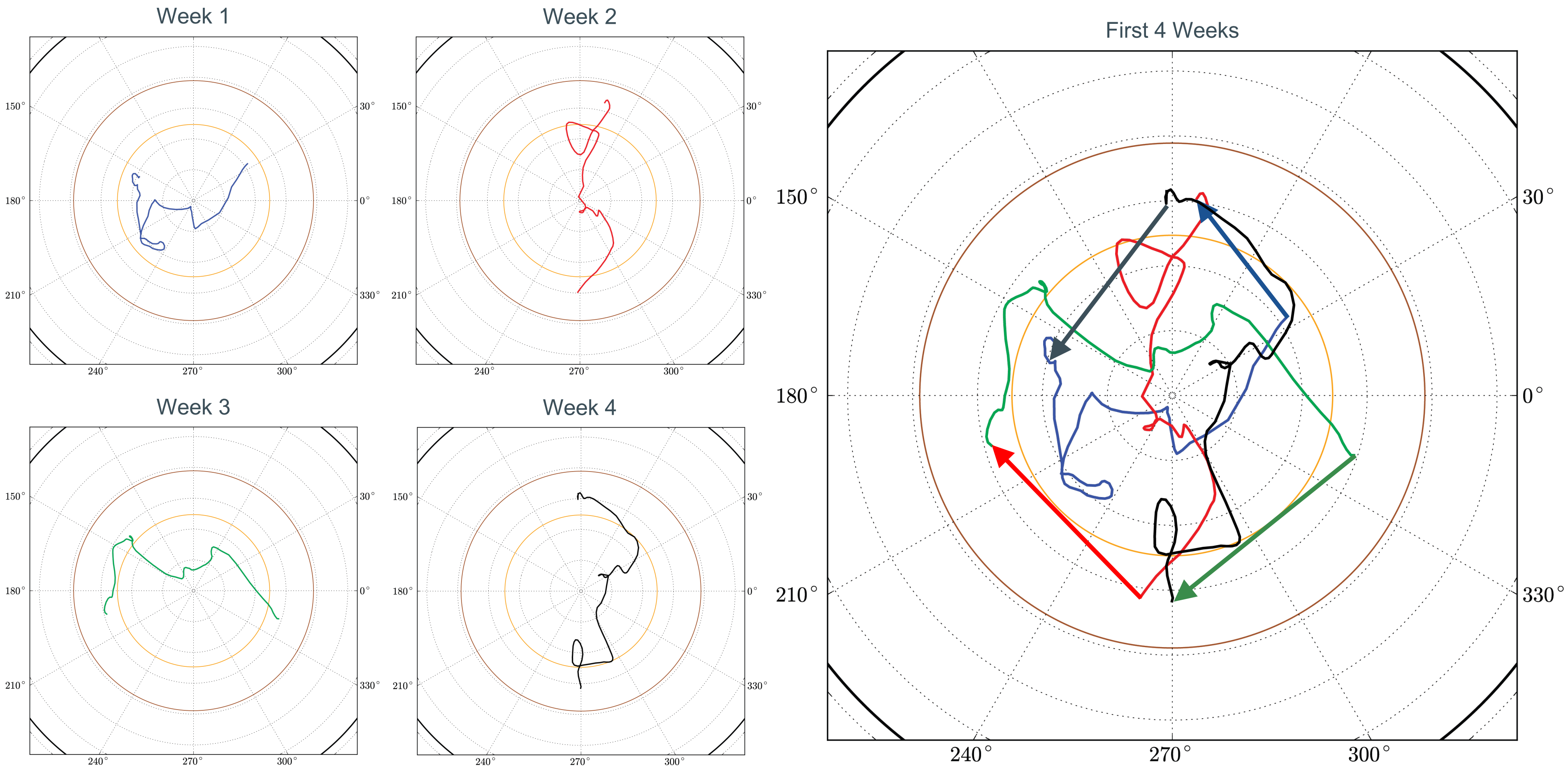
Making the 7-day Reset Option Work

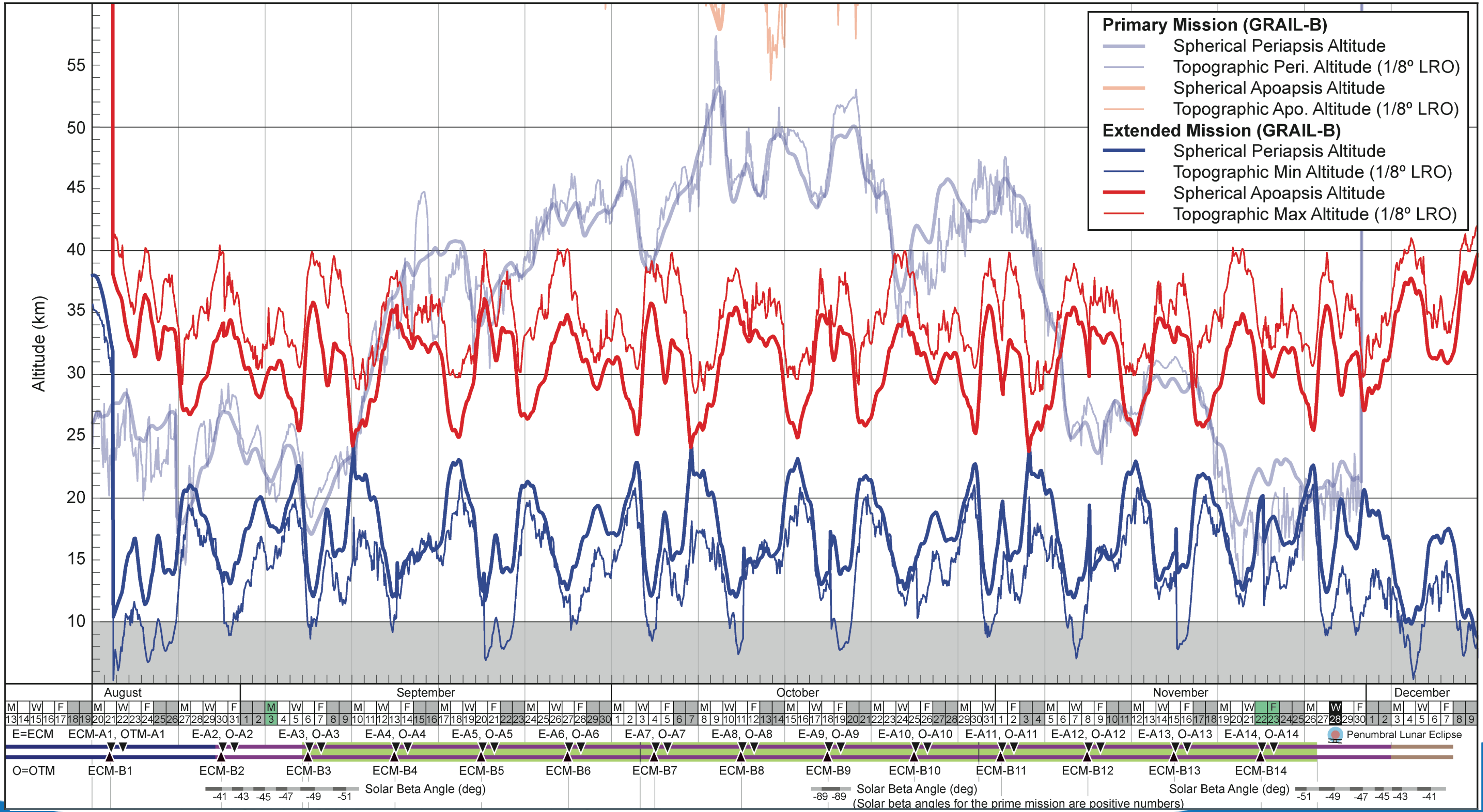
- Centering the weekly e-ω segments (with maneuvers on Thursdays) – 1st month



and repeat for 2 more months ...

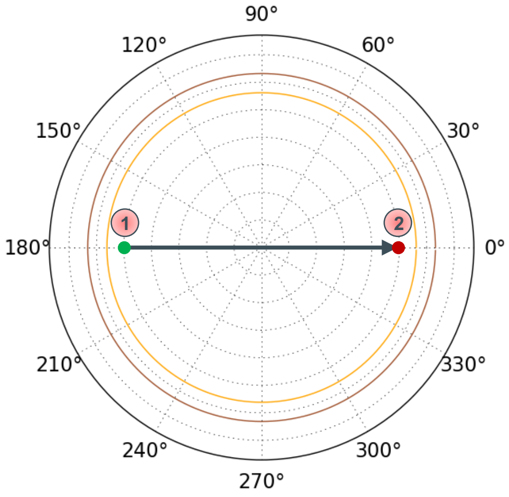
and then repeat again varying the ECM day-of-the-week, optimizing ΔV, and so on …

Science Orbit Comparison (PM vs XM)

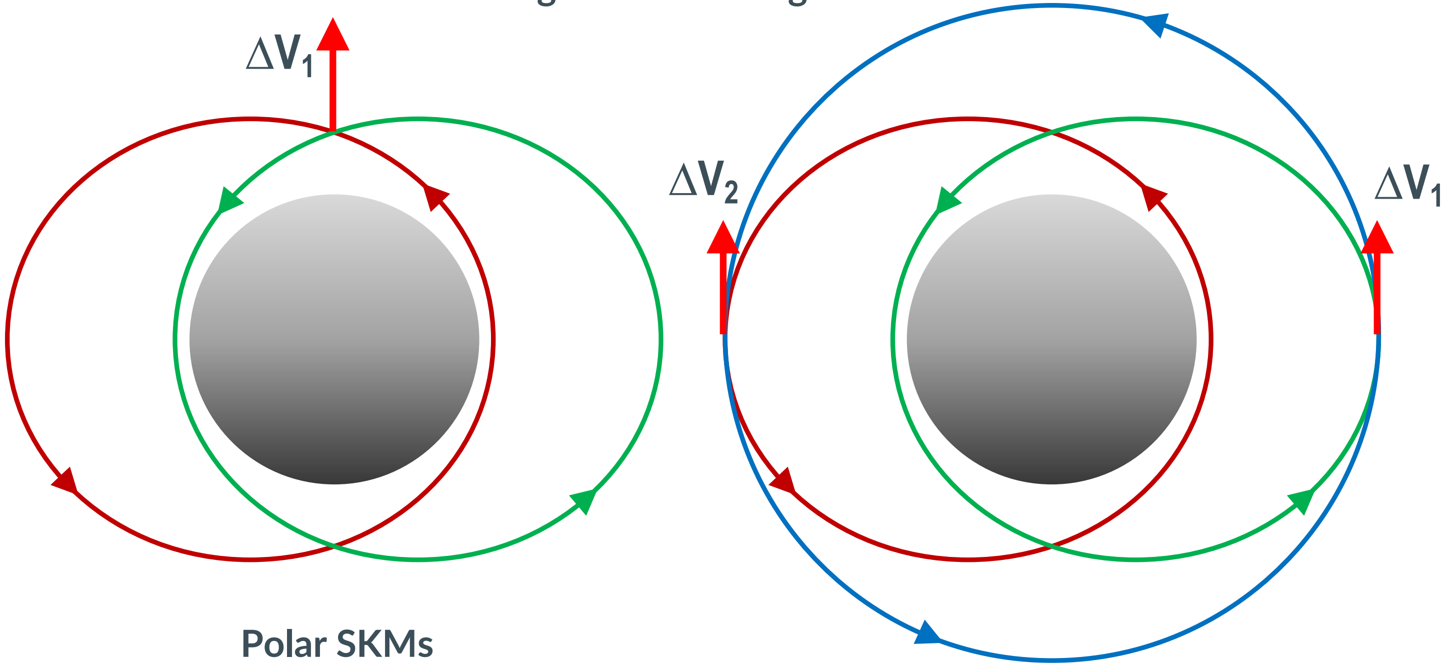


Maneuvering around in Eccentricity State Space

- We like positioning stationkeeping maneuvers either over the poles (for global mapping) or over the equator (for polar monitoring/mapping).
- We can do either, but they are not equivalent! One costs more than the other, and it depends on how you need to shift!



Exaggeration, showing AOP moving from left to right



Polar SKMs
1 burn is sufficient

Equatorial SKMs
2 burns

Parameter	SMA	ECC_0	AOP_0	ECC_f	AOP_f	DV_1	DV_2	Total DV
Polar	1747.4	0.004578	180 deg	0.004578	0 deg	15.338 m/s	0 m/s	15.338 m/s
Equatorial	1747.4	0.004578	180 deg	0.004578	0 deg	3.854 m/s	3.854 m/s	7.709 m/s

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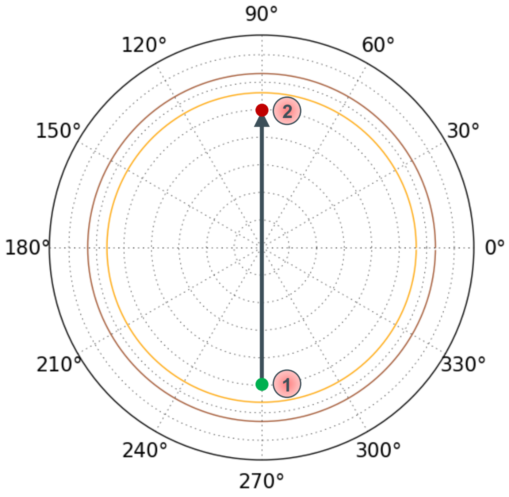

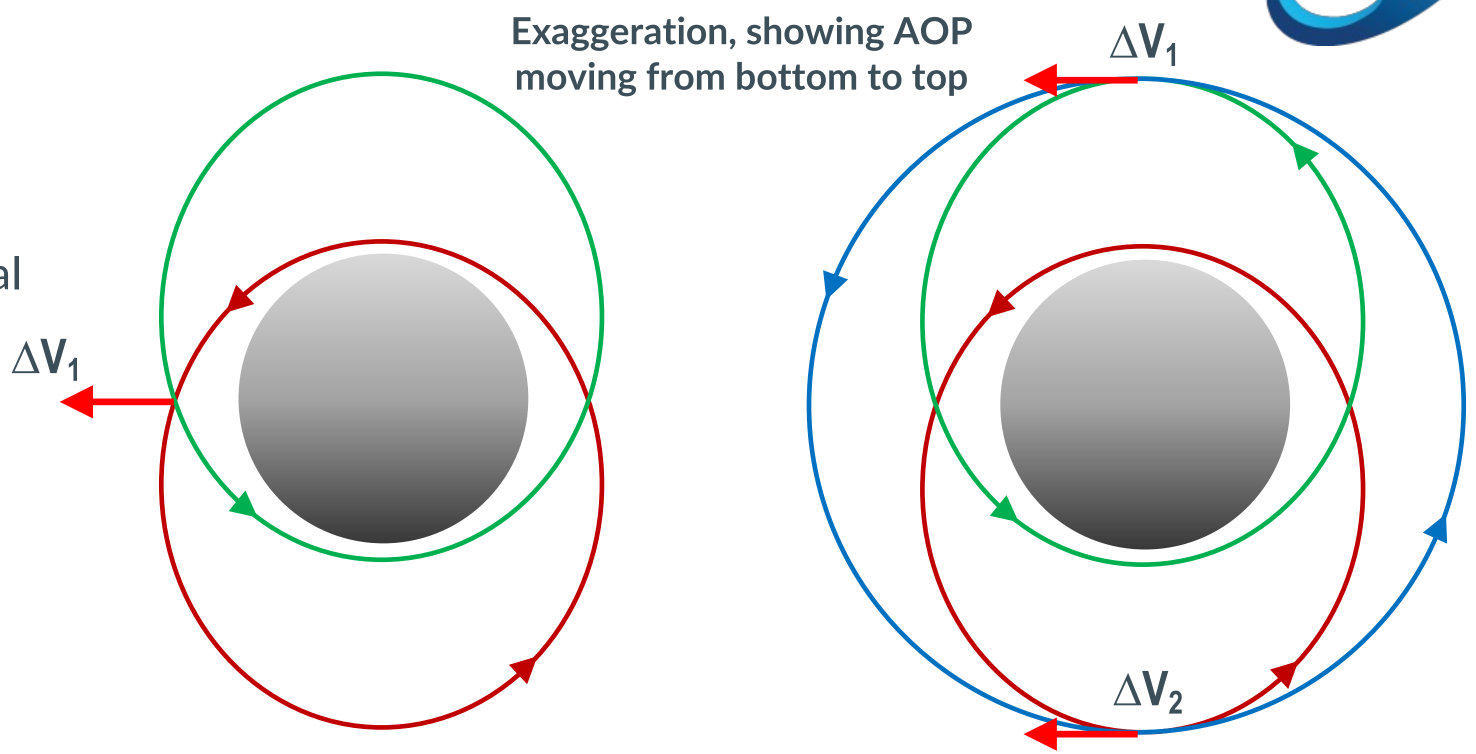

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1 burn is sufficient

Polar SKMs
2 burns

Parameter	SMA	ECC_0	AOP_0	ECC_f	AOP_f	DV_1	DV_2	Total DV
Equatorial	1747.4	0.004578	270 deg	0.004578	90 deg	15.338 m/s	0 m/s	15.338 m/s
Polar	1747.4	0.004578	270 deg	0.004578	90 deg	3.854 m/s	3.854 m/s	7.709 m/s

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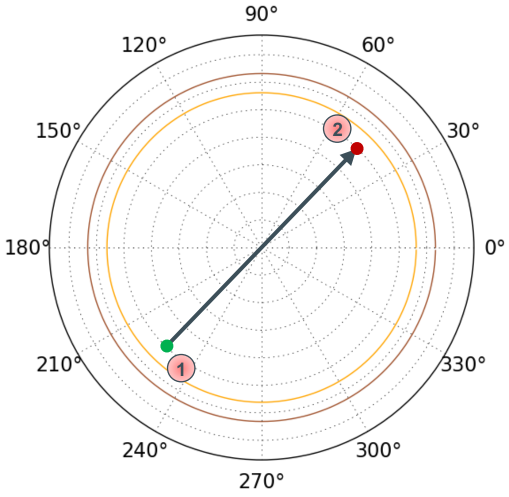
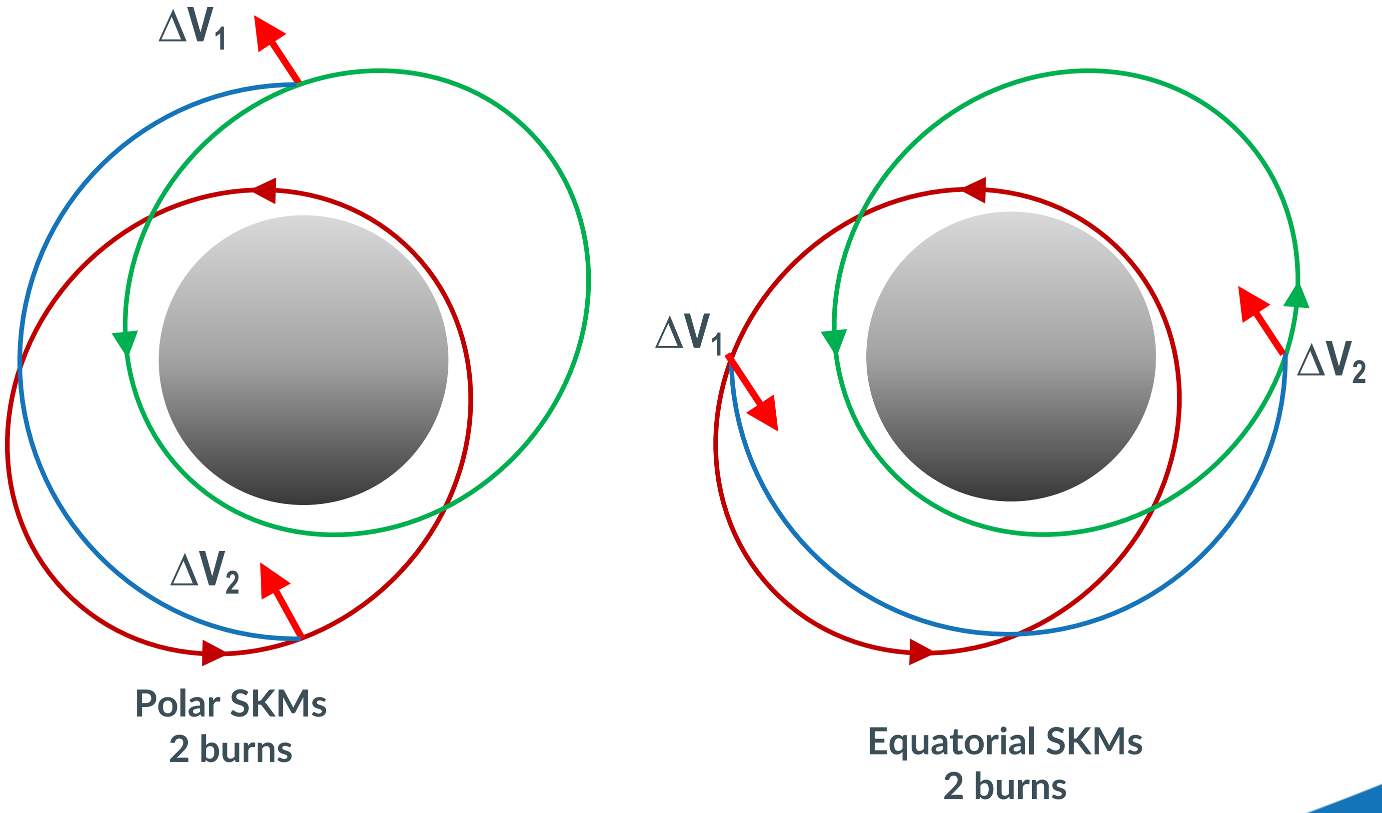




Parameter	SMA	ECC_0	AOP_0	ECC_f	AOP_f	DV_1	DV_2	Total DV
Equatorial	1747.4	0.004578	225 deg	0.004578	45 deg	6.095 m/s	6.095 m/s	12.190 m/s
Polar	1747.4	0.004578	225 deg	0.004578	45 deg	6.095 m/s	6.095 m/s	12.190 m/s

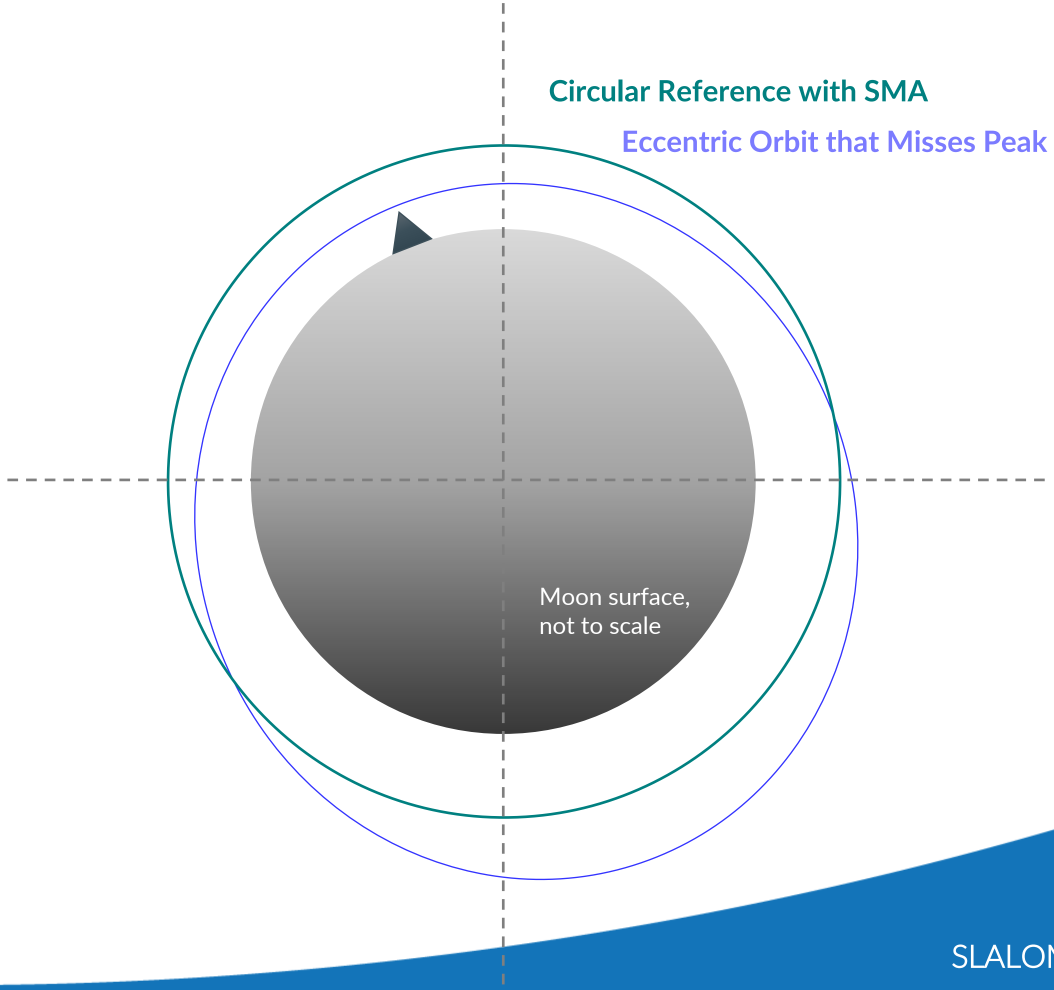
Diving Lower

✦When we dive even lower, we have to avoid lunar topography.

Given:
- r_M = 1737.4 km
- SMA = 1747.4 km (10 km average altitude)
- A peak with an altitude of 4 km will require
  - R_p = 1742.4 km (1 km buffer)
  - R_a = 1752.4 km (15 km altitude)
  - and eccentricity to be < 0.00286

Given:
- r_M = 1737.4 km
- SMA = 1745.4 km (8 km average altitude)
- A peak with an altitude of 4 km will require
  - R_p = 1742.4 km (1 km buffer)
  - R_a = 1748.4 km (11 km altitude)
  - and eccentricity to be < 0.00172

But only if the periapse is over the peak!



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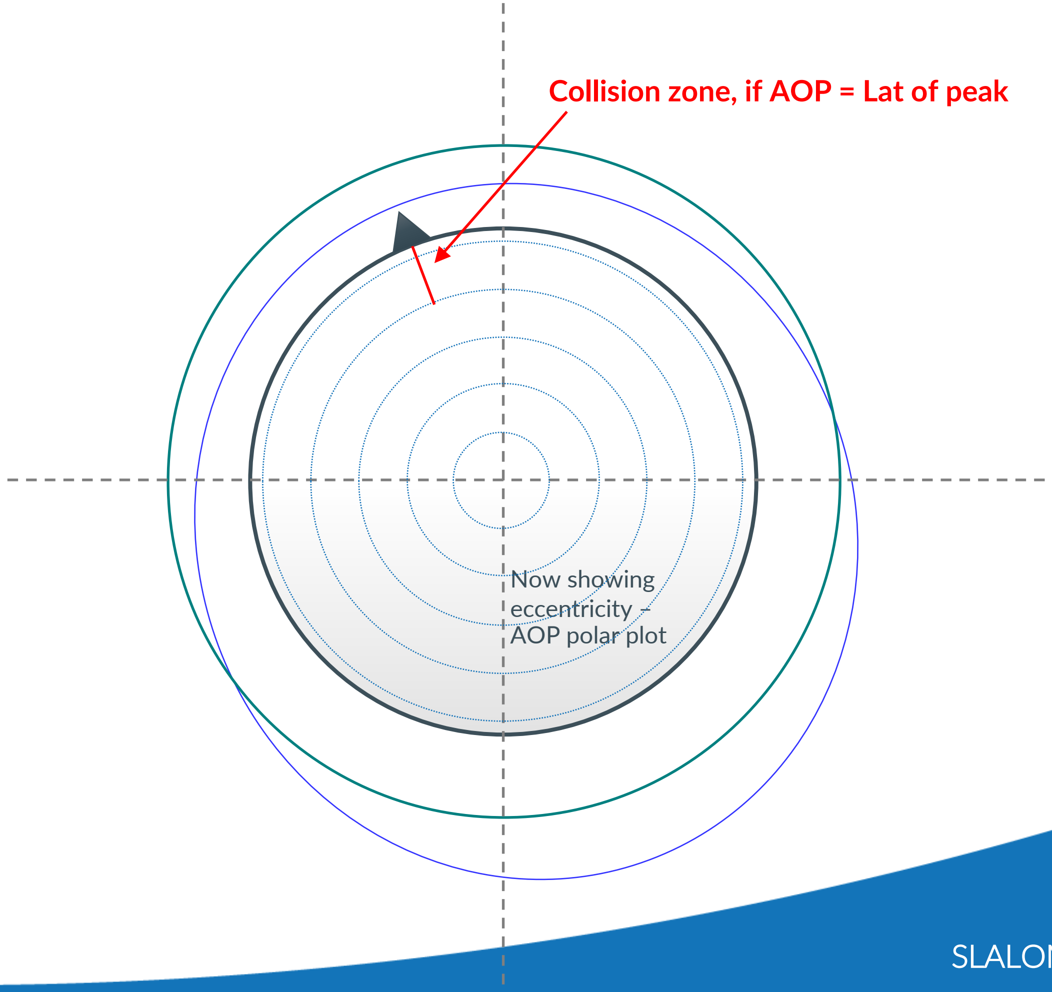

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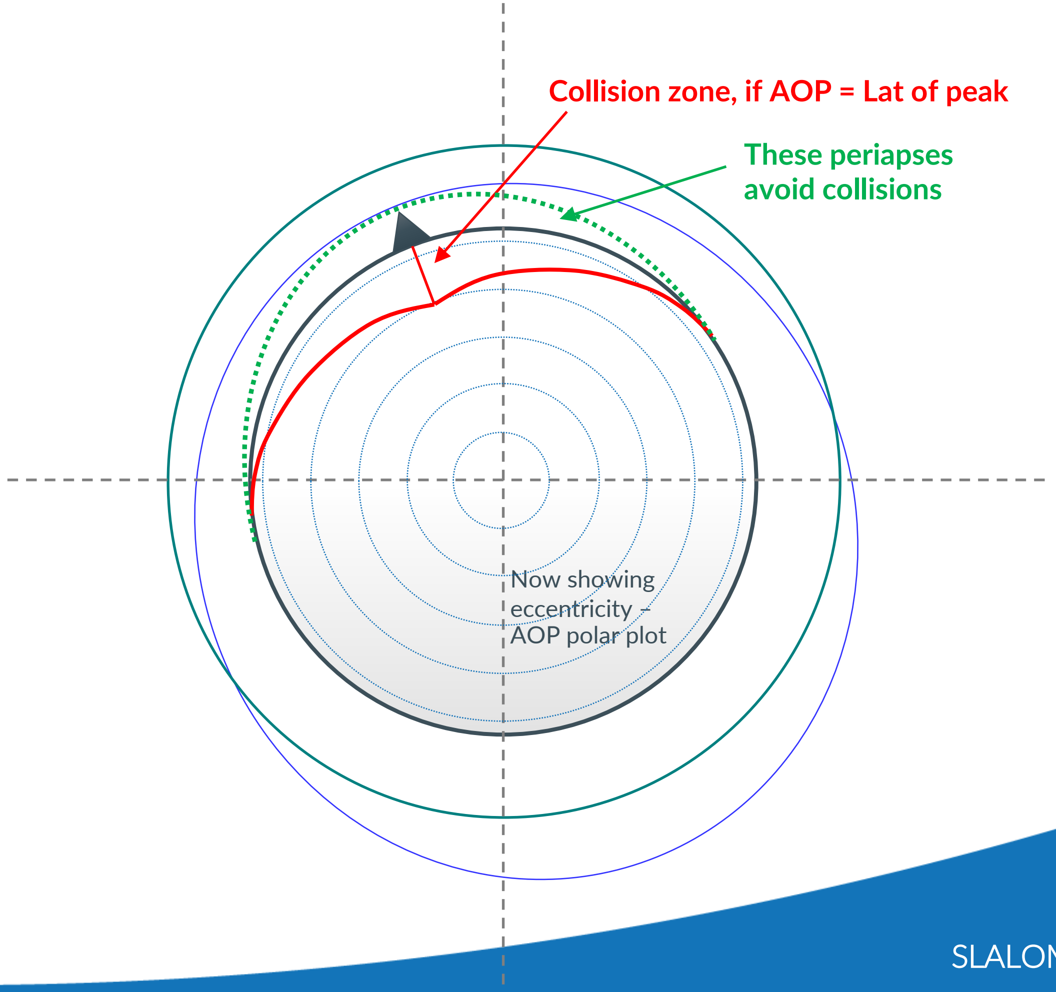
Rotate the AOP of the orbit to sweep out the collision zone



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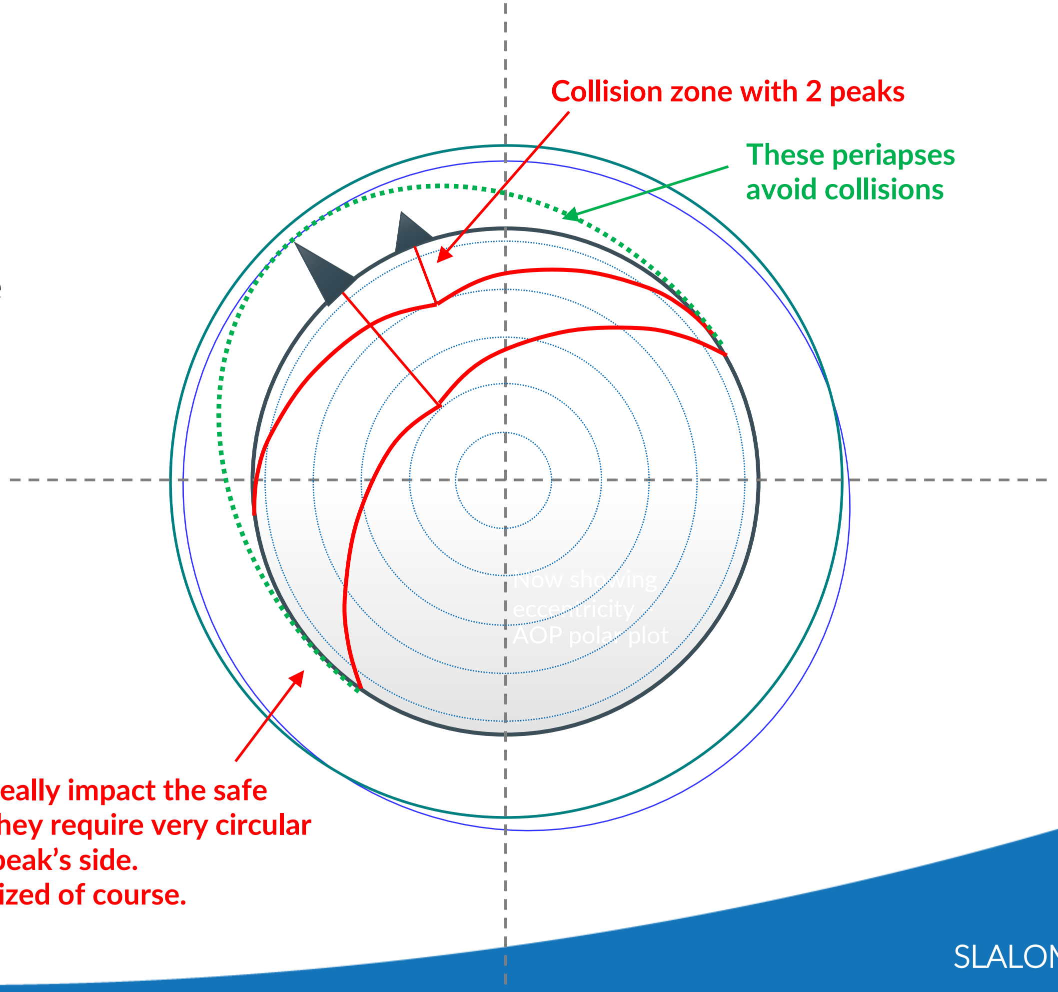

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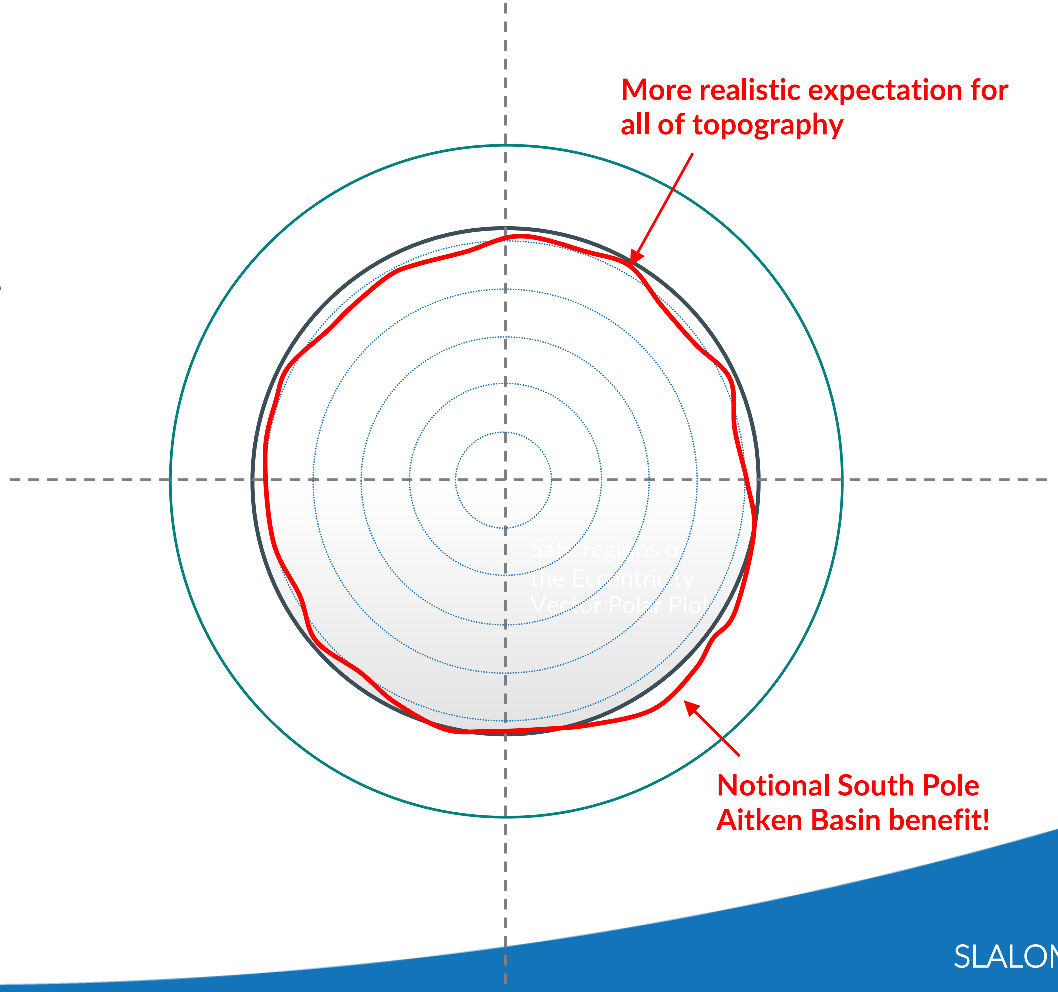
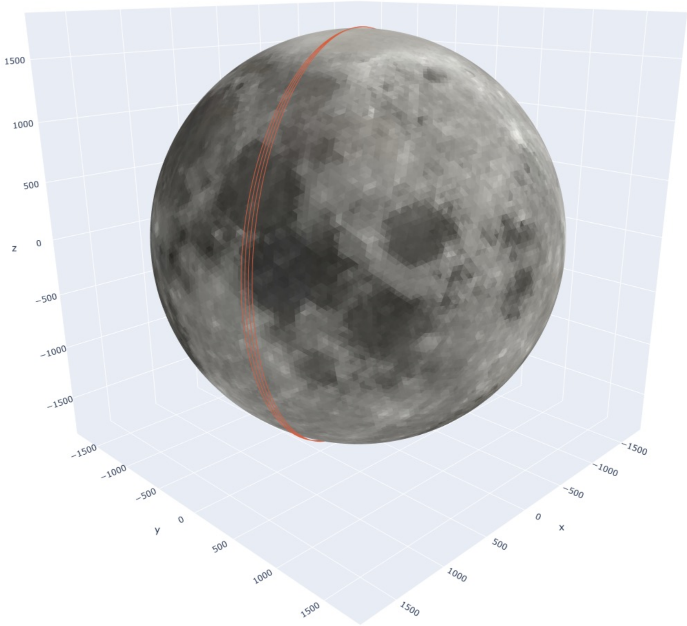
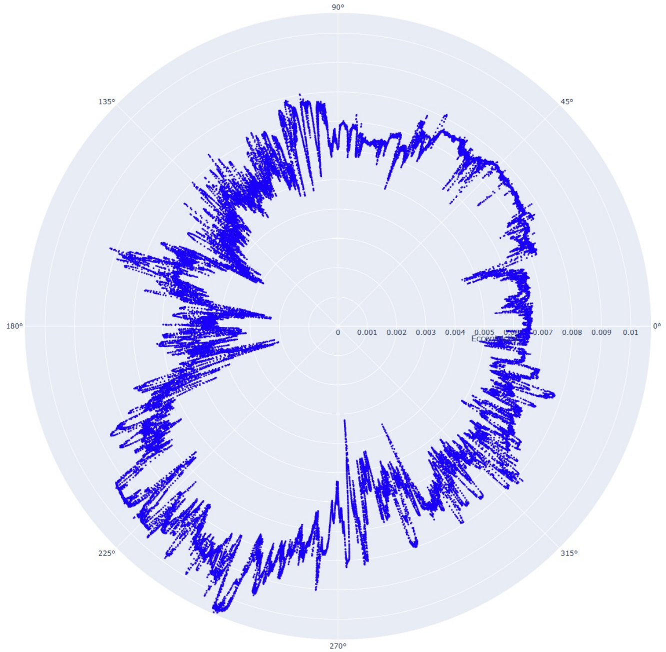


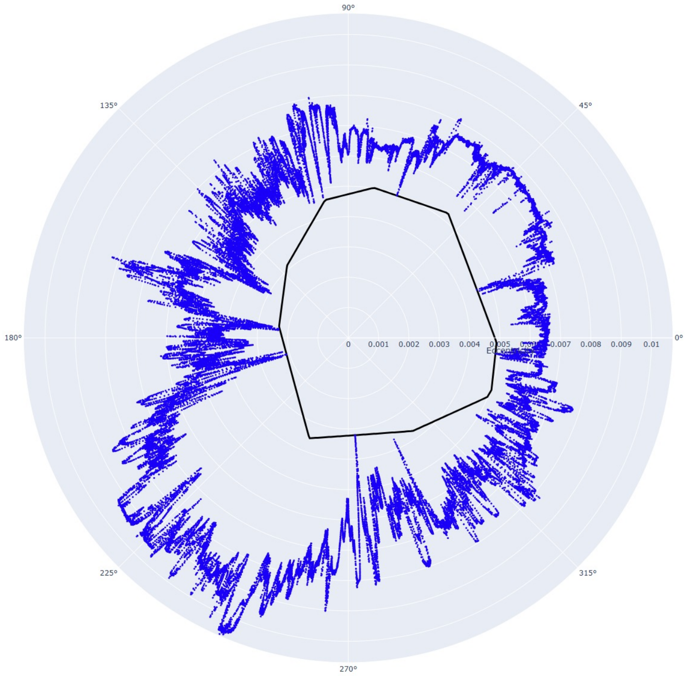
Eccentricity Vector Safe Corridor



Lunar Trajectory

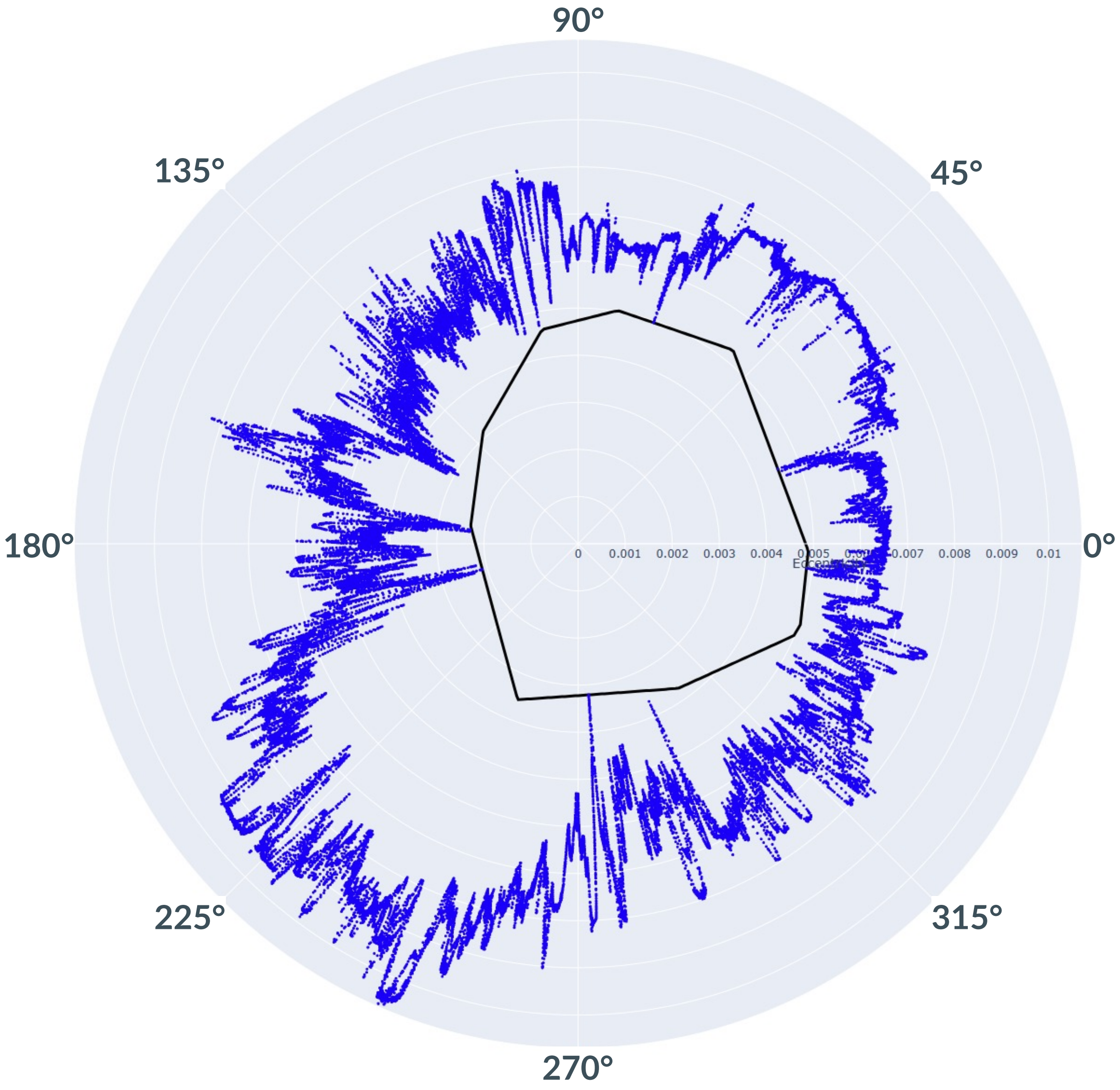


Topography transformed to vector space



Boundary drawn in topography

Eccentricity Vector Safe Corridor



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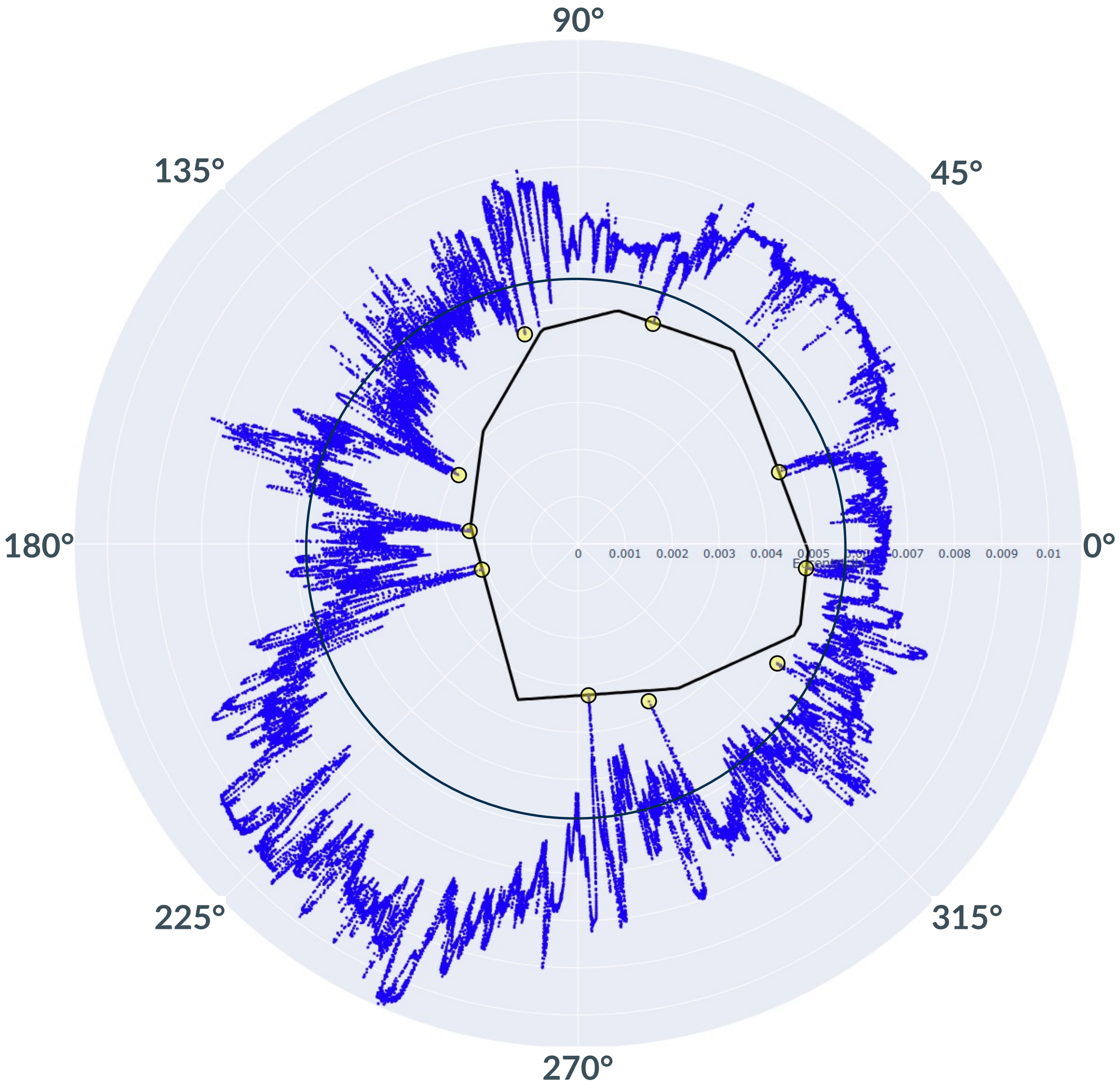

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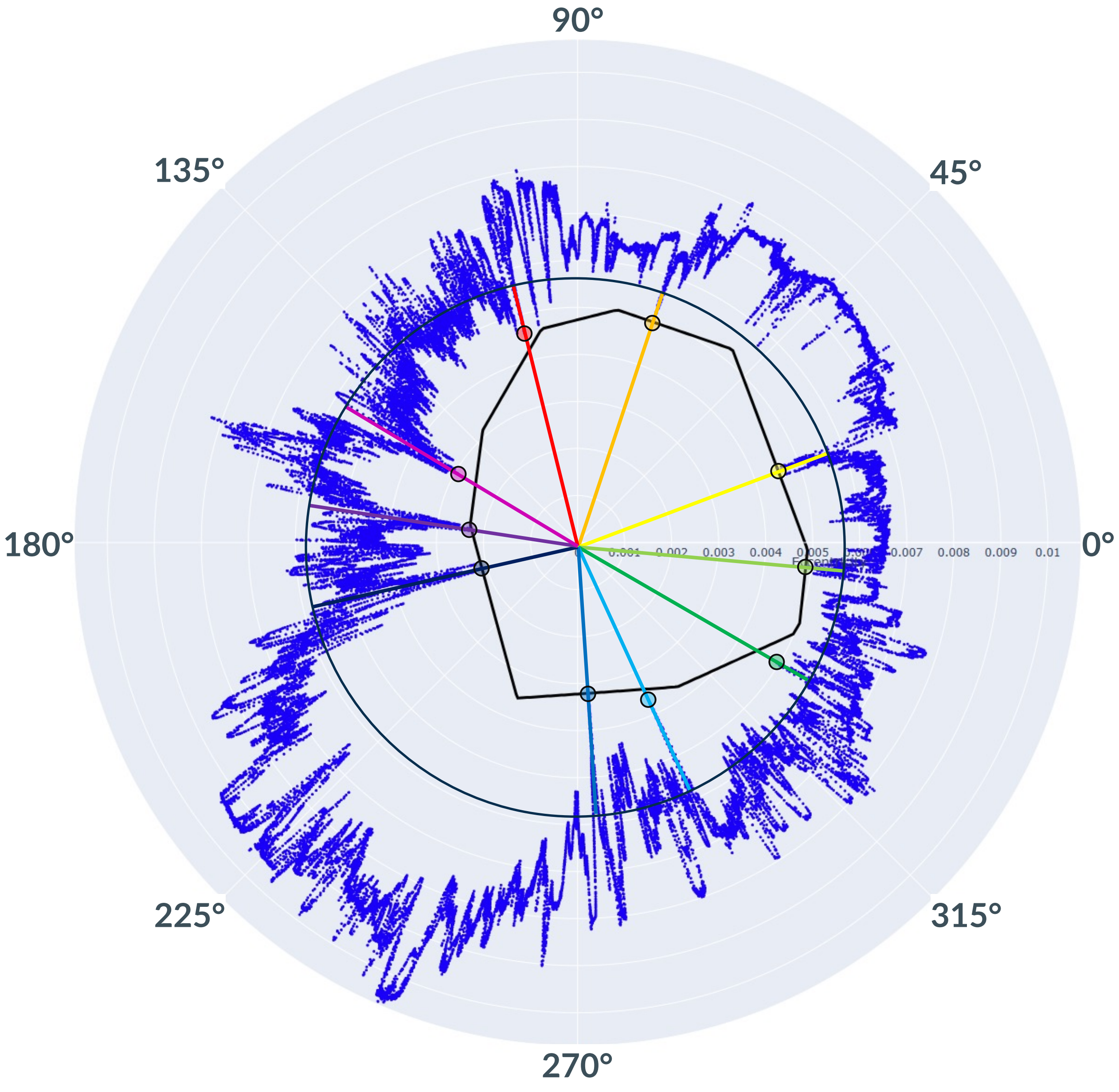

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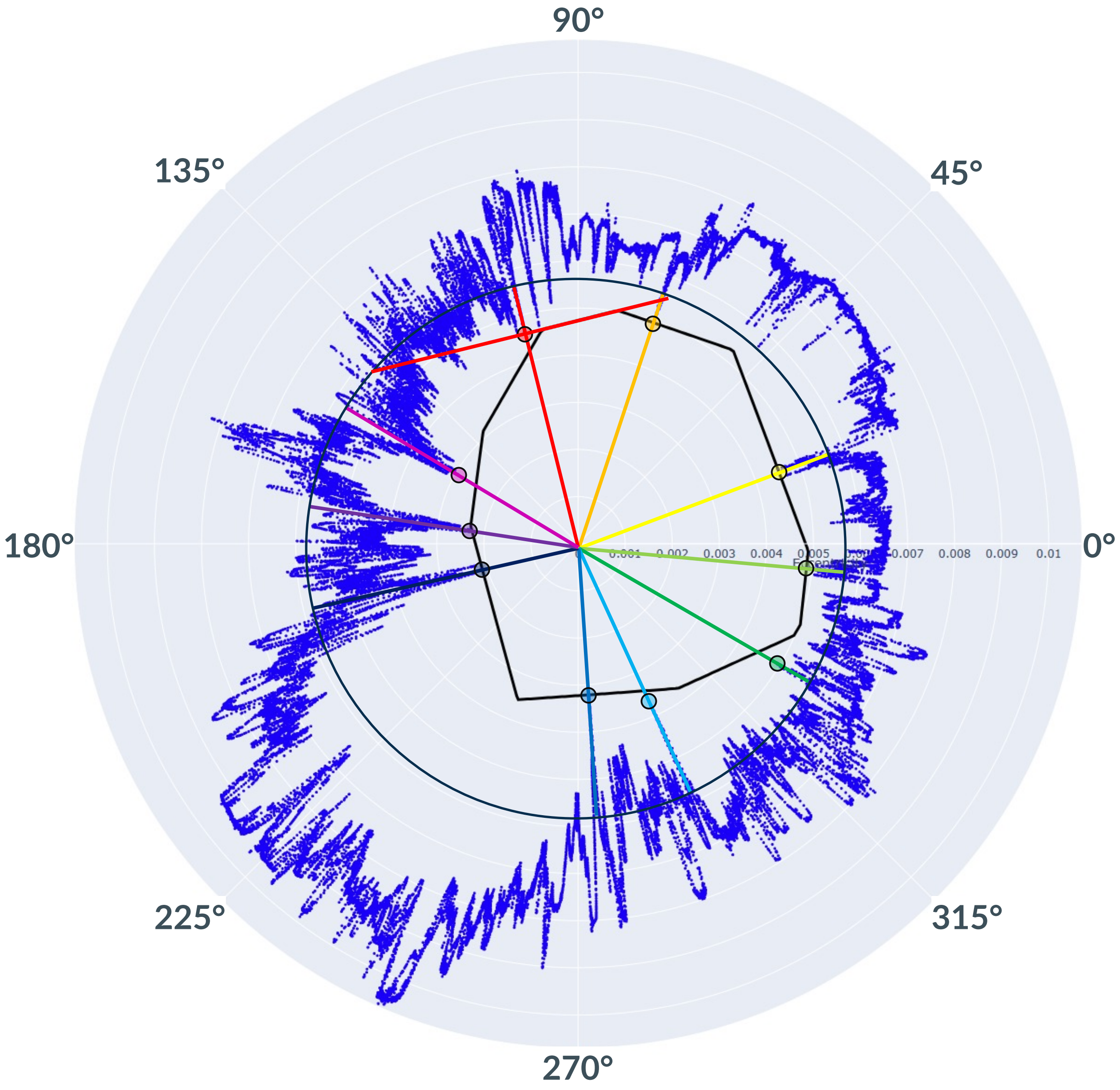

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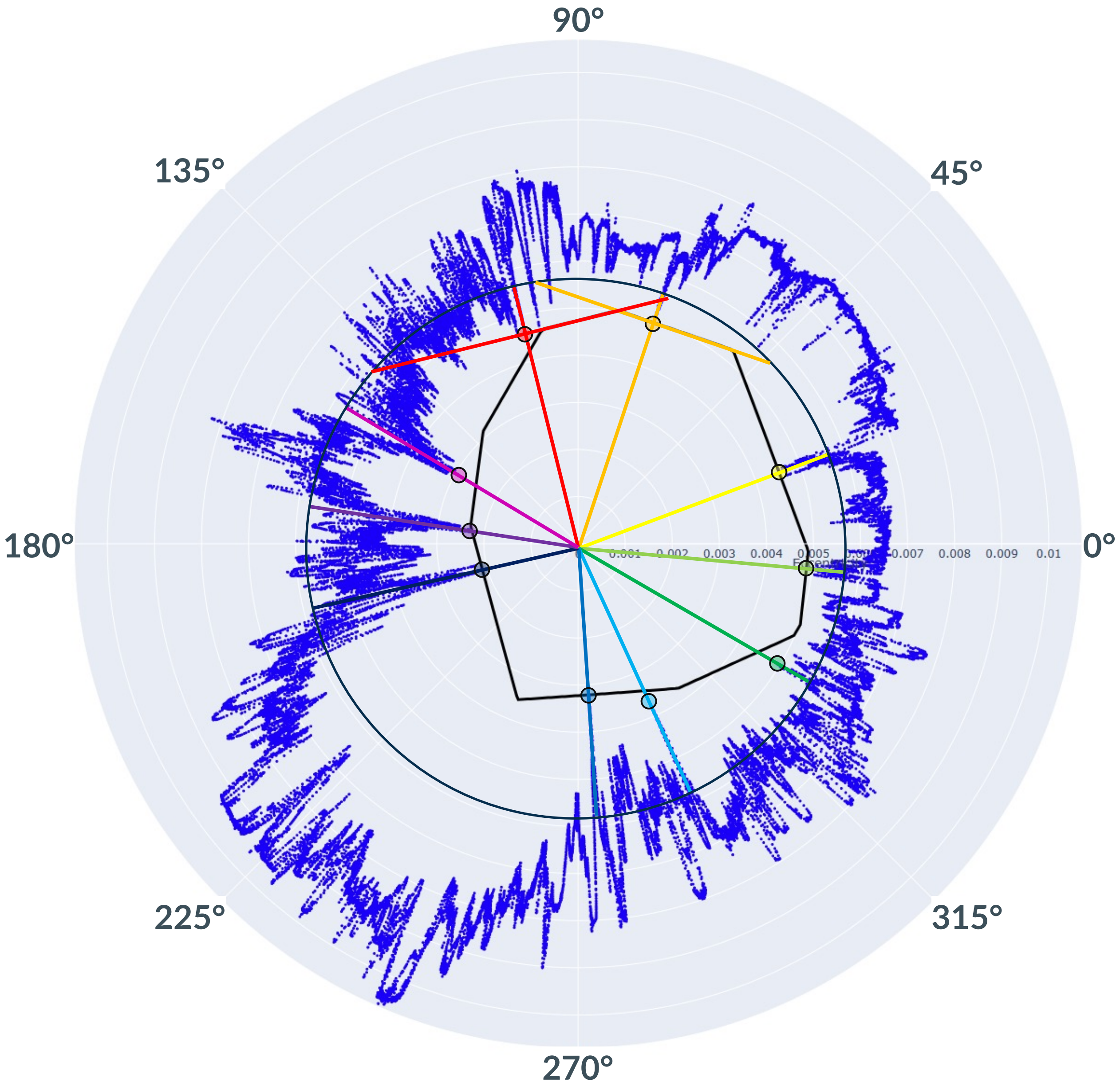

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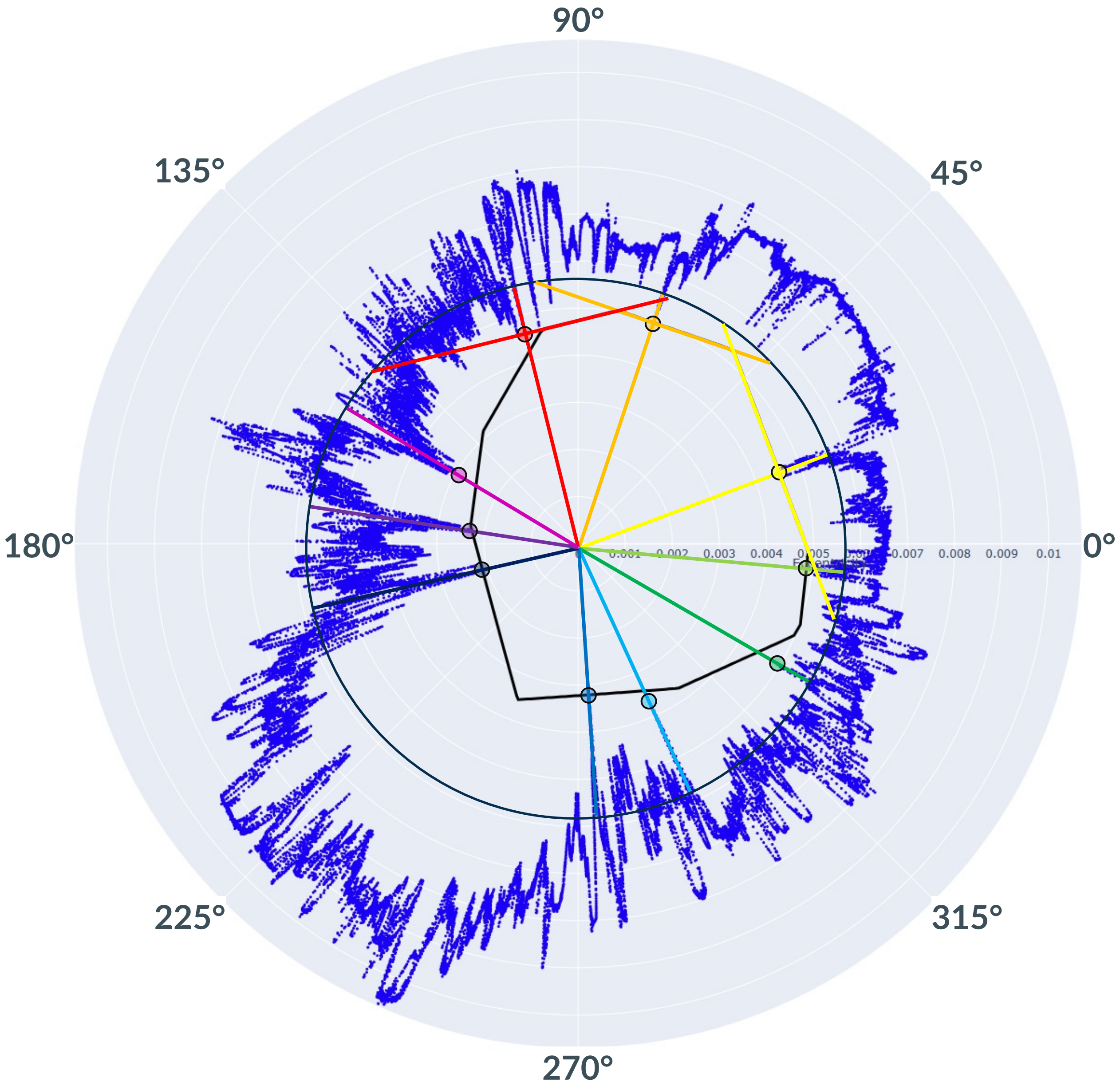

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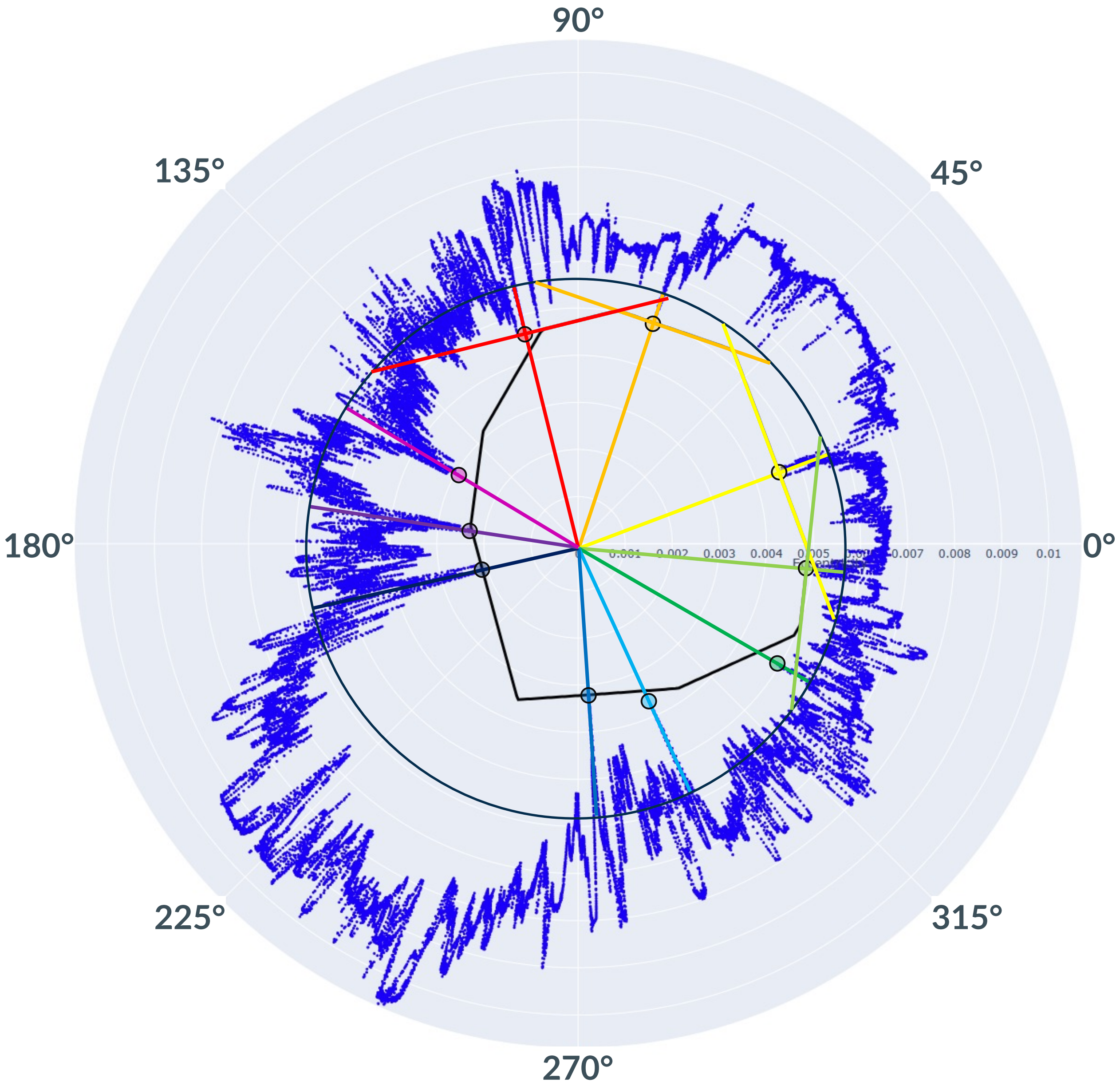

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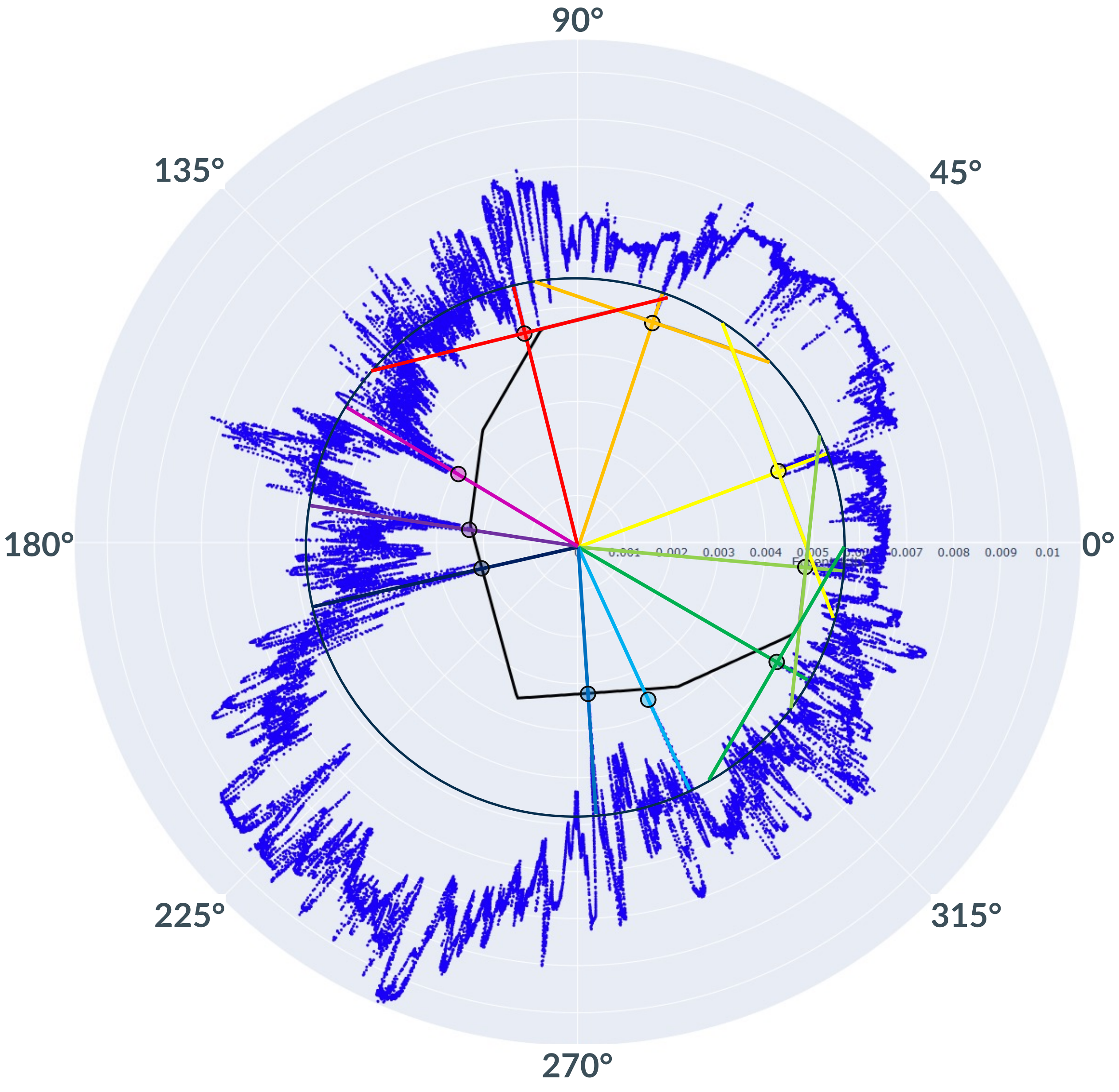

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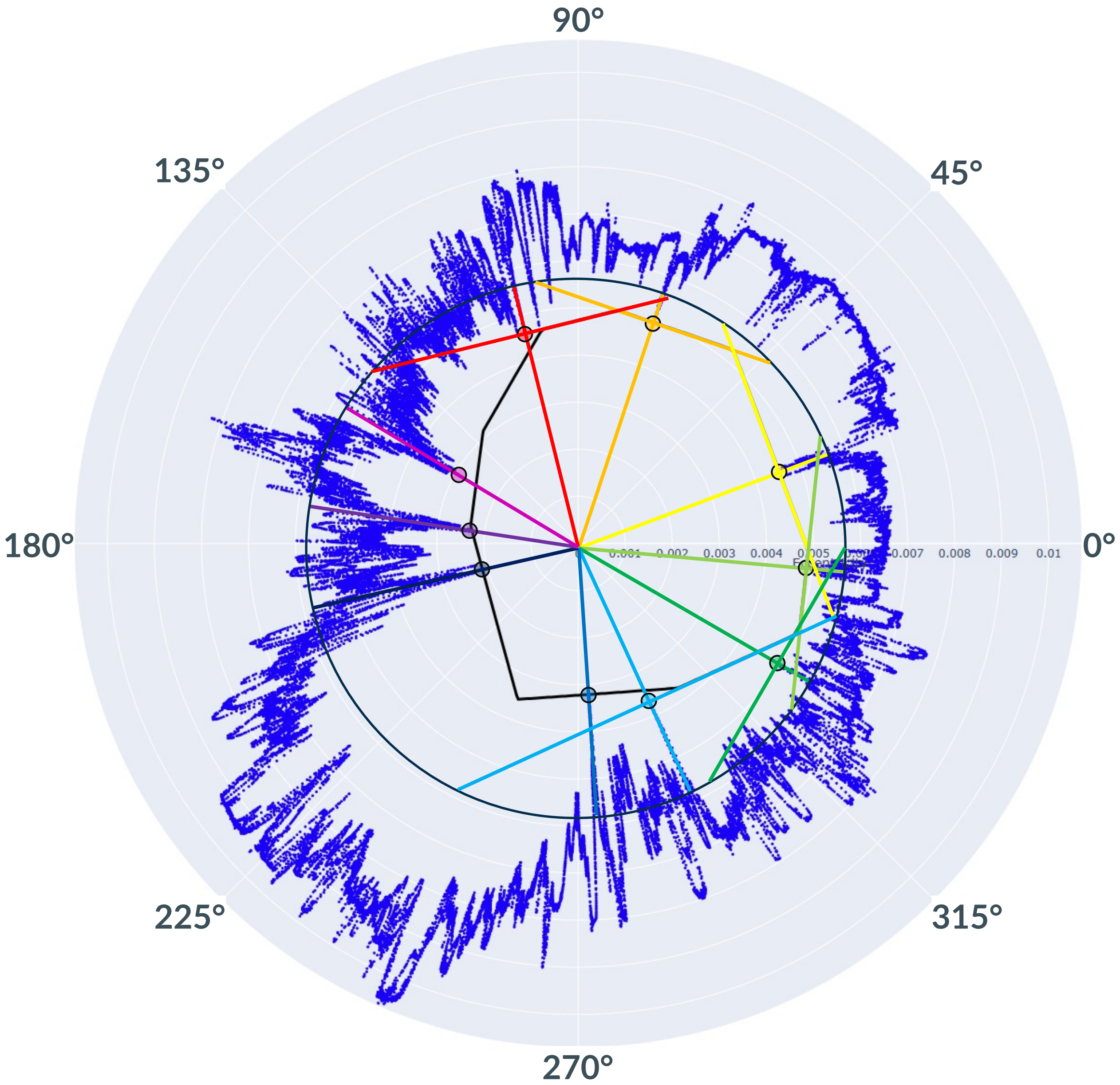

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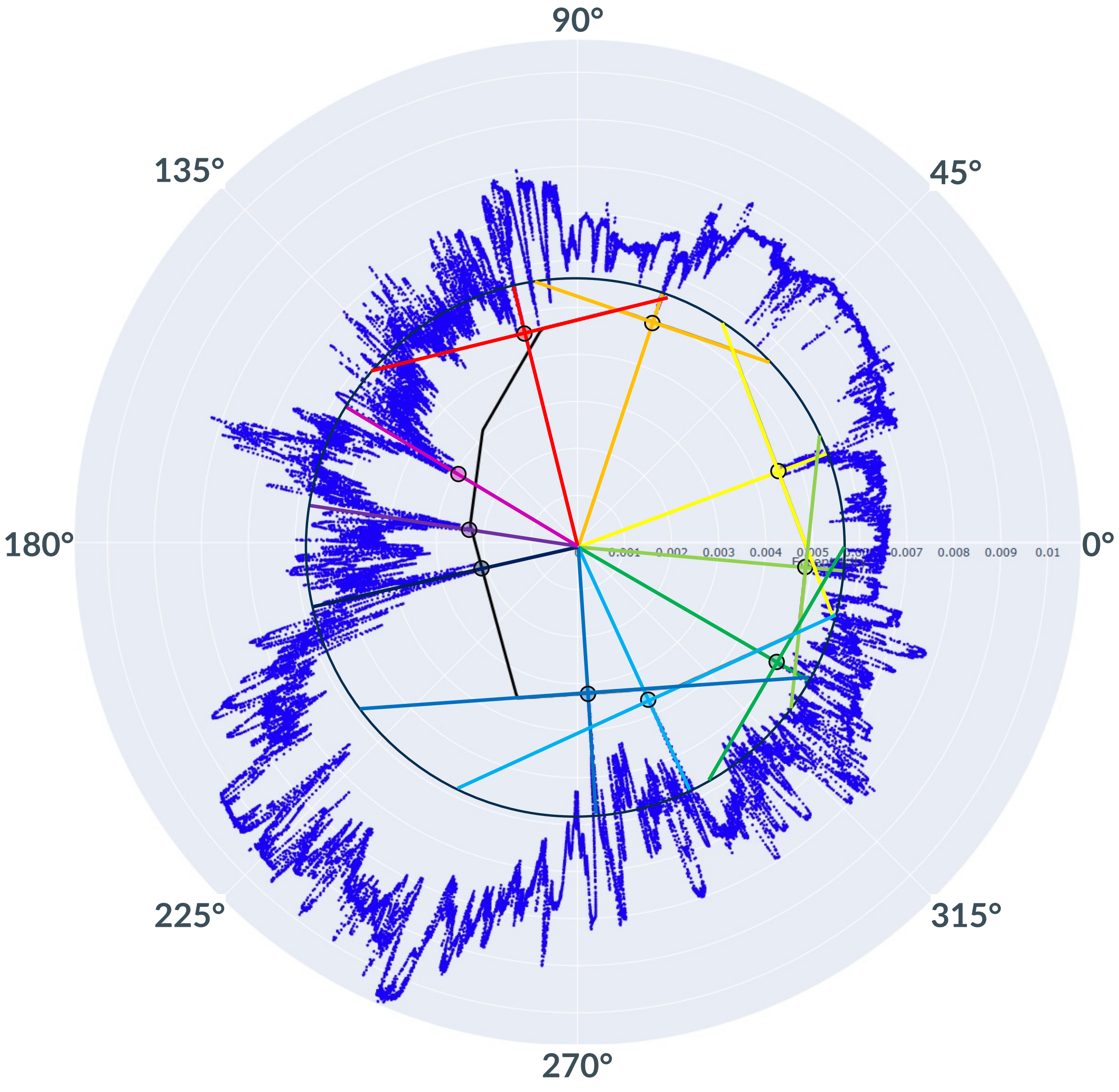

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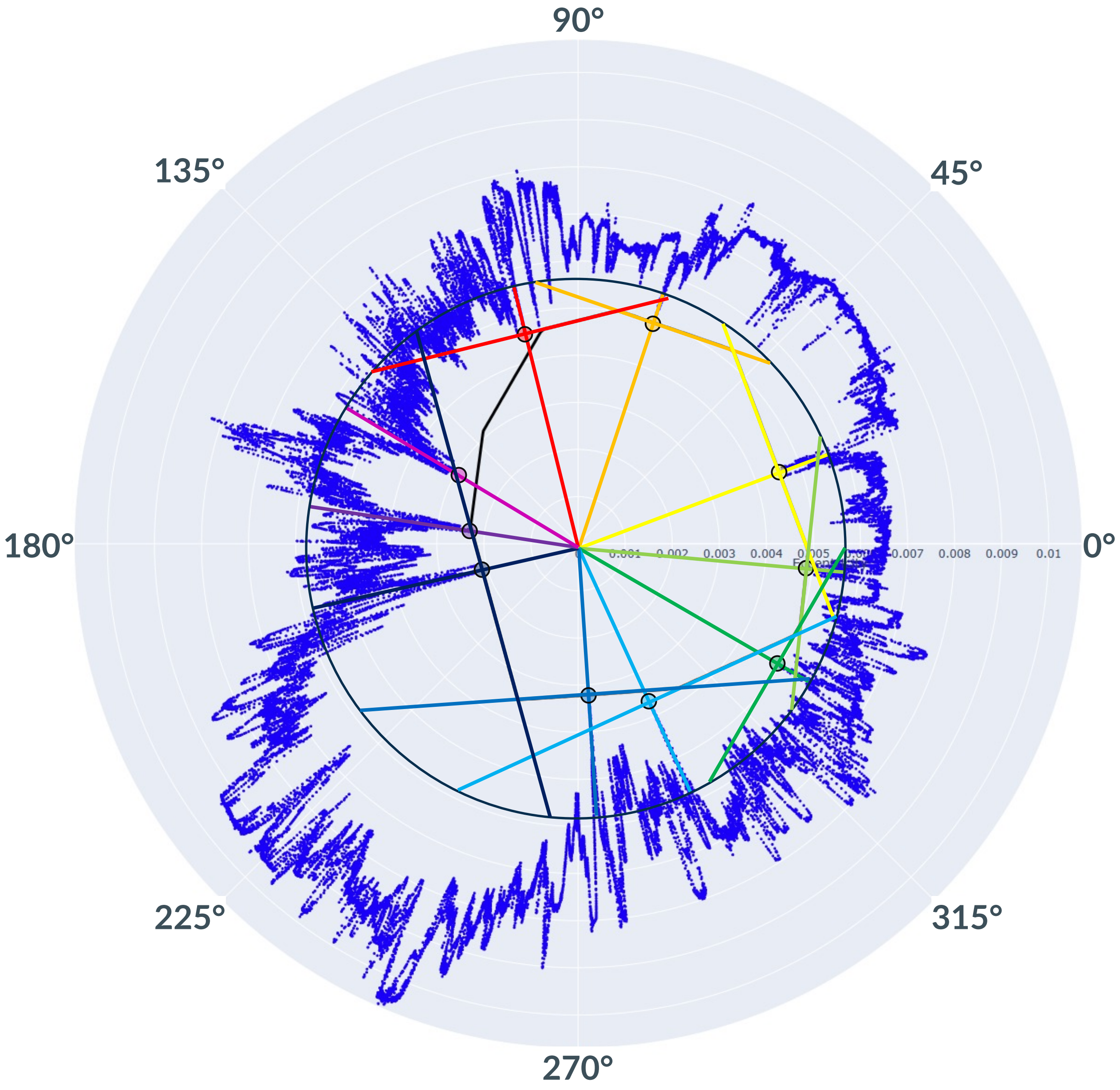

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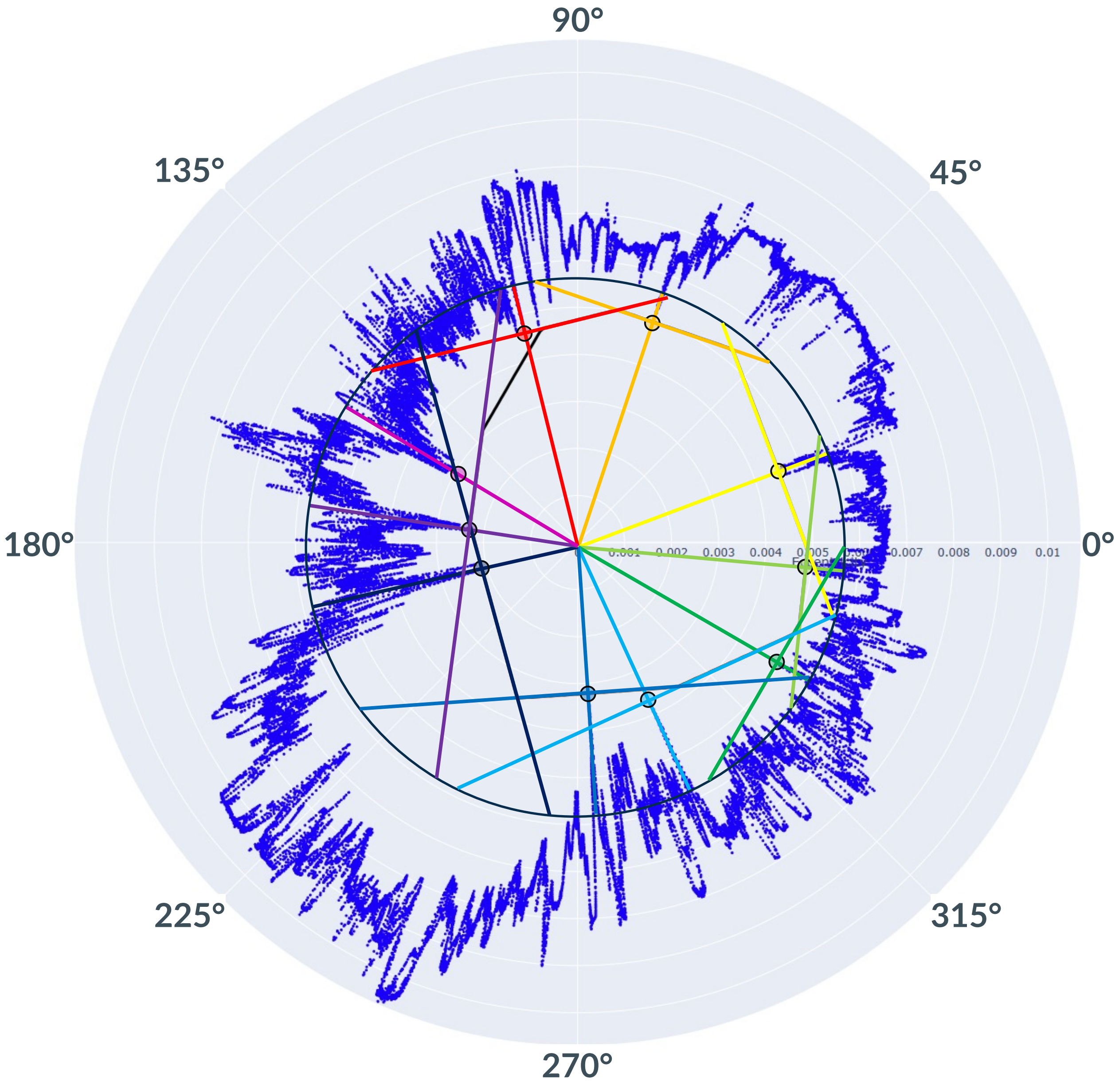

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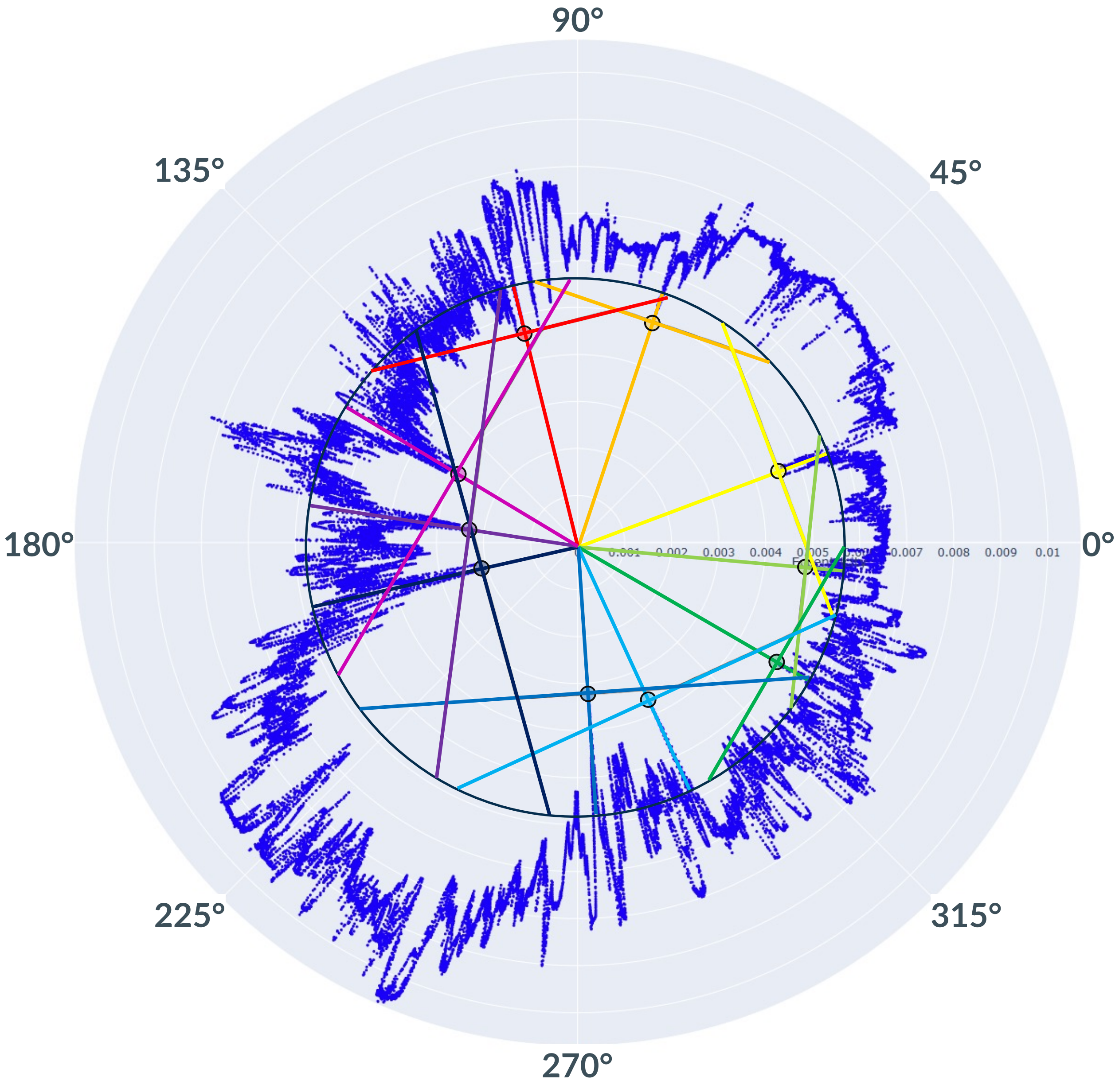

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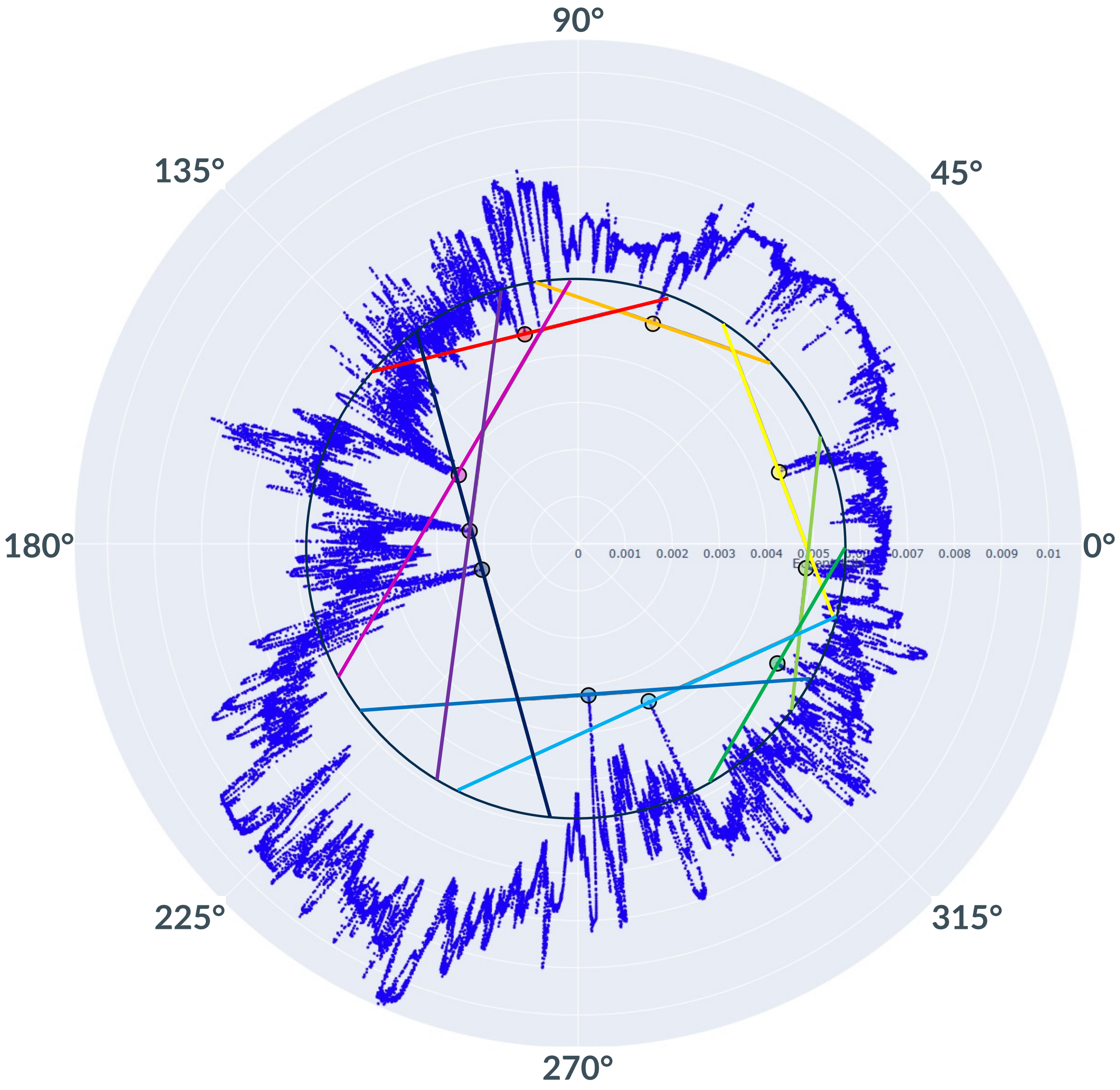

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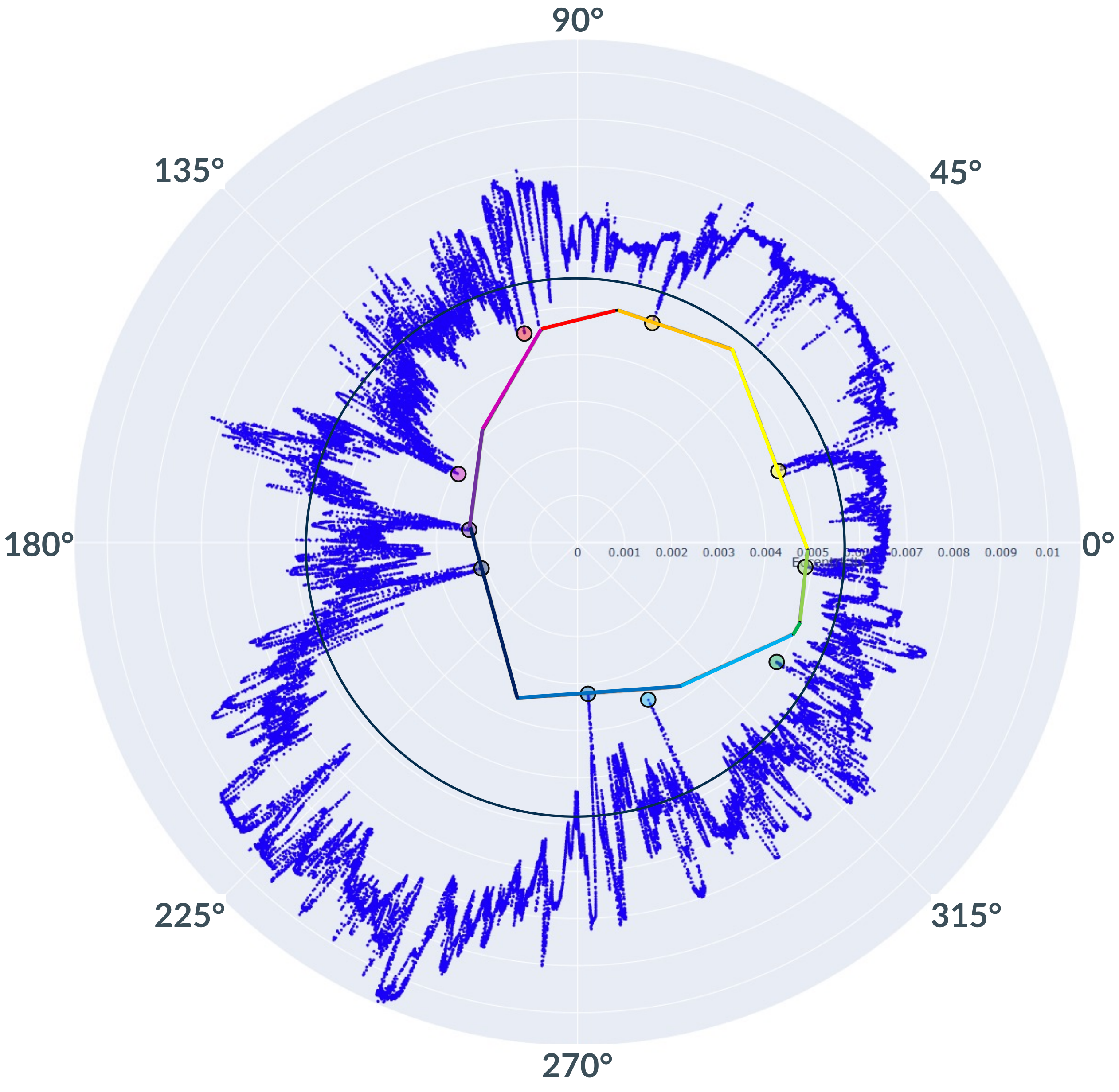

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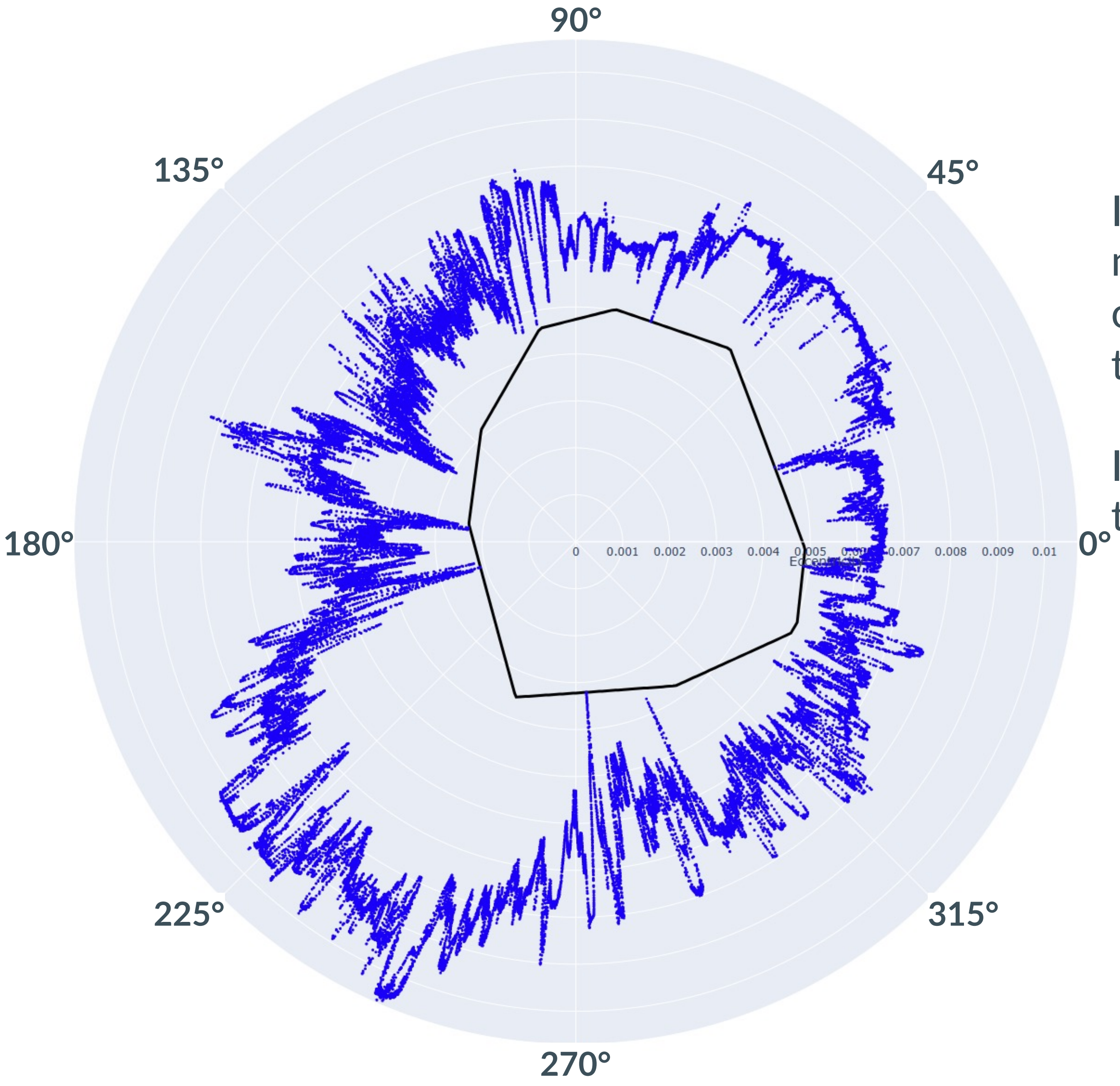

In this instant in time, there is more safety putting the periapse on the Northern side, closer to the ascending equator crossing!

If this is too tight, we can raise the orbit, or vice versa.

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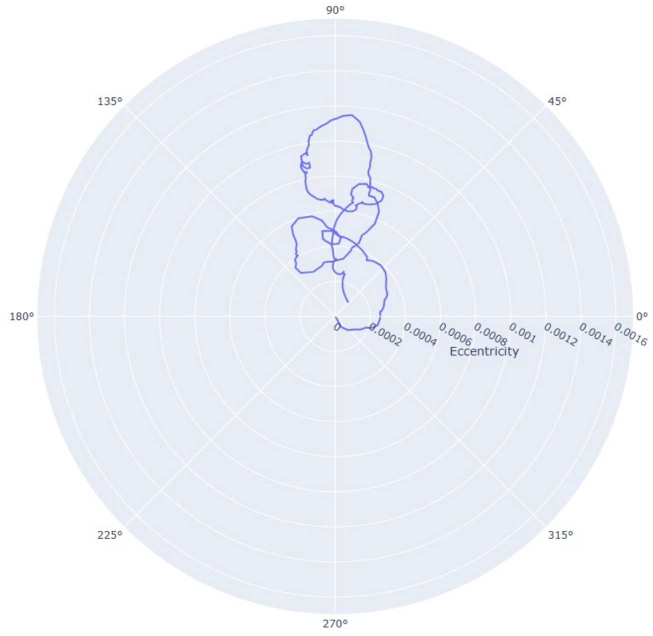
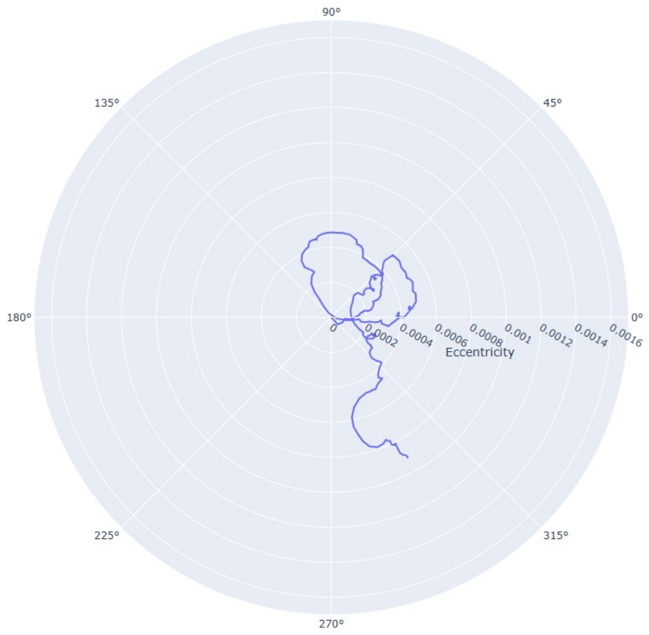
Eccentricity Vector over a single orbit

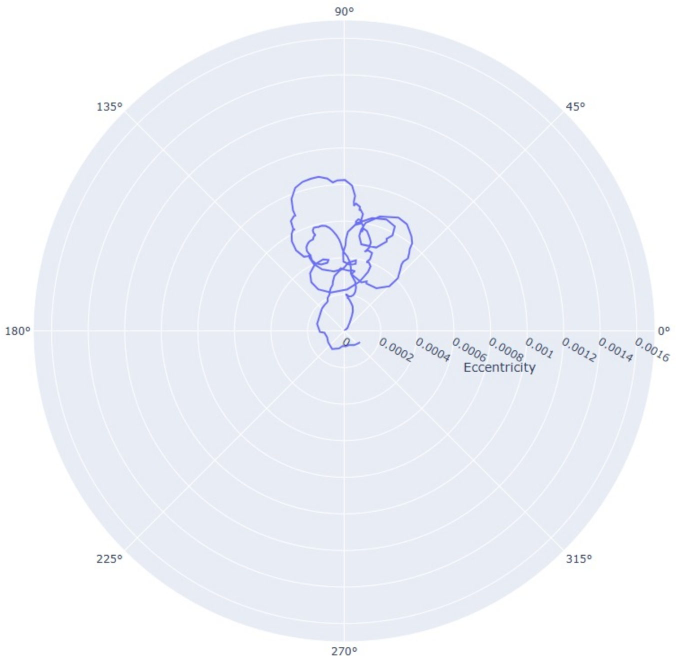


1-Period, Init Node = 0 deg



1-Period, Init Node = 69 deg

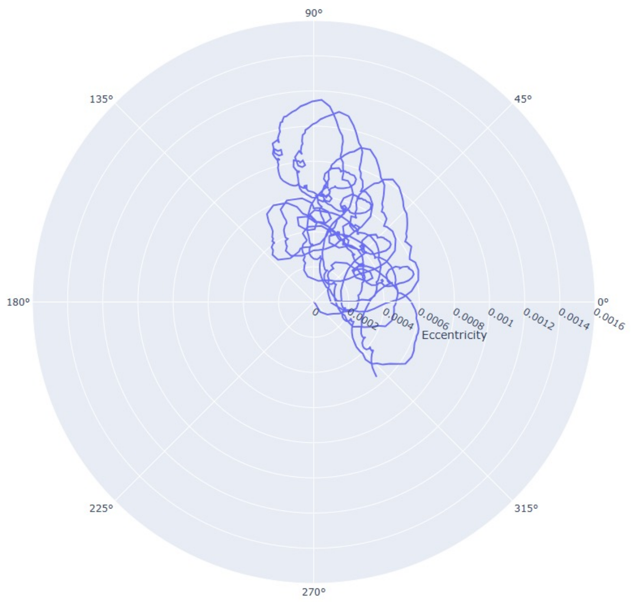
Unstable node case



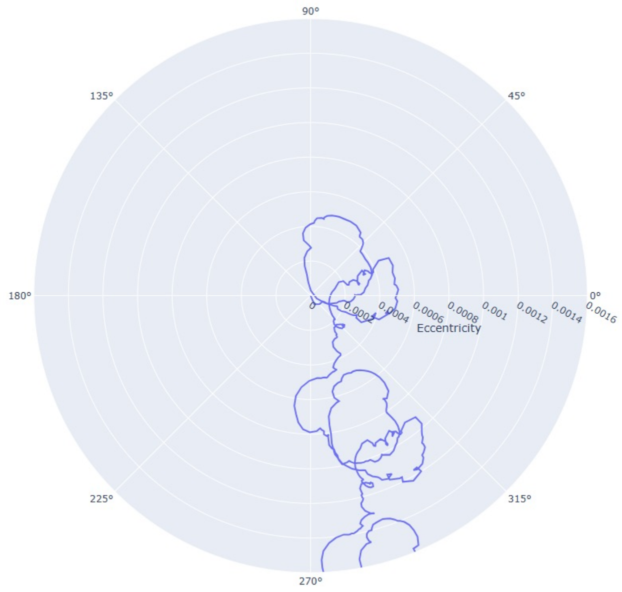
1-Period, Init Node = 144 deg

Stable node case

Eccentricity Vector over 4 orbits

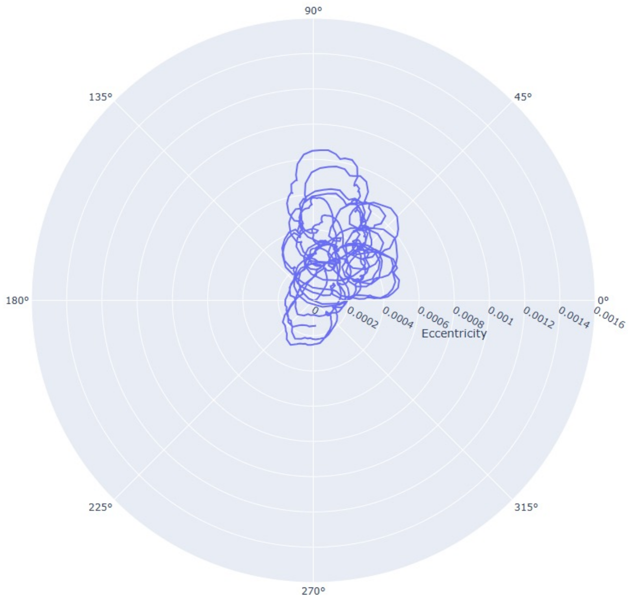


4-Period, Init Node = 0 deg



4-Period, Init Node = 69 deg

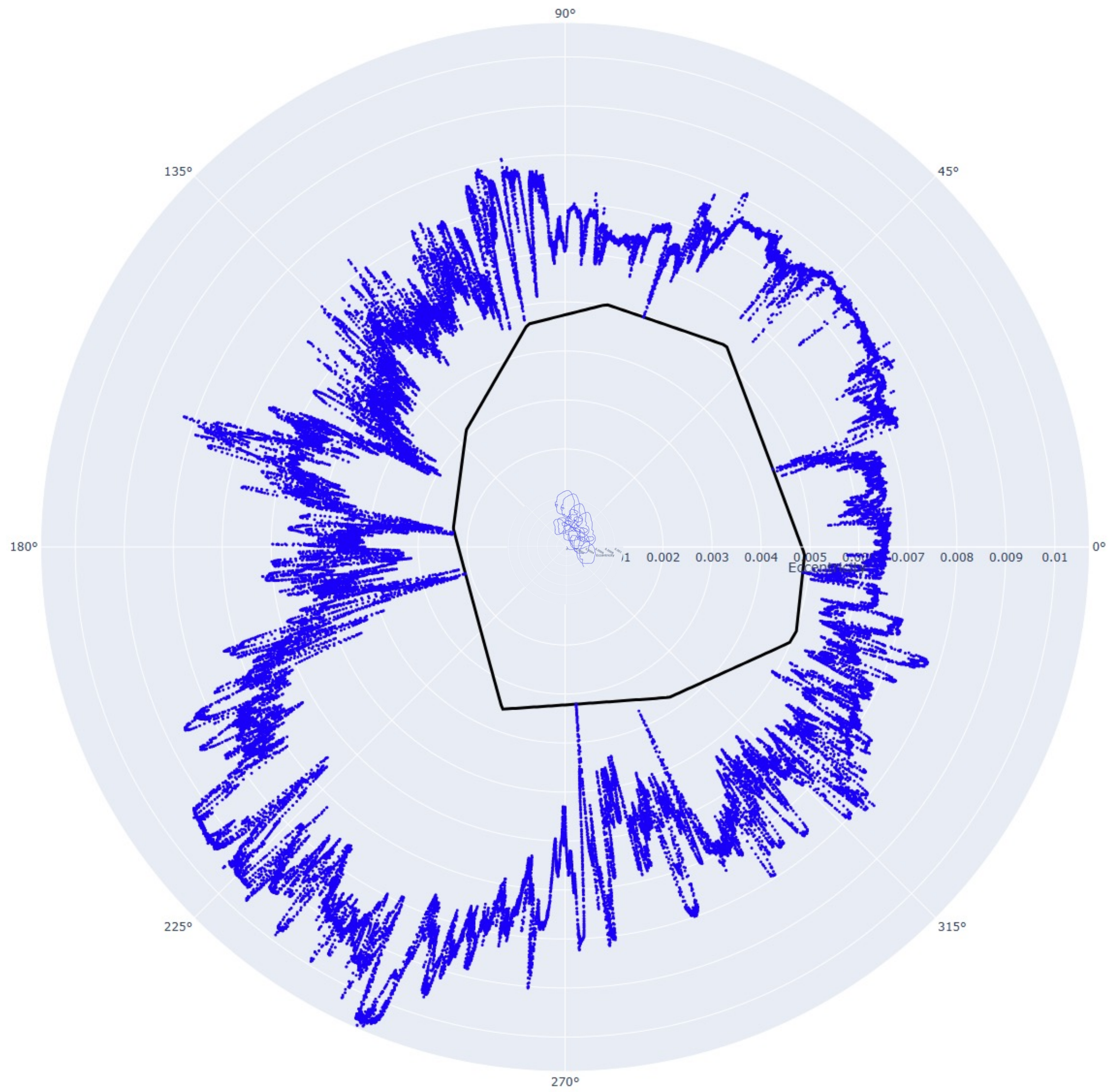
Unstable node case



4-Period, Init Node = 144 deg

Stable node case

Eccentricity Vector Safe Corridor



How quickly do we move toward the corridor wall?

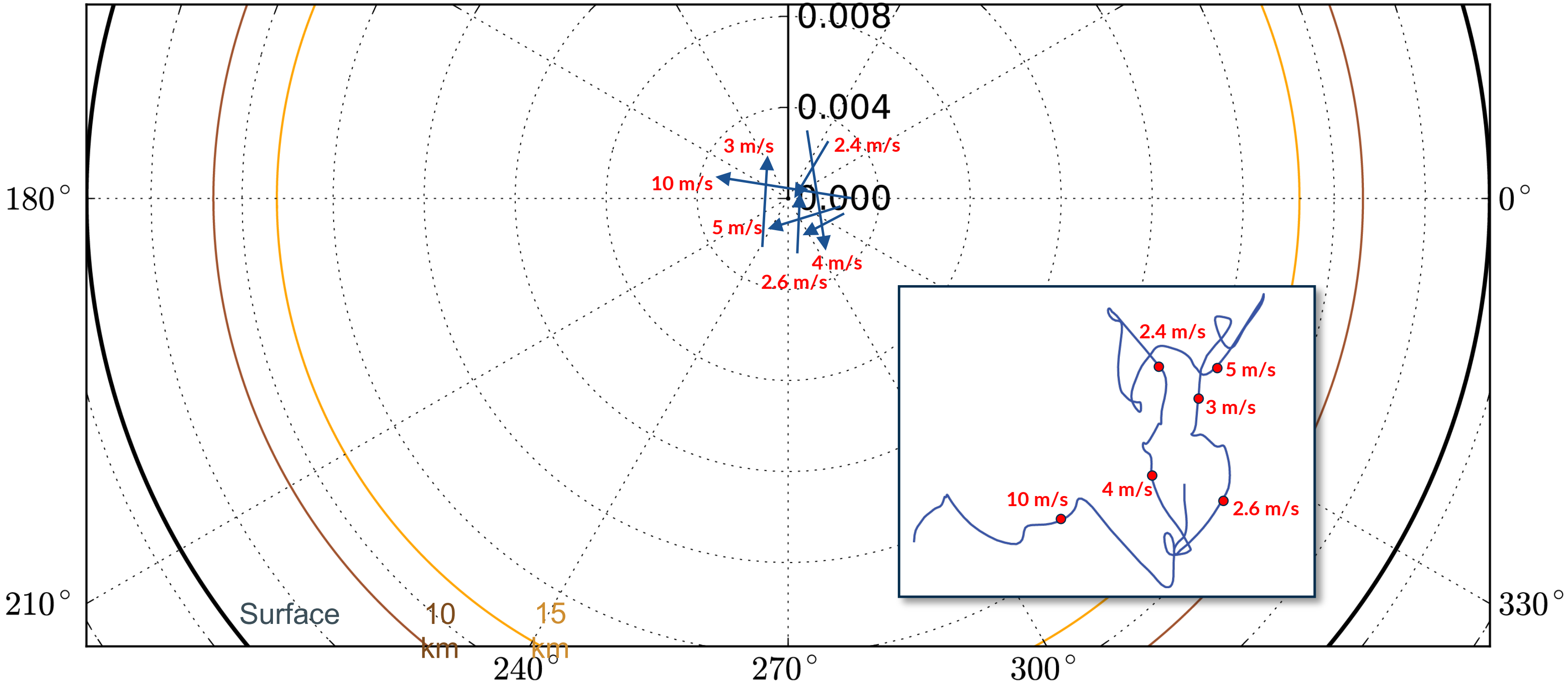
Shown here is 7 hours of motion.

Managing the e-ω Evolution

- Adding Maneuvers
  - To minimize the maximum altitude variation and potentially lower the mean orbit altitude

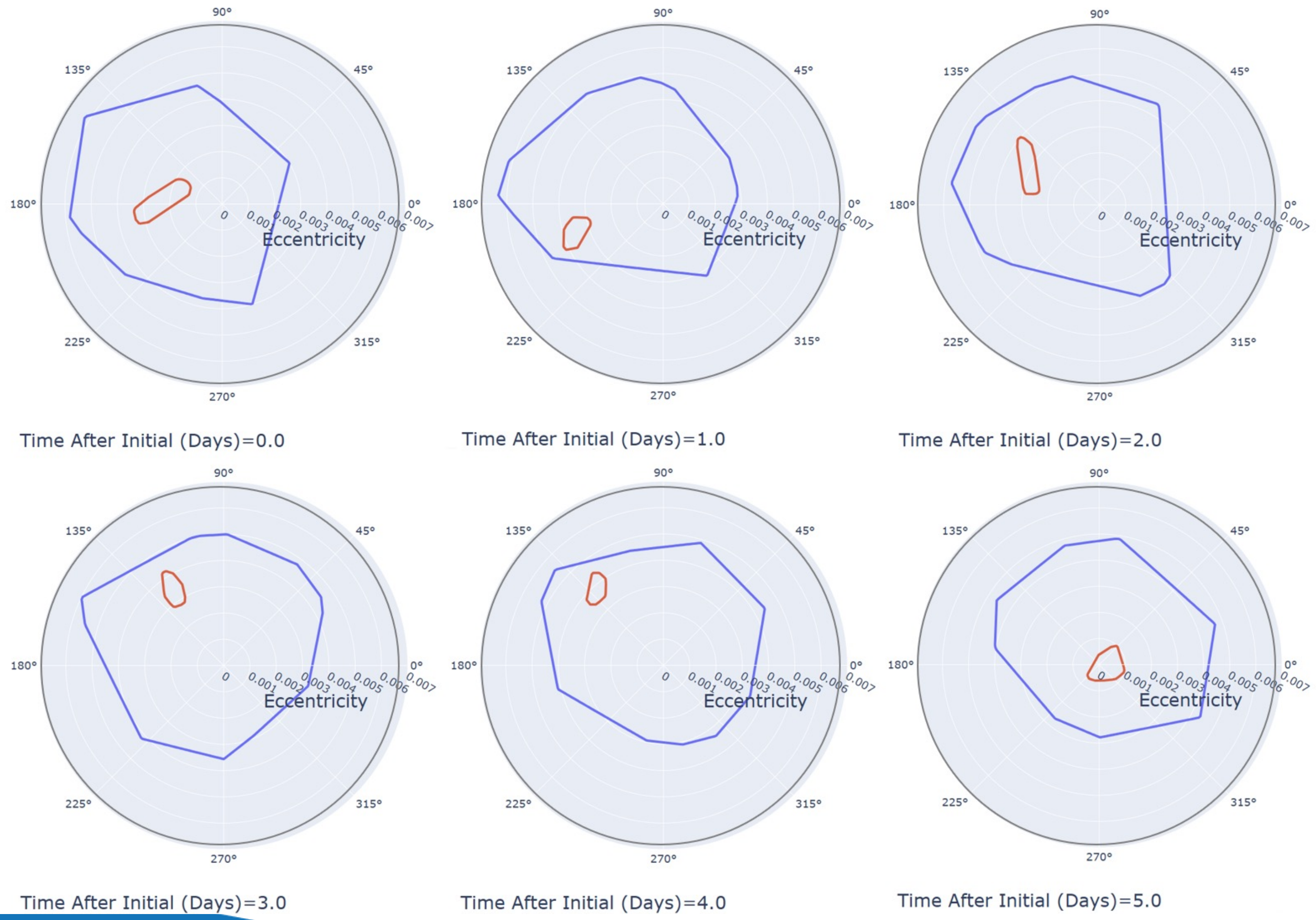
Consider the case of performing a maneuver after each Mapping Cycle (27.3 days)

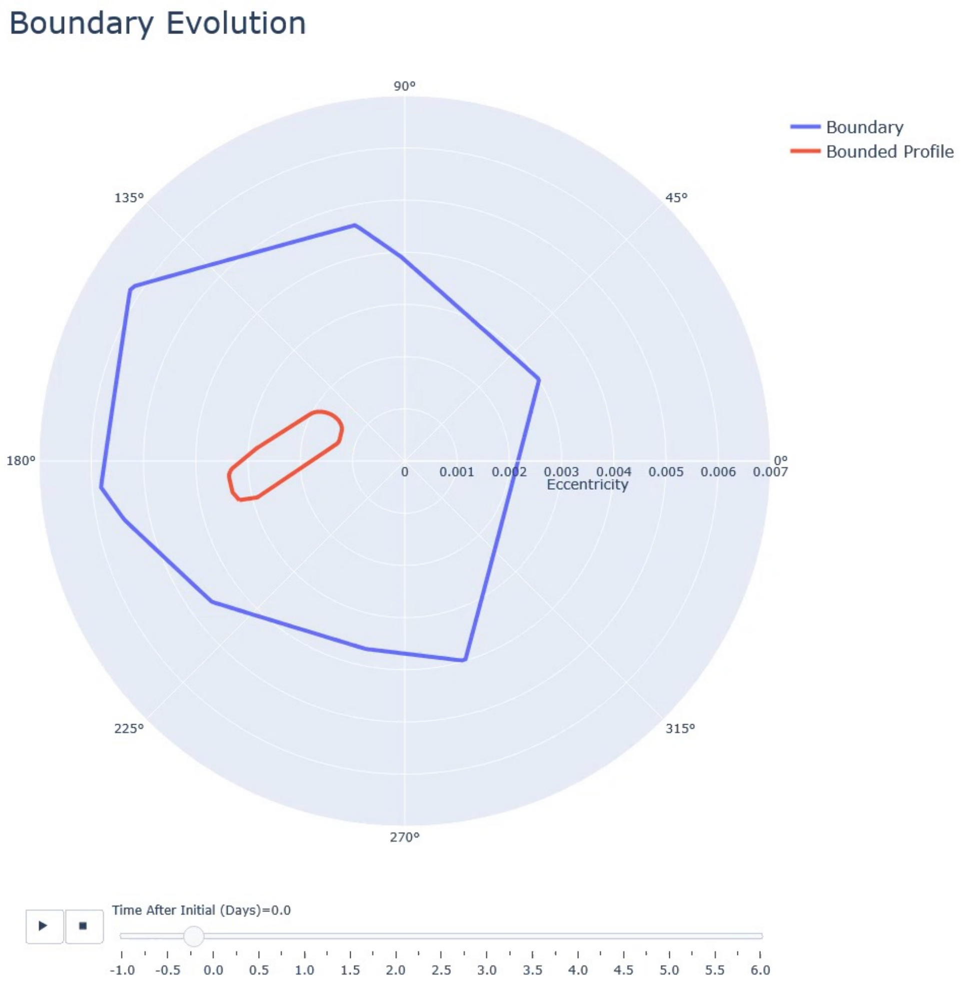
Centering the e-ω evolution minimizes the maximum altitude variation



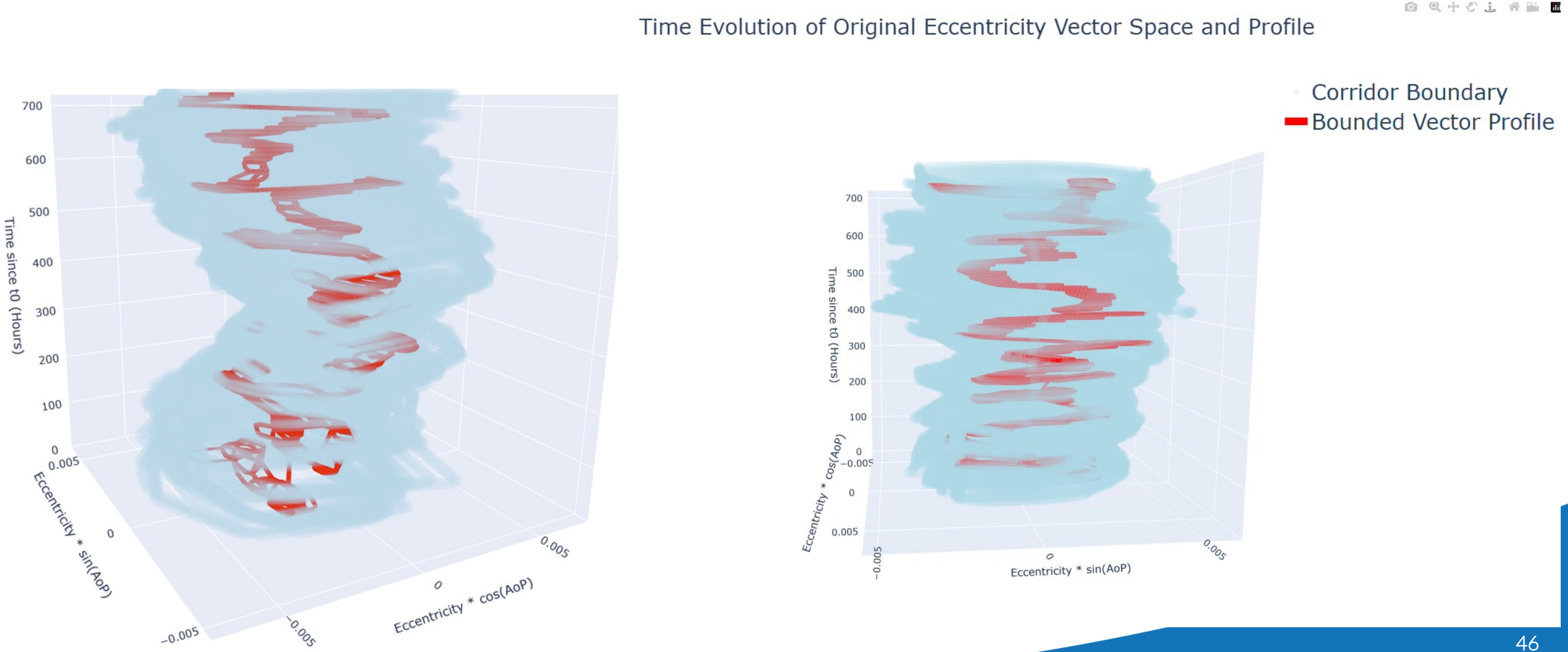
Lunar gravity field = LP150Q (150x150)

Snapshots along a 6-day ballistic arc

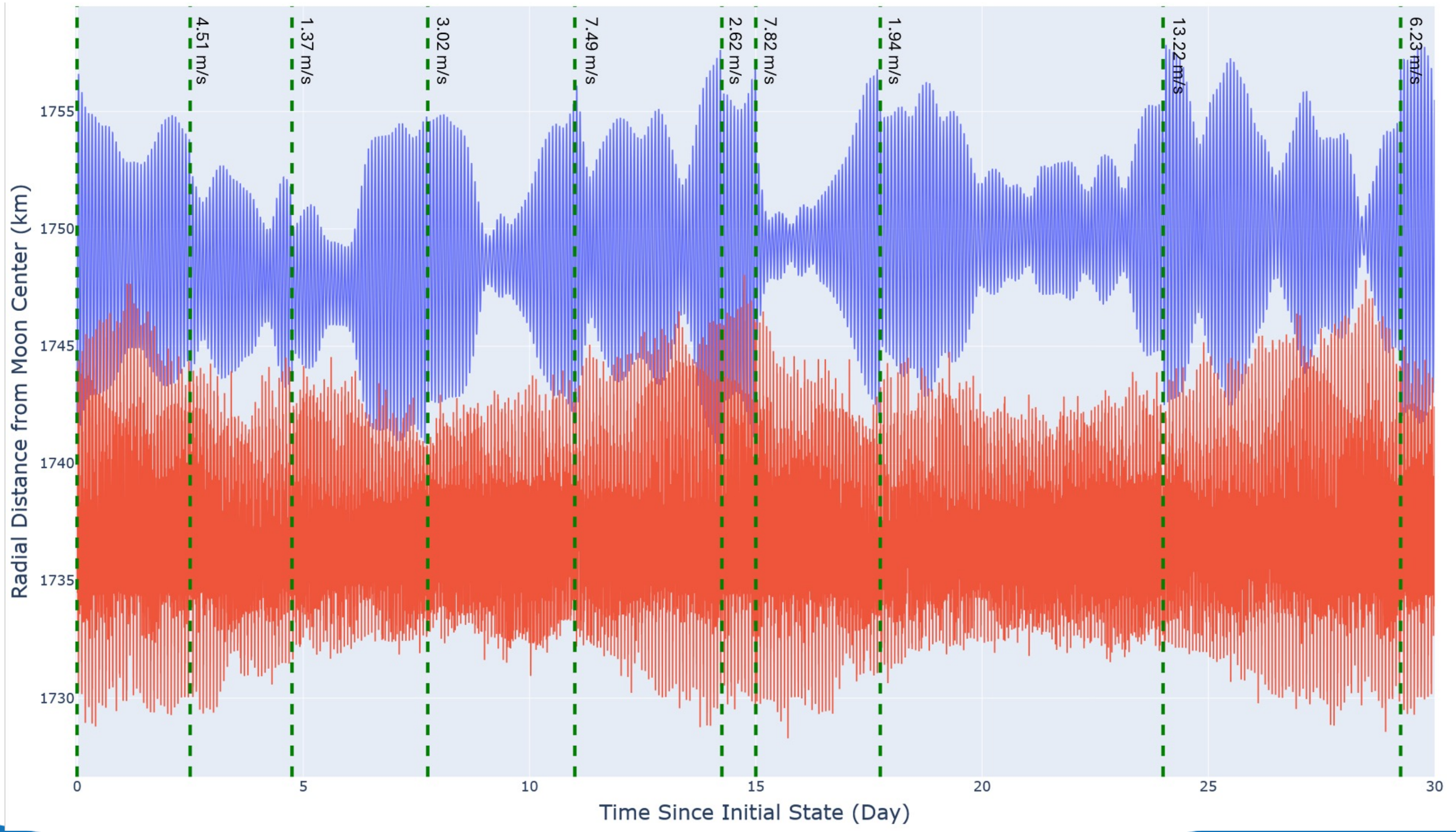




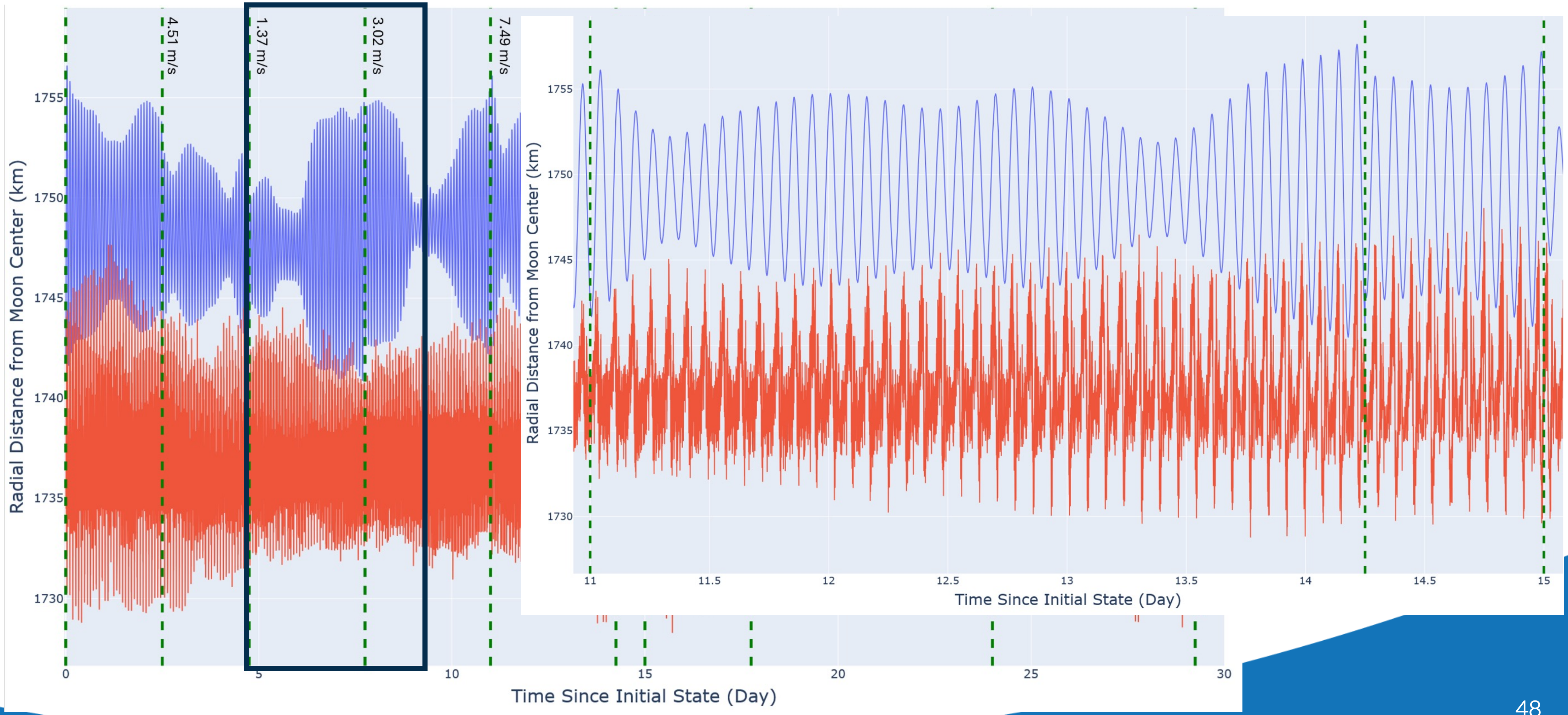
Navigating a SLALOM Corridor



Example SLALOM Profile



Example SLALOM Profile



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 12 months, assuming 2 m/s per day	730.0 m/s	5 km x 10 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	**1831.5 m/s**	

Conclusions

- It is feasible to navigate a Sustained Low-Altitude Lunar Orbit for a month or more for under 2 m/s per day and potentially 1 m/s per day.
- This places maneuvers over the poles *or* over the equator. If there are no constraints then it is strictly easier / lower cost.
- Conventional interplanetary missions have the fuel capacity and often the maneuver execution performance to achieve this.
- Many applications.

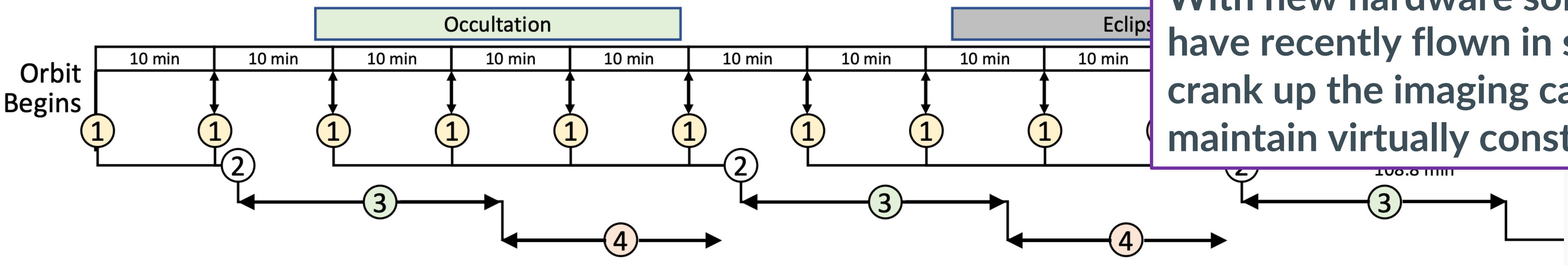
Questions and Additional Information?

Email: parker@advancedspace.com

Thank You!

SLALOM Concept of Operations

SLALOM ConOps: Orbit in the Life



With new hardware solutions that have recently flown in space, we can crank up the imaging cadence to maintain virtually constant custody.

(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.