Orbit Design and Analysis Challenges in Cislunar Space Caused by Lunisolar Perturbations

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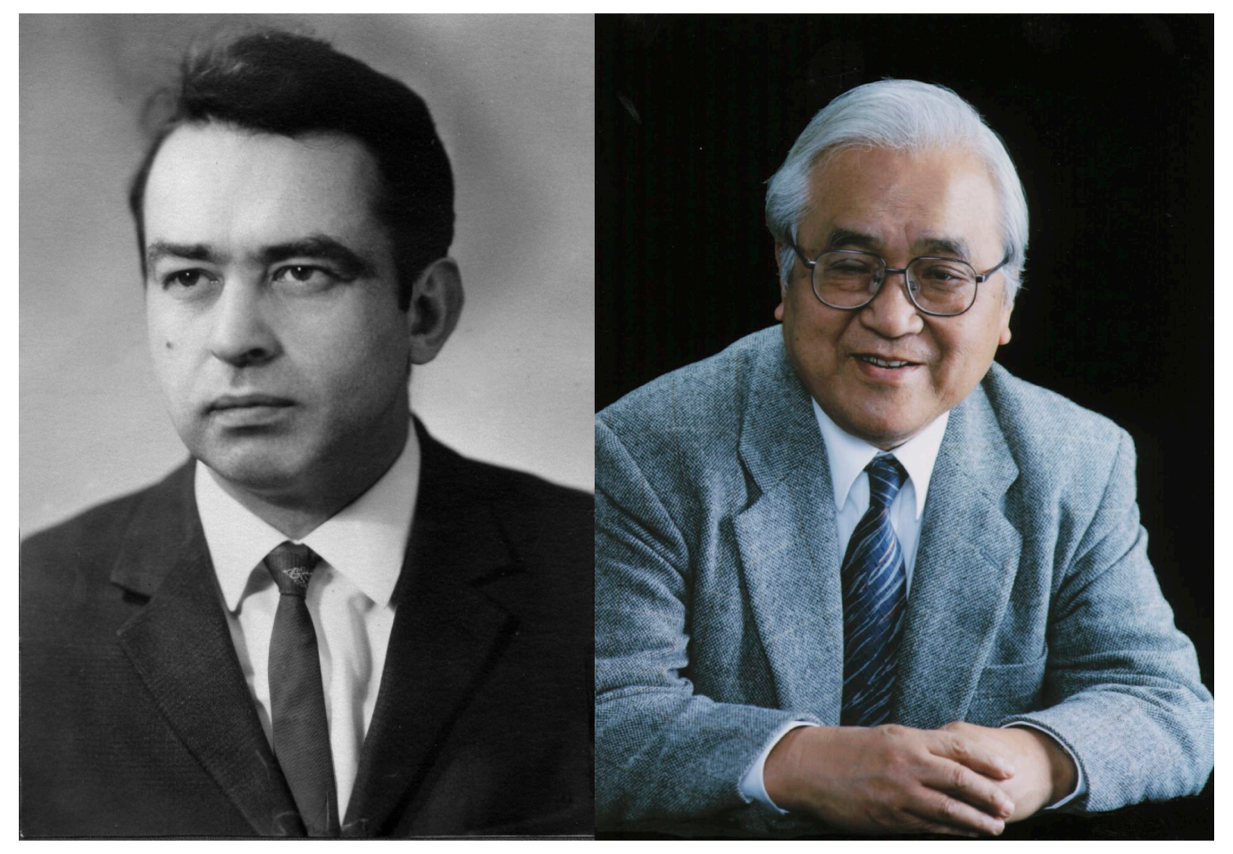
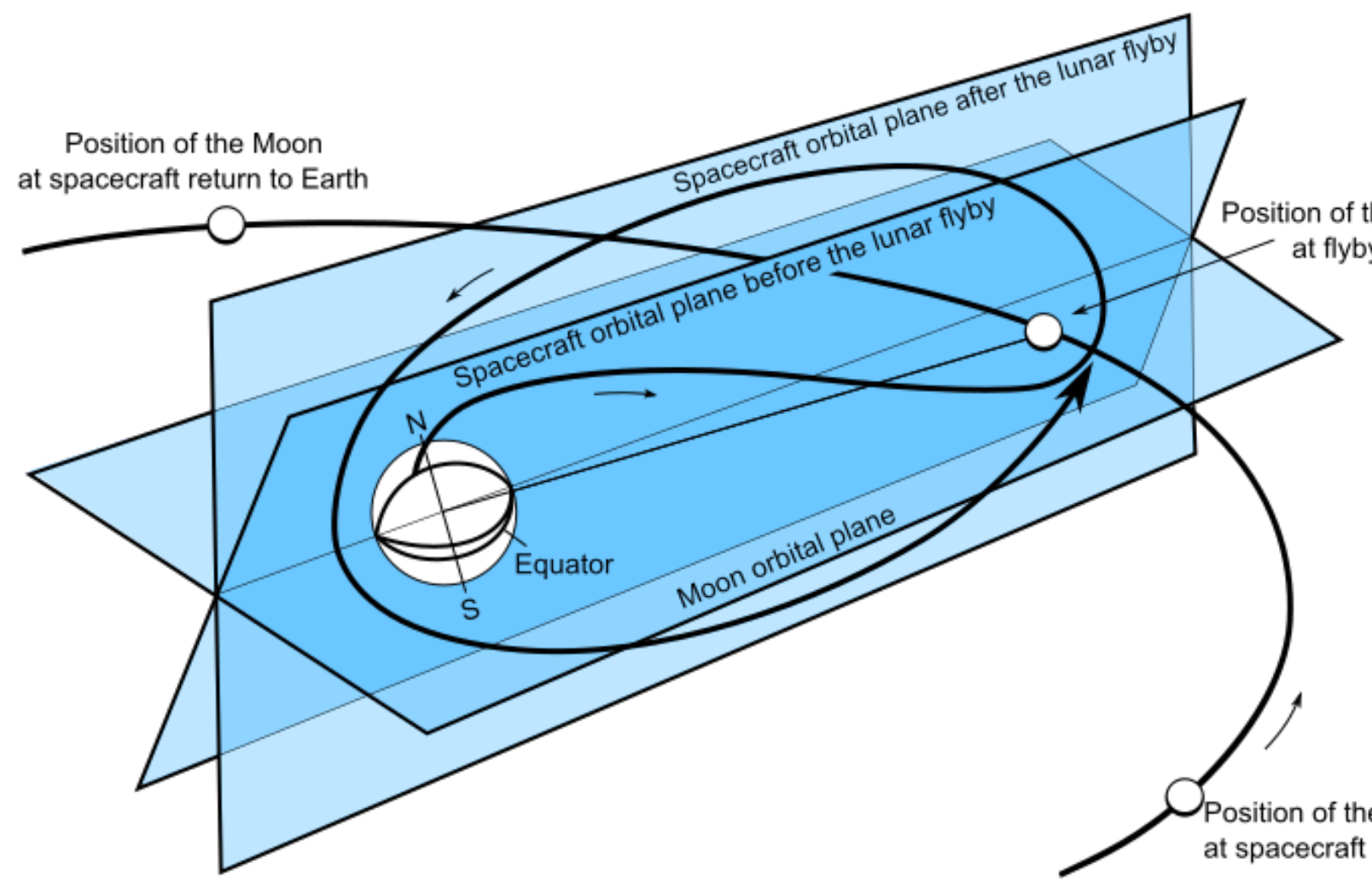
Background

Lunisolar perturbations from both the Moon and Sun can cause complicated long-term orbital behavior in the cislunar regime. The third body effects which perturb a satellite's orbit can be described by the **Lidov-Kozai (L-K) Mechanism**.

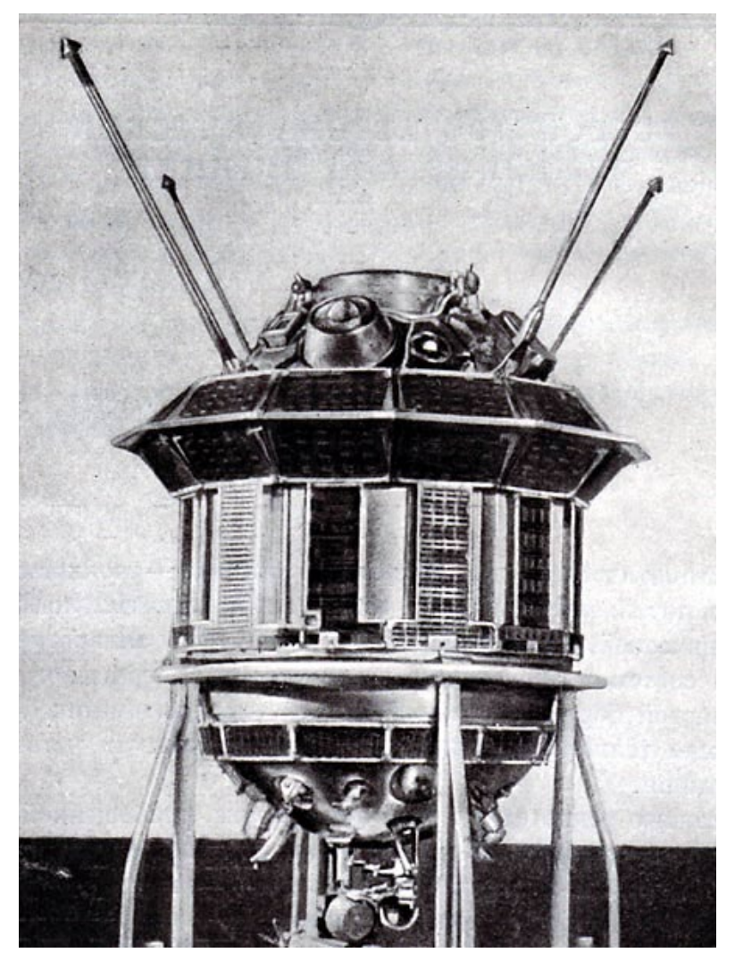


Mikhail Lidov (left) and Yoshihide Kozai (right)

Russian flight dynamicist Mikhail Lidov published results in 1961 from his analysis of the Luna 3 mission, which re-entered 6 months after launch due to lunisolar effects. Japanese astronomer Yoshihide Kozai studied similar effects on asteroid orbits.



Lunar Effects on Luna 3 Orbit Plane



Luna 3 Spacecraft

More recently, the L-K Mechanism has proved useful in the study of exoplanetary systems and cislunar dynamics. The L-K effects can be such that the orbit of one planet can be affected significantly by the gravitational attraction of the others, to the extent of being "flipped" to become retrograde [1].

Motivation

This work examines the conditions under which the L-K model applies well, and when it does not. Several classes of cislunar orbits were studied: NASA Magnetospheric Multiscale Mission (MMS), Astrobotic's Peregrine lander, ISRO Chandrayaan-3 Propulsion Module (CH3PM), Lunar Resonance (1:2 and 1:3 resonance), and nearly polar orbits.

For each orbit class, the behavior with different semi-major axes (SMA) has been examined, to see at what geometry the L-K dynamics break down. **The goal of this study is to find the upper limit of SMA.**

Methodology

Double-averaging of the circular restricted three-body problem (CR3BP) provides three constants of motion to describe L-K dynamics:

- Semi-major axis (SMA): c_0
- Component of orbital angular momentum normal to the Ecliptic: c_1

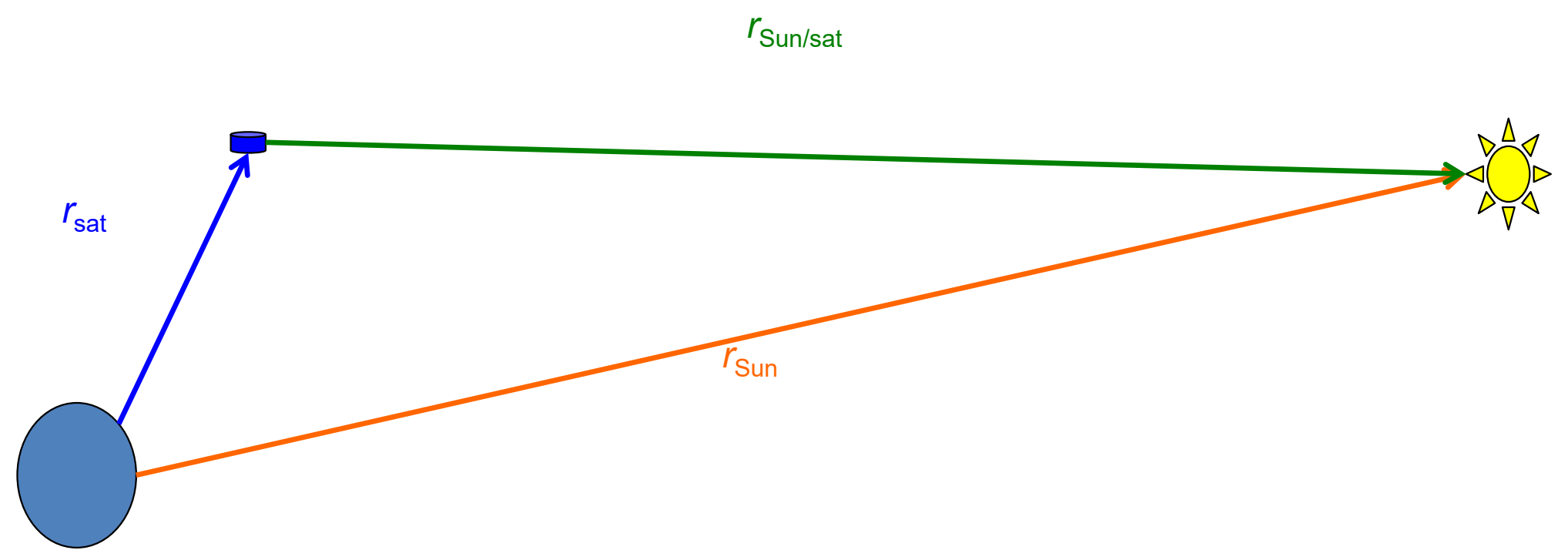
$$\mathbf{c_1 = (1 - e^2)\cos^2 i_{ecl}}$$

- L-K Hamiltonian: c_2

$$\mathbf{c_2 = e^2\left\{\frac{2}{5} - \sin^2 i_{ecl}\sin^2\omega_{ecl}\right\}}$$

The c_1 constant implies that eccentricity (and hence perigee radius) and ecliptic inclination must evolve together. Additionally, the orbital plane is a key quantity of L-K theory. The ecliptic plane will serve as the approximate orbital plane for both Sun and Moon since their orbits are nearly coplanar.

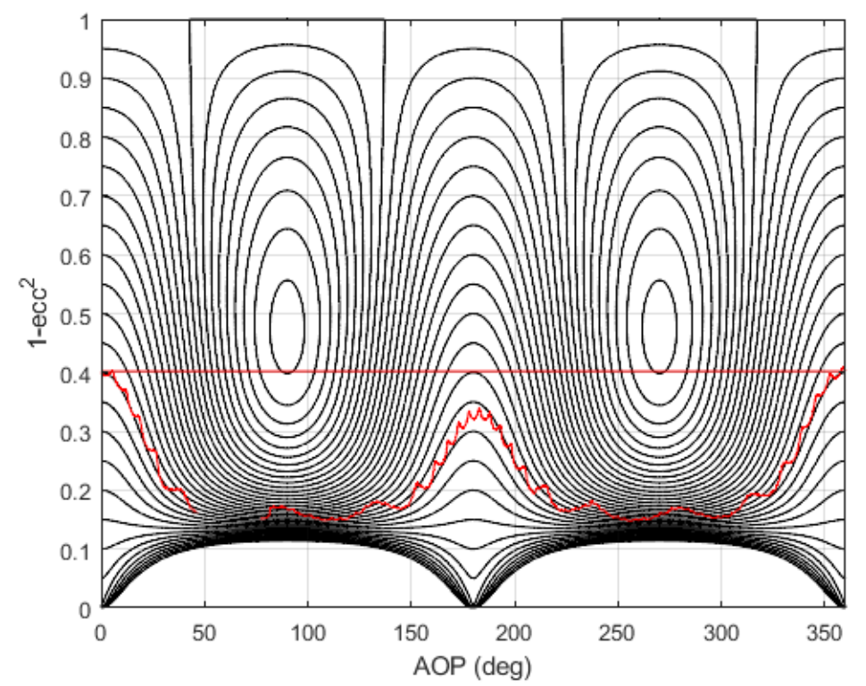
Contour plots were utilized [2] to show the secular (10 years or longer) effects of the eccentricity and argument of perigee (AoP) for initial conditions of c_1 and SMA. **If the orbit lies along one of the contours, the behavior can be explain by the L-K Mechanism.**



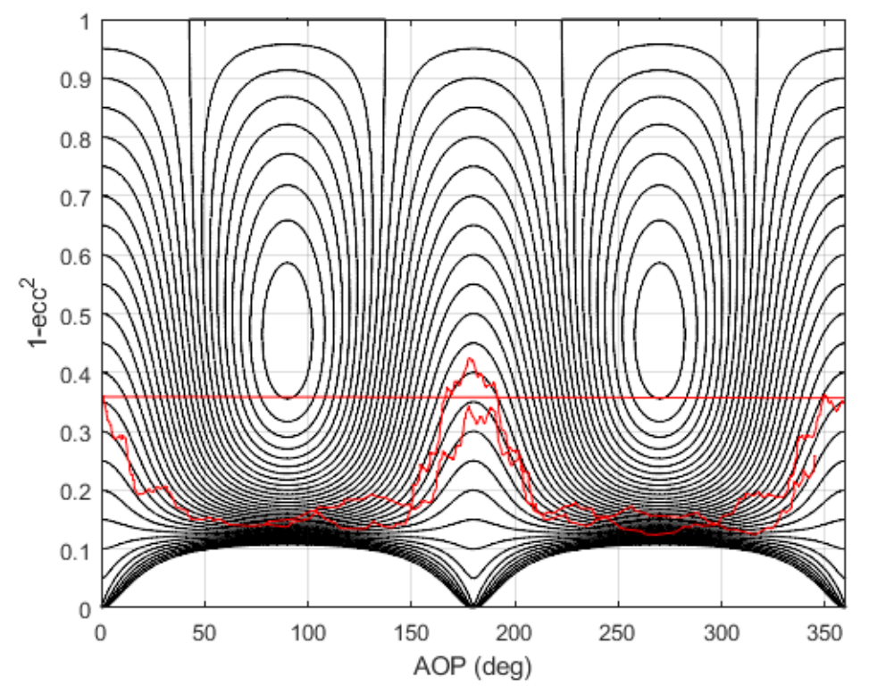
Earth, Sun/Moon, Spacecraft Geometry

Case Studies

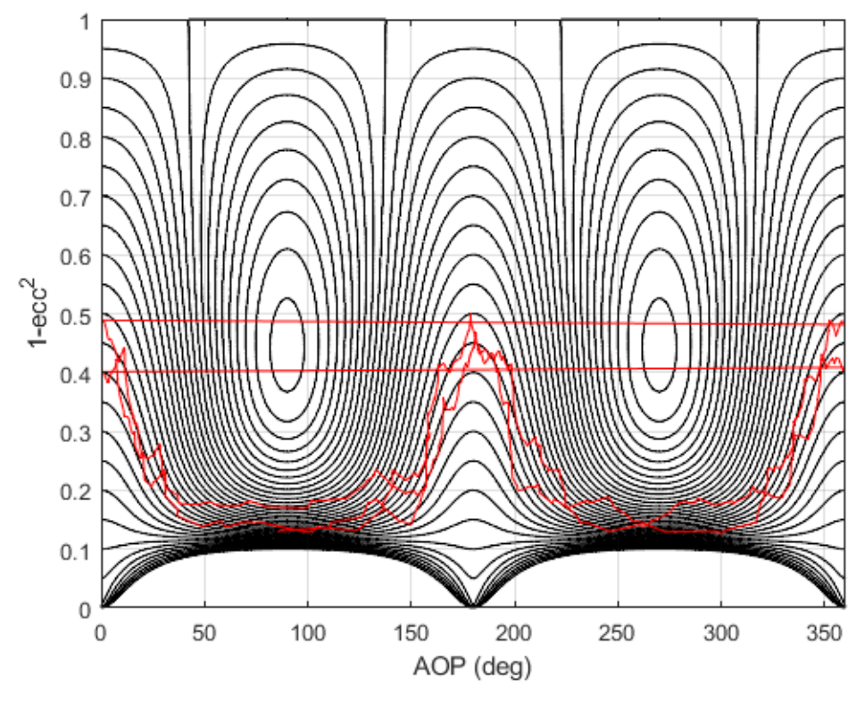
(1) MMS



Current orbit: 15.2RE SMA, 29.3RE apogee radius*

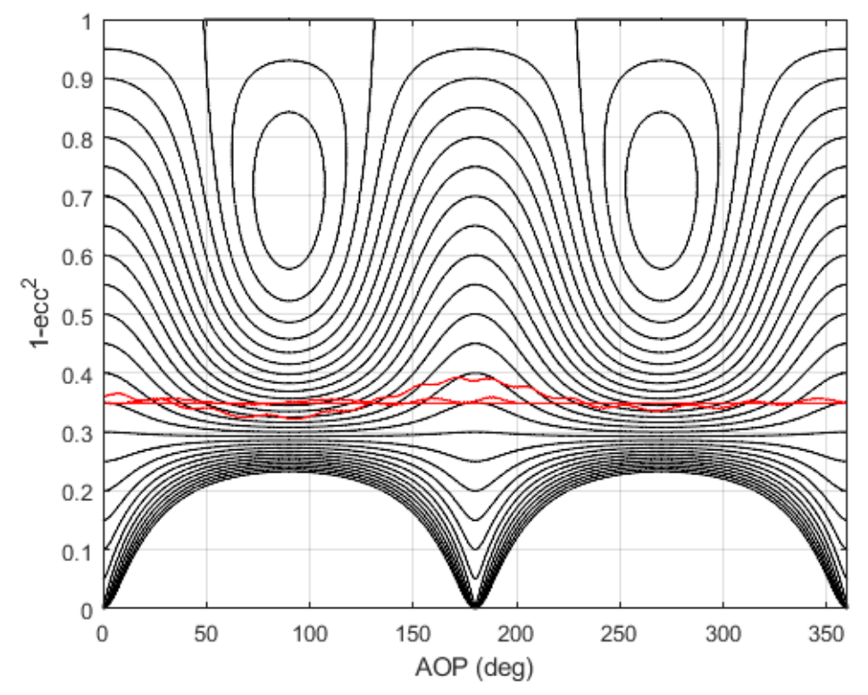


22RE SMA, 42.24RE apogee radius

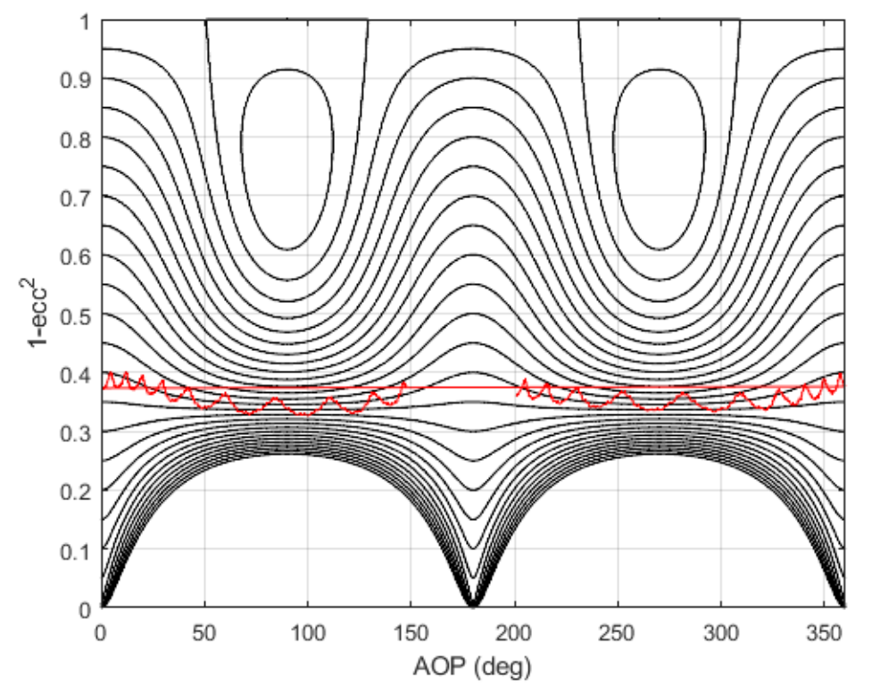


25RE SMA, 48RE apogee radius

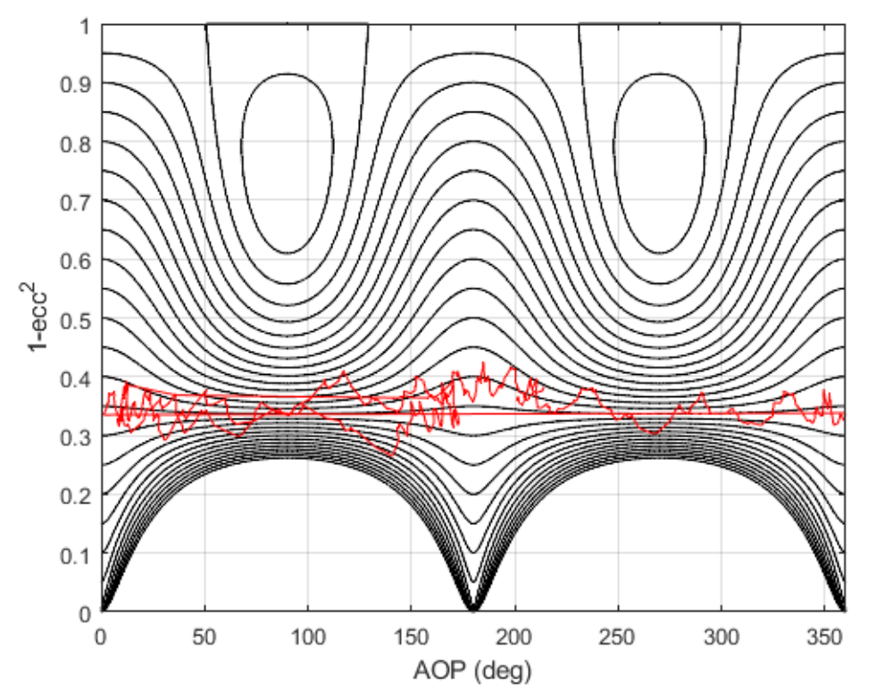
(2) Peregrine



7RE SMA, 12.6E apogee radius

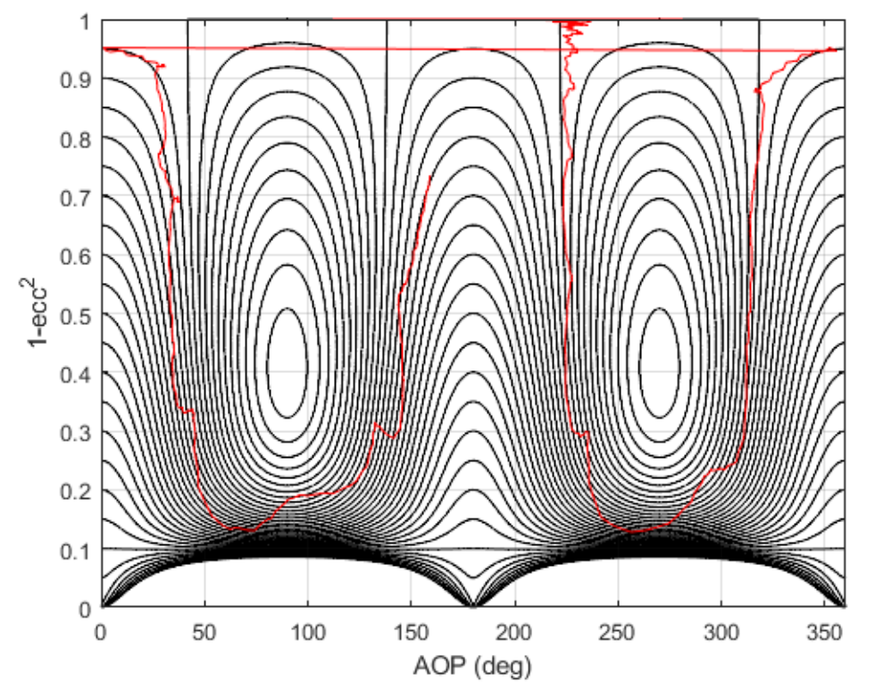


15.7RE SMA, 28.2E apogee radius

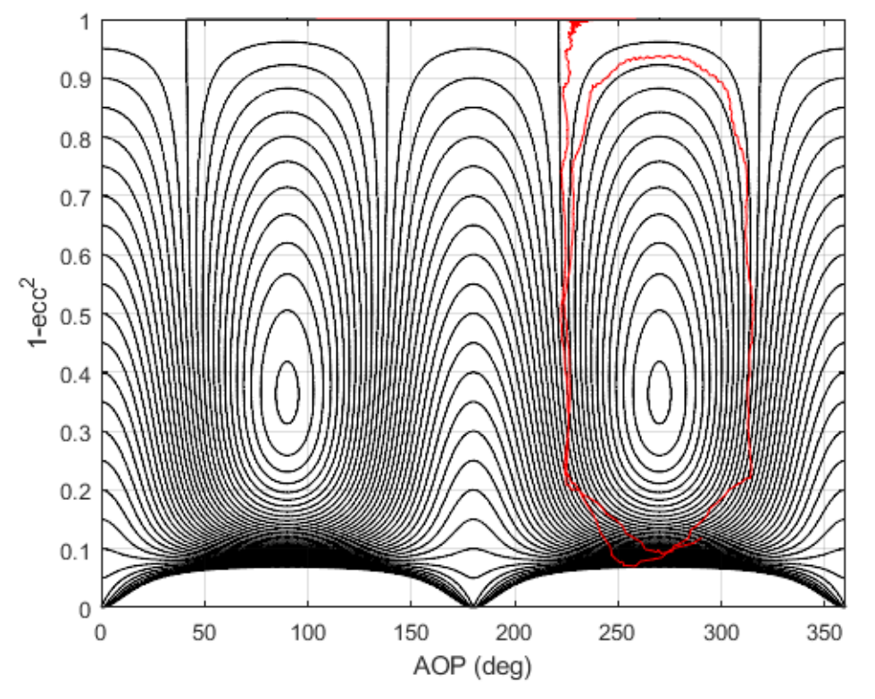


25RE SMA, 48RE apogee radius

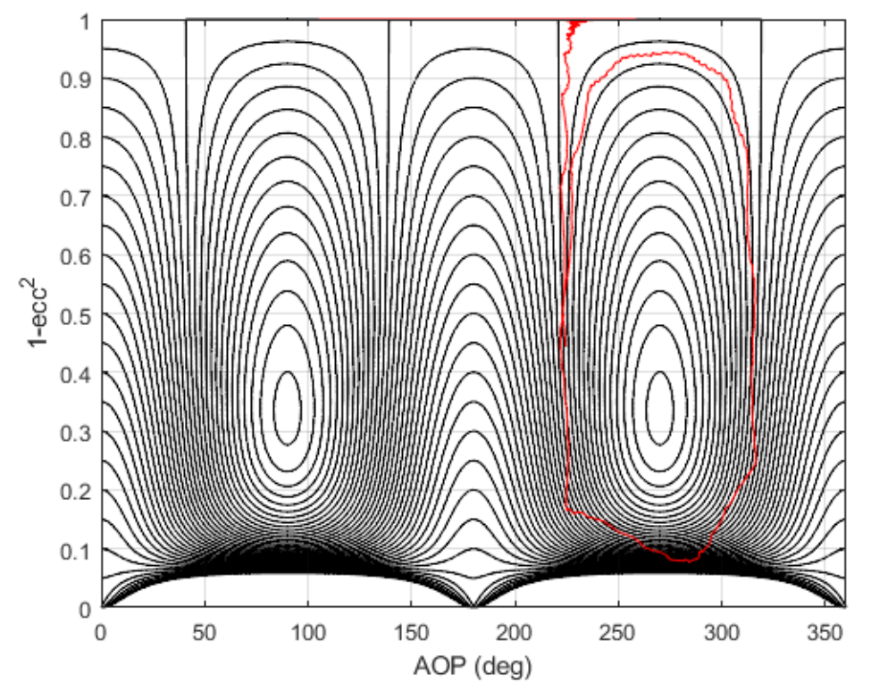
(3) Near-Polar



30RE SMA, Ecliptic Inclination: 71.805 deg

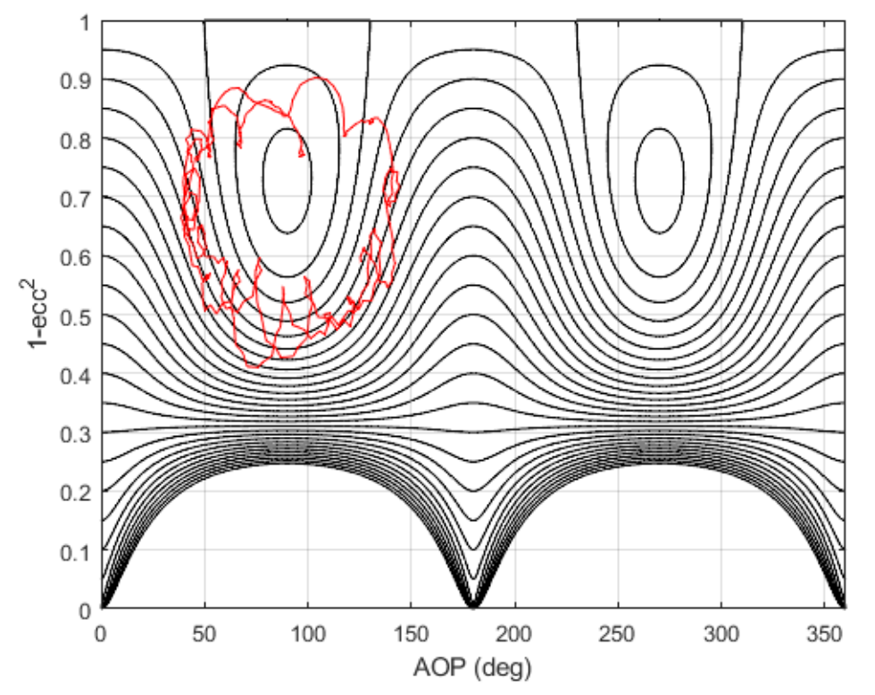


30RE SMA, Ecliptic Inclination: 106.26 deg

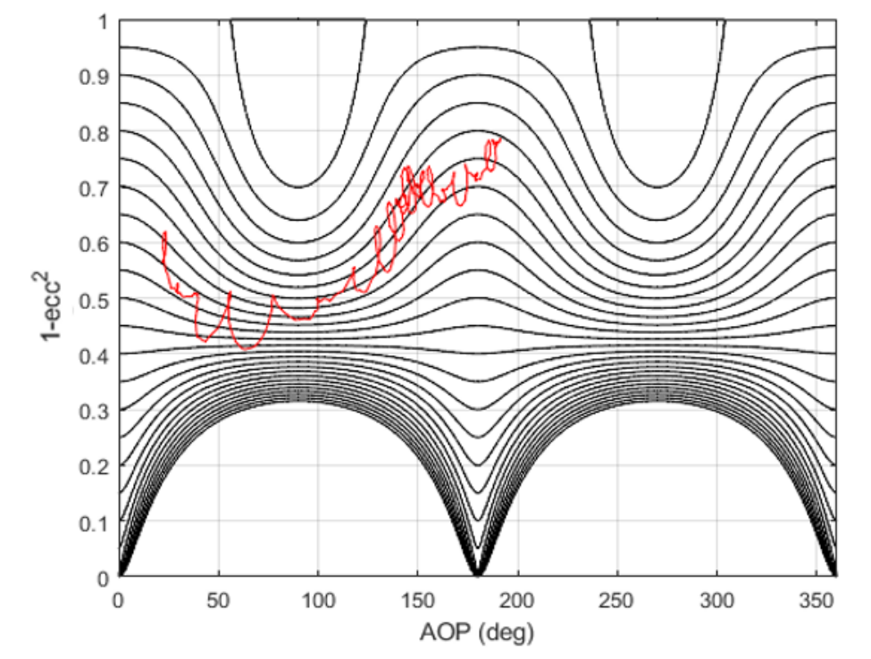


30RE SMA, Ecliptic Inclination: 104.951 deg

(4) Lunar Resonance



TESS (1:2): 38.89RE SMA, 53.32RE apogee radius



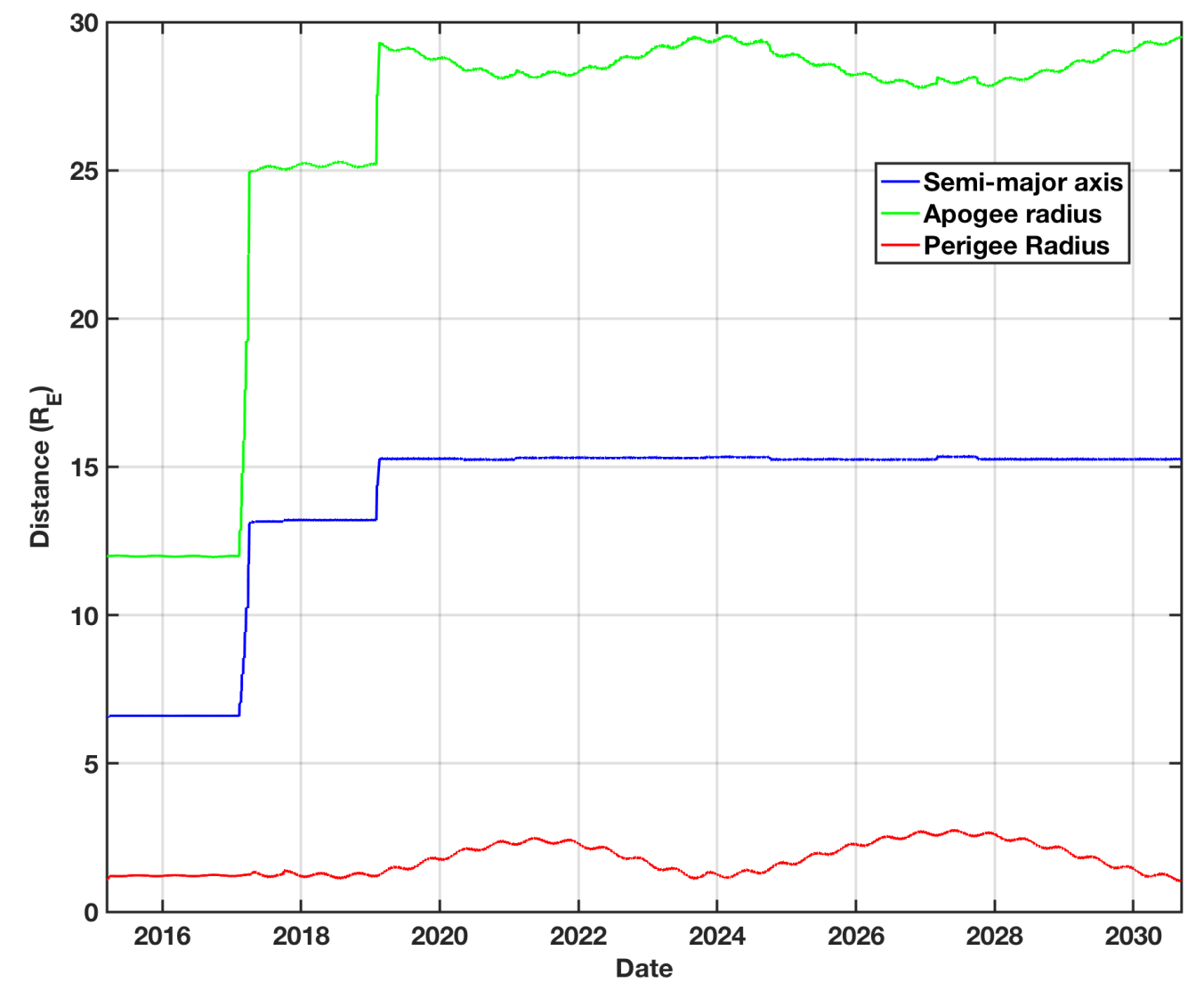
IBEX (1:3): 28.4RE SMA, 47.14RE apogee radius

Region of L-K validity was concluded to be approximately **15-22RE SMA**

**RE = 6378 km*

Discussion

As mentioned, the L-K model holds well within a region of 15-22RE SMA. Above 25RE SMA, the L-K model begins to break down as increasingly chaotic behavior is observed.



Lunisolar Effects on MMS Orbit after Apogee Raises [1]

Below Earth's Laplace Radius (8.41RE SMA), two-body effects are dominant. This can be seen in the first Peregrine plot where the SMA is 7RE.

For lunar resonance orbits, both cases are outside of the L-K validity region and the dynamics cannot be explained by the L-K model.

For the near-polar cases, despite a high SMA the orbits appear to follow the L-K model. It was discovered that inclination is another factor in predicting L-K behavior.

Conclusion

The L-K Mechanism explains the large coupled variations in eccentricity and inclination due to the presence of a third body. Over a long period, these effects can cause complex orbit behaviors.

Through analyzing several orbit classes, it was concluded that the L-K validity region occurs between 15-22RE. However, further investigation is necessary to study the effects of inclination on L-K behavior.

References

[1] Williams, T., Palmer, E., Hollister, J., Godine, D., Ottenstein, N., and Burns, R. "Lunisolar Perturbations of High-Eccentricity Orbits Such as the Magnetospheric Multiscale Mission," AAS Paper 19-914, 2019

[2] Shevchenko, I. *The Lidov-Kozai Effect – Applications in Exoplanet Research and Dynamical Astronomy.* Springer, 2017. Available at: https://link.springer.com/book/10.1007/978-3-319-43522-0. Accessed December 04, 2024