Low Lunar Orbit Design via Graphical Manipulation of Eccentricity Vector Evolution

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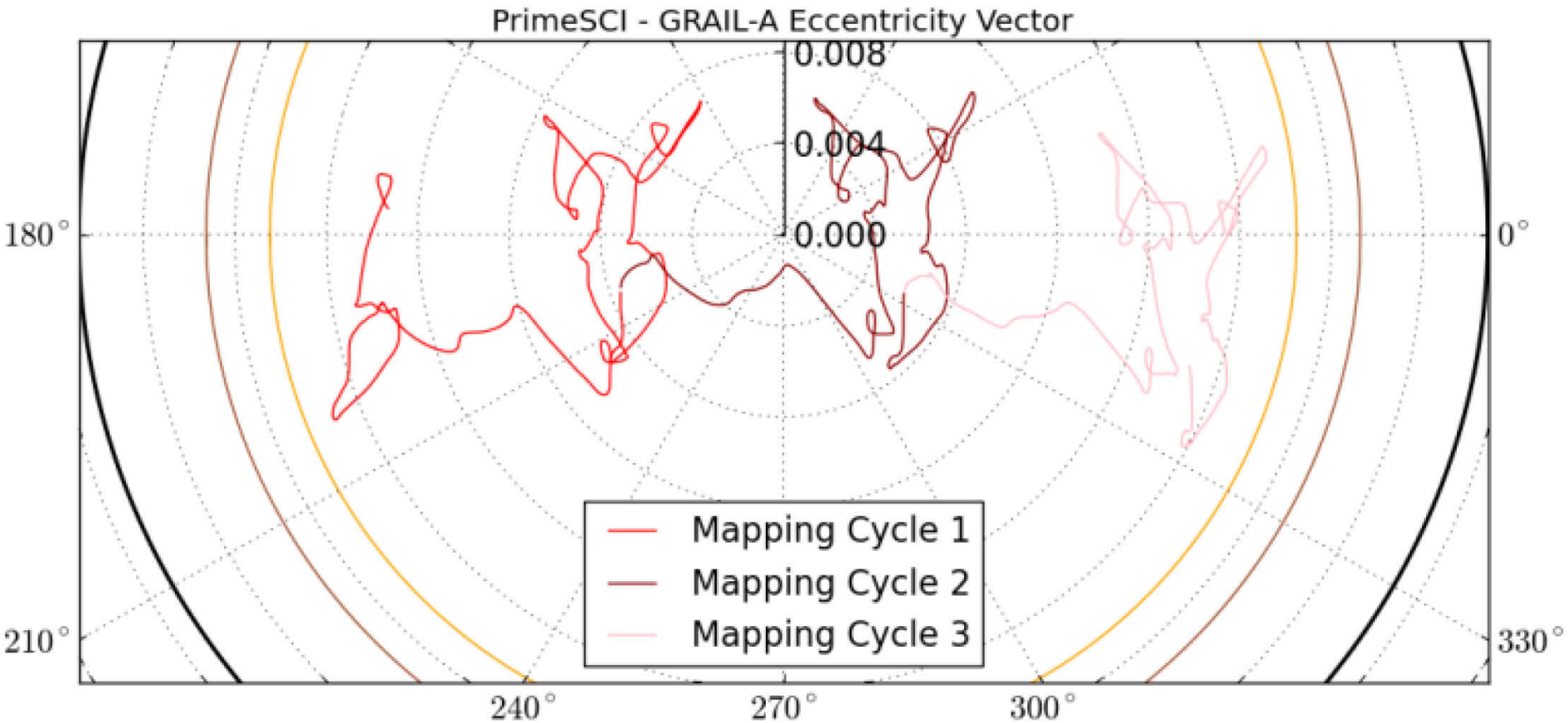
Government sponsorship acknowledged.

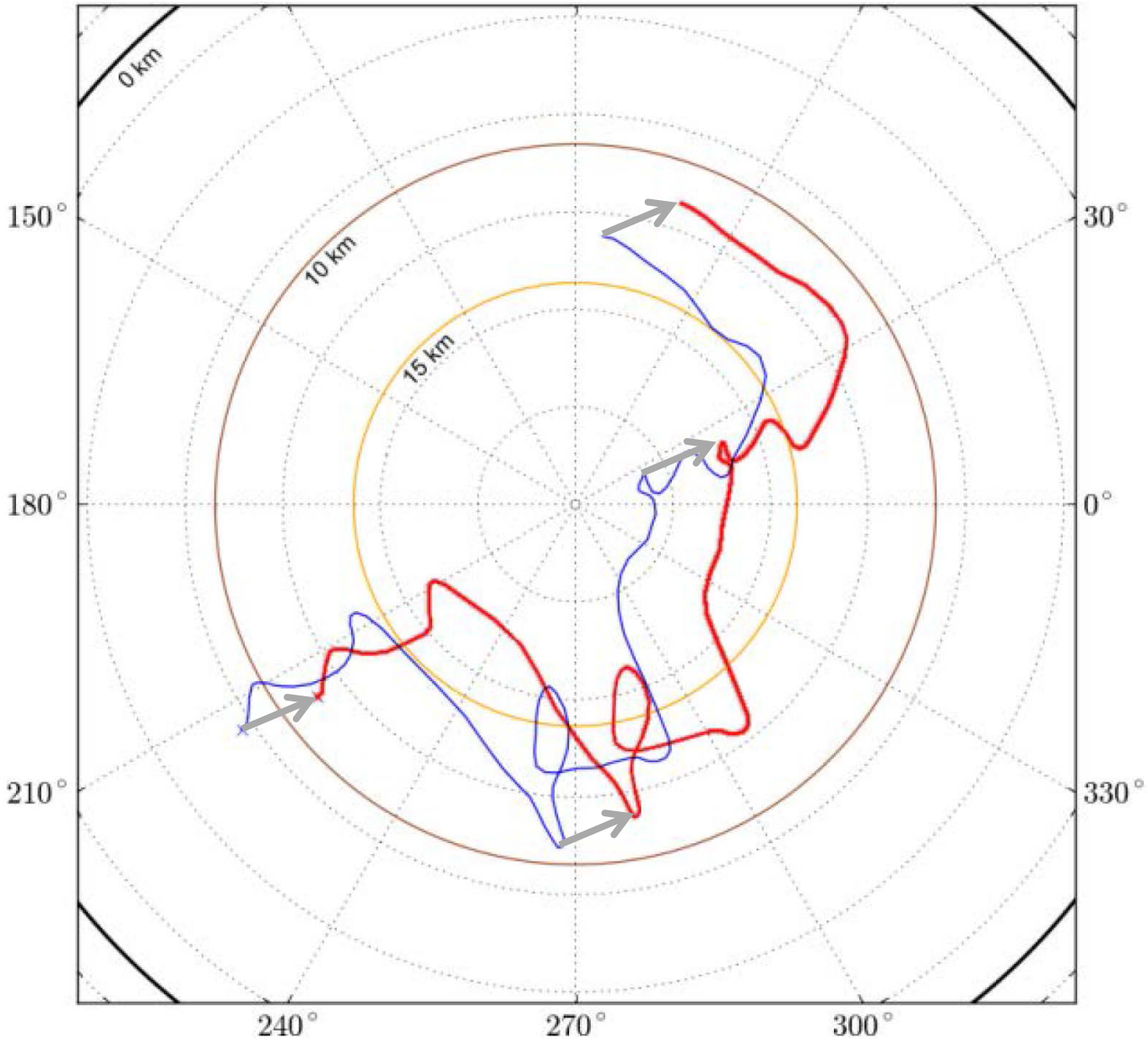
Context



The GRAIL primary science mission orbit experiences three repetitions of its e-ω evolution.

Evolution is Insensitive to Initial Condition

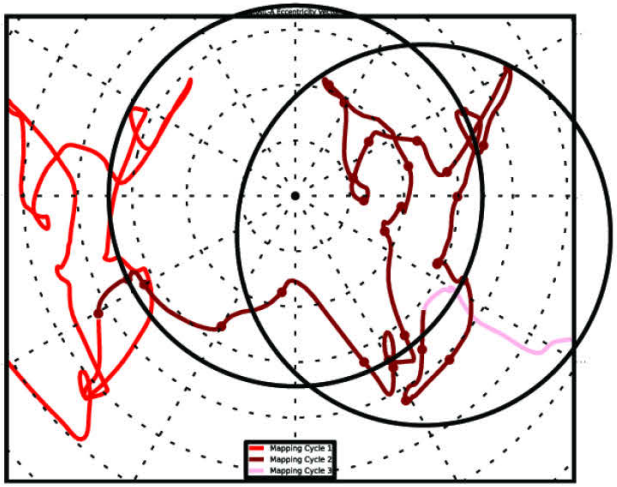
Changes in the initial *e*-ω point (marked with an x) do not change the major structure of the *e*-ω evolution.

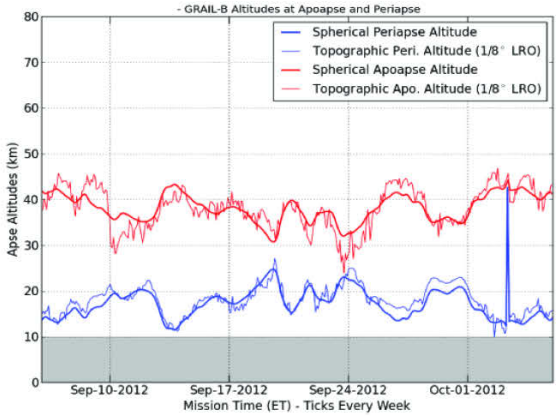


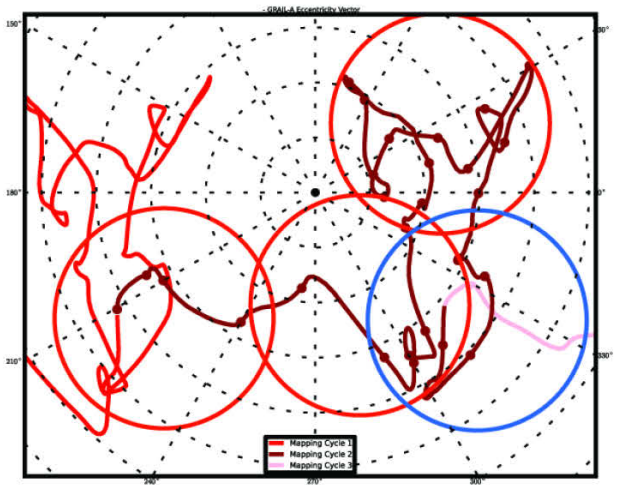
Three Techniques

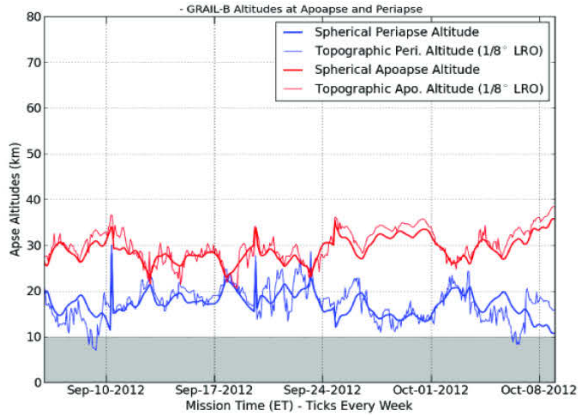
- Lay down circles on a single propagation
  - Trade maneuver frequency vs. maximum eccentricity
  - Purely manual
- Center each "segment"
  - Determine minimum achievable mean altitude and periapse altitude
  - Straightforward numerical process
- Optimize for ΔV given constraints in e-ω space.
  - Highly computational
  - Reduction in run-time by factor of 1000.

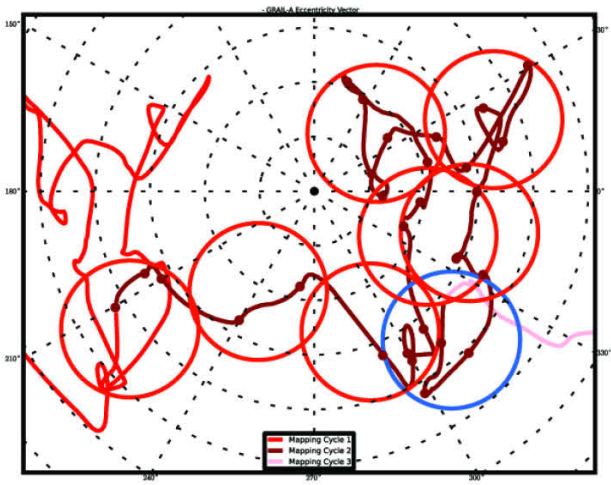
Maneuver Freq. vs. Altitude Variation

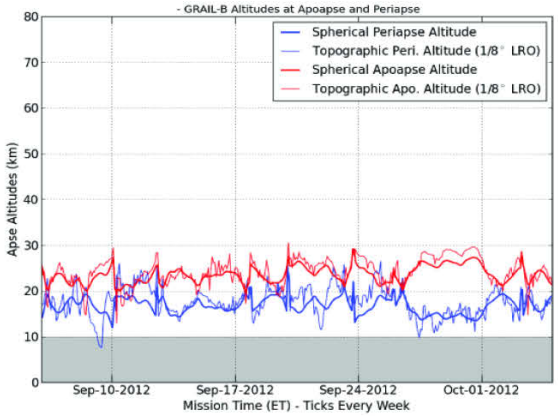




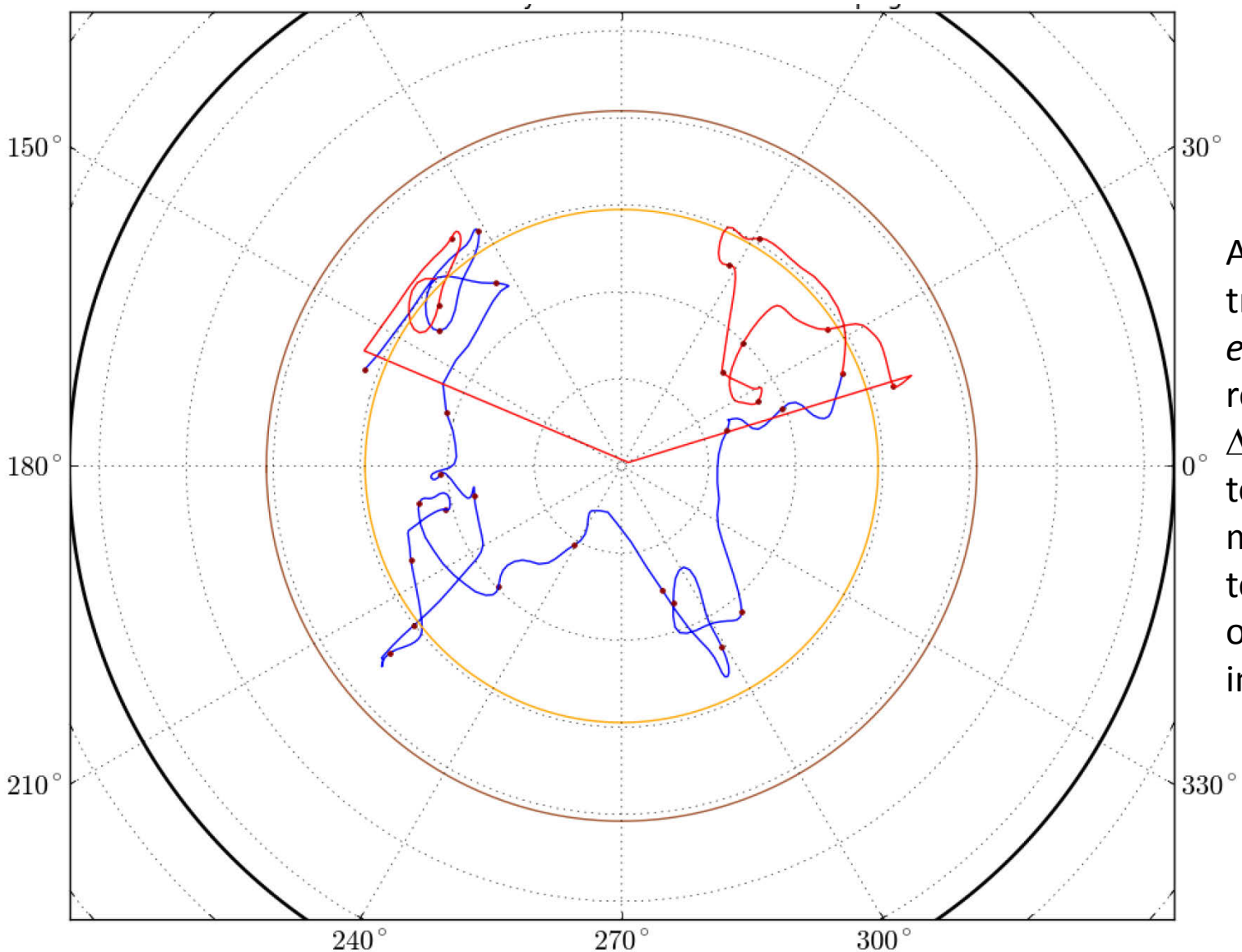








Changing e-ω without changing period



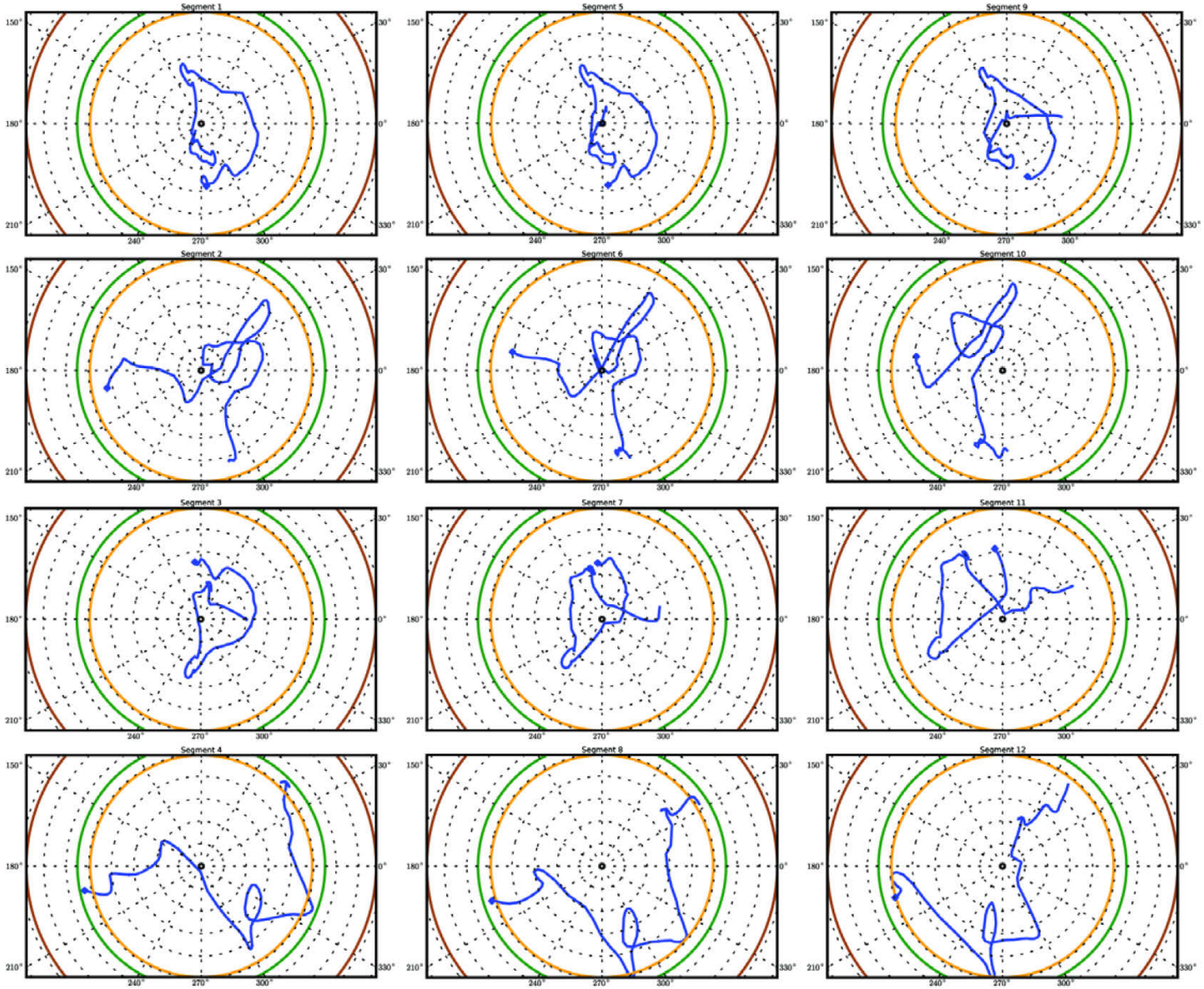
A "Hohmann-like" transfer to shift the *e-ω* evolution can reduce the required ΔV in half relative to a single radial maneuver. The last ten days of this orbit evolution are in red

Centering Each Segment

- Choose initial a, e, ω and propagate a segment
- Determine minimum circumscribing eccentricity circle.
  - Center determined numerically by minimizing the maximum distance from the center of a circle to each e-ω point within the segment
  - Used centroid as initial guess
- Shift e-ω to place the center of the circle at the center of e-ω space.
- Iterate until the shift is small.

Iteration	Eccentricity	Argument of Periapse	Shift
1	7.917e-03	135.0	
2	2.798e-03	277.6	1.028e-02
3	2.782e-03	284.3	3.269e-04
4	2.709e-03	284.7	7.523e-05

Result

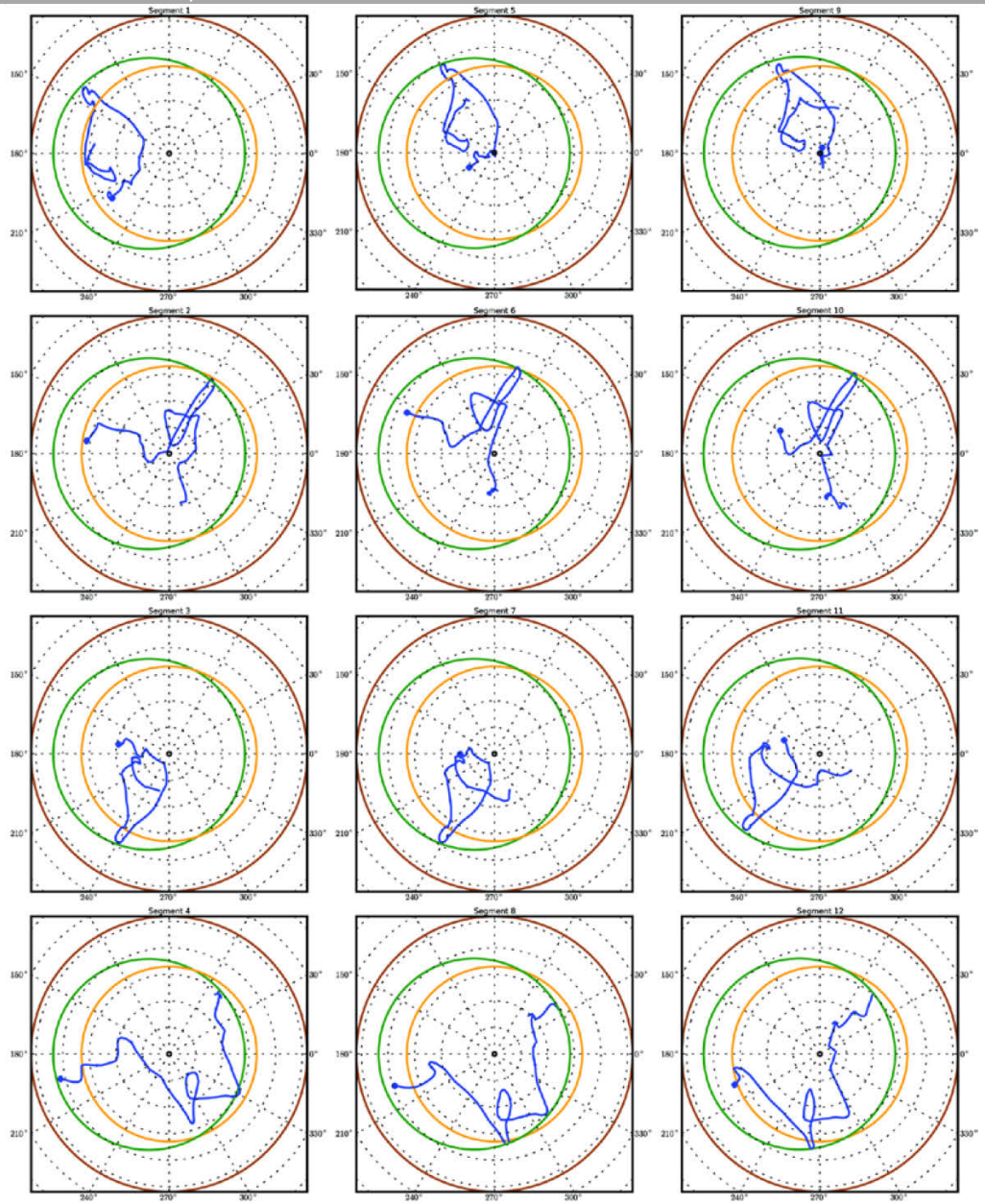

Segment 1
Segment 2
Segment 3
Segment 4
Segment 5
Segment 6
Segment 7
Segment 8
Segment 9
Segment 10
Segment 11
Segment 12
150°
30°
180°
0°
210°
330°
240°
270°
300°

Optimizing ΔV Required

- Can shift some segments to reduce ΔV while maintaining the same maximum eccentricity over the mission.
- Method:
  - Cost is the scaled change of eccentricity vector across maneuvers.
  - Constrain segments to be within a designated circle in e-ω space.
  - Solve the sub-problem and re-propagate with new e-ω targets until change in cost is small.
- Take advantage of the near-invariability of the evolution to reduce the run-time to optimize by a factor of 1000.
  - 18 hours vs. 17,430 hours

Major Iteration	Optimizer Iterations	Cost	Change in Cost	Change in Cost (%)
0	N/A	135.6		
1	8779	97.1	38.5	28.4%
2	3905	93.2	3.9	4.0%
3	4739	91.2	2.0	2.1%
4	7612	92.7	-1.5	-1.6%
5	5735	91.7	1.0	1.0%
6	4862	89.6	2.2	2.4%
7	4244	93.0	-3.5	-3.9%
8	7304	91.1	2.0	2.1%
9	5302	91.3	-0.2	-0.3%

Result


Segment 1
Segment 5
Segment 9
Segment 2
Segment 6
Segment 10
Segment 3
Segment 7
Segment 11
Segment 4
Segment 8
Segment 12

Conclusions

- These were not the only techniques we used to design the GRAIL Extended Mission.
  - They do not consider topographic altitude or missed maneuver constraints
  - But they did offer a good starting point for manual adjustments.
- Final design was within 8 m/s of the optimized design from this paper.

Any Questions?