

HELIO SWARM

THE NATURE OF TURBULENCE IN SPACE PLASMAS

Eclipse Mitigation Strategies in P/2 Lunar Resonant Orbits

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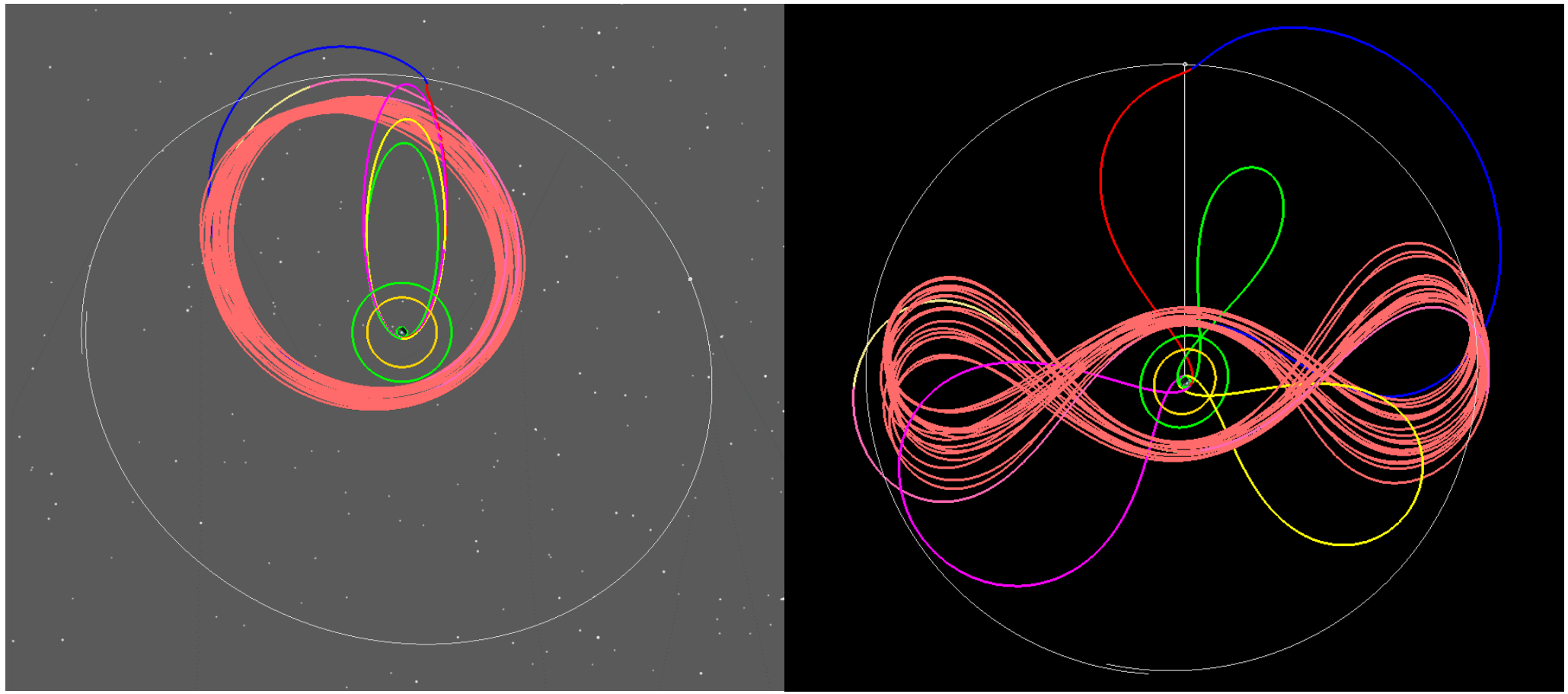
2021 AAS/AIAA Astrodynamics Specialist Conference

Virtual, 9-12 August 2021

Outline

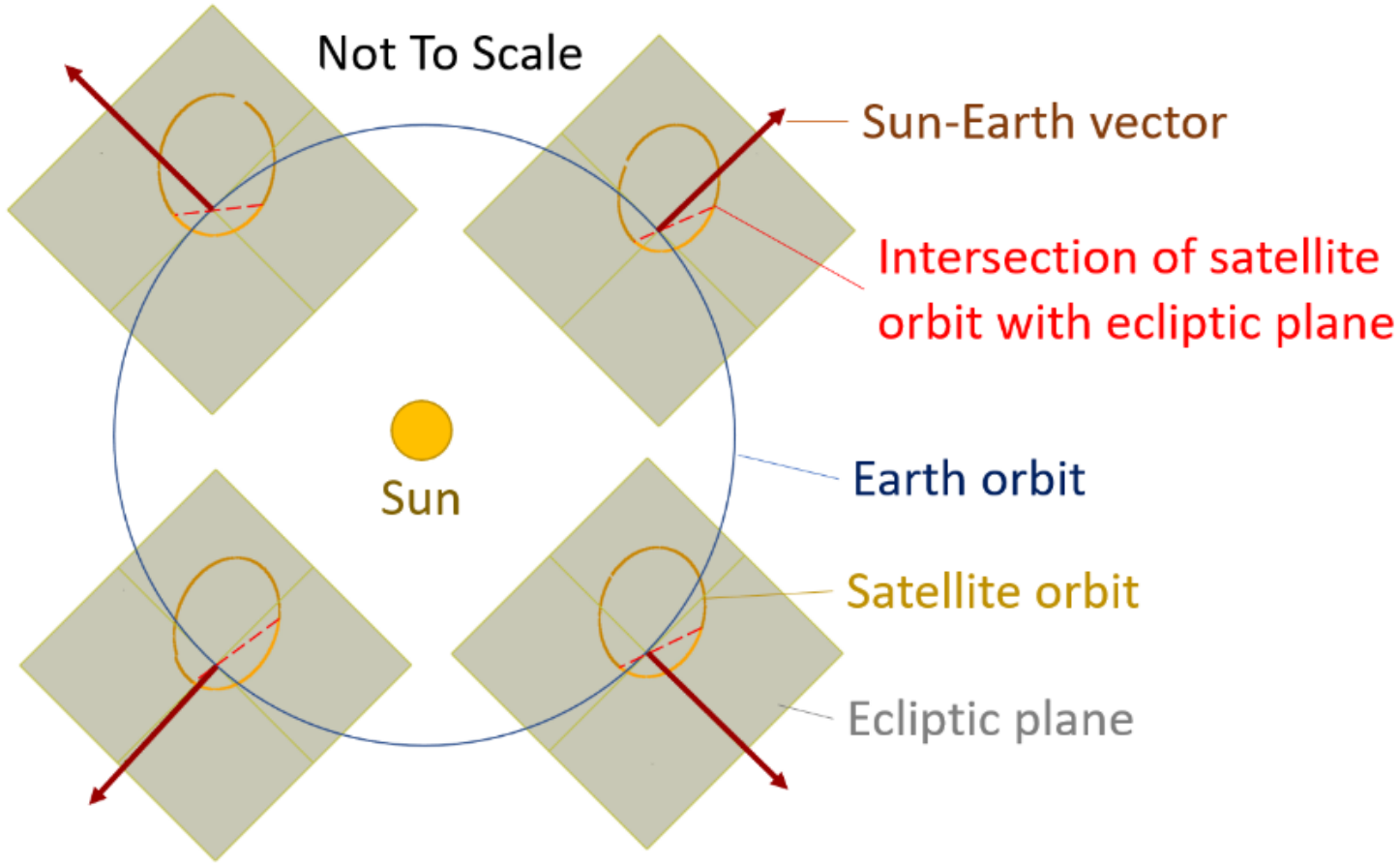
- Background
  - P/2 Lunar Resonant Orbits
  - Ecliptic Plane
- Mitigation Methods
  - Ecliptic Inclination
  - Ecliptic Argument of Perigee
  - Eclipse Phasing Maneuvers
- Mission Design Applications
- Conclusion

Background



Phasing loops leading to a P/2 LRO, in Earth Centered Inertial (ECI) and Earth-Moon rotating (ROT) frames. An eccentricity of approximately 0.65 places apogee near the Moon orbit radius and perigee above GEO (gold circle) and the outer Van Allen belt (green circle).

Background

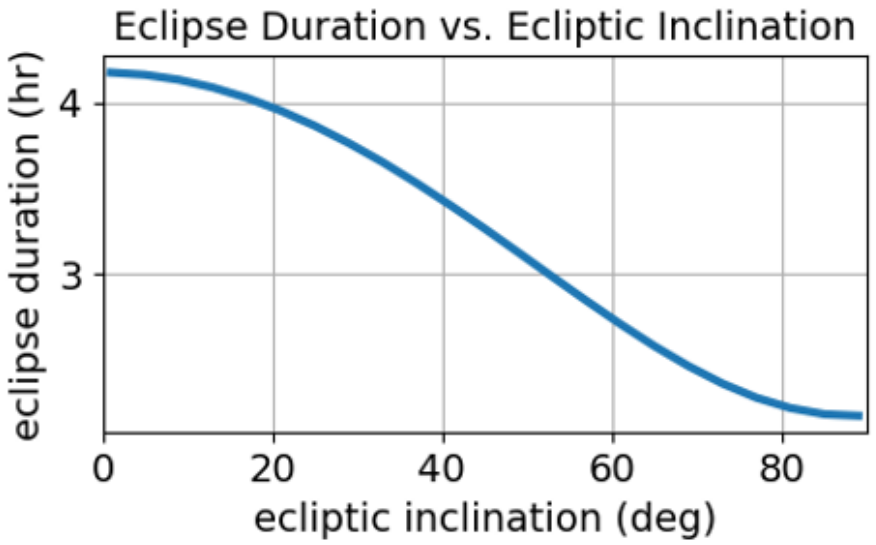


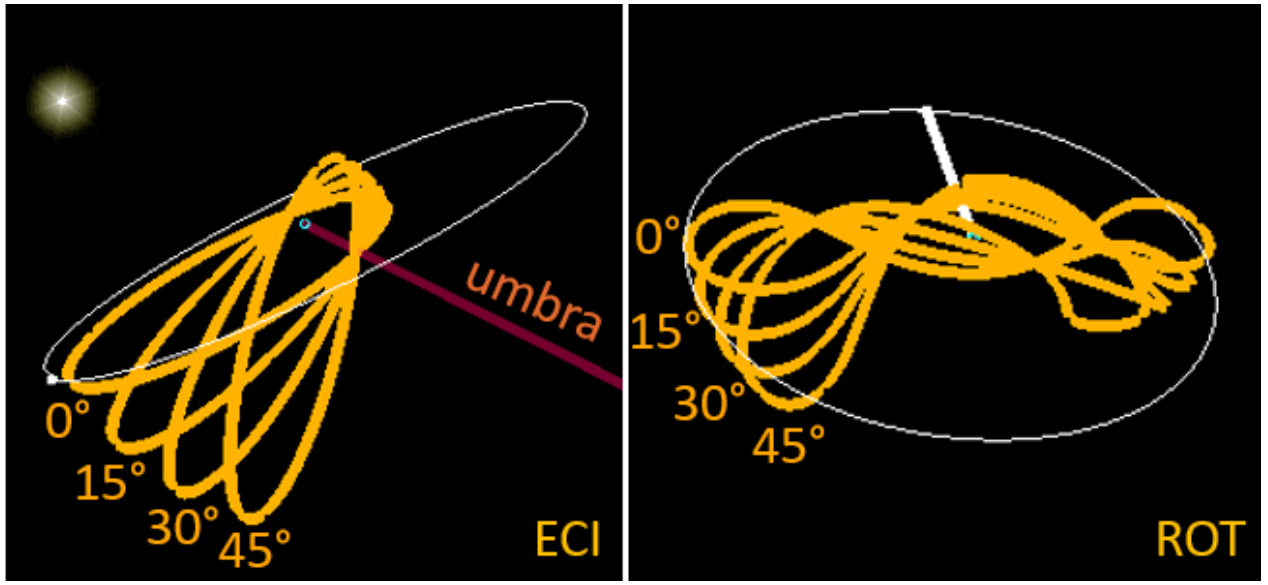
- The Earth orbits the Sun in the ecliptic plane
- Earth eclipses occur when satellite crosses the ecliptic plane
- Ecliptic inclination (i_e) and argument of perigee (ω_e) define orbit orientation relative to ecliptic plane

Note that the intersection of the satellite orbit with the orbit plane is shown as an example only; the orientation of this intersection would vary for different orbit geometries.

Ecliptic Inclination

- For a given orbit with all other parameters fixed, i_e determines the speed of ecliptic crossings
- Spending less time in the vicinity of the ecliptic plane reduces the likelihood of eclipses
- In most cases, higher i_e values correspond to shorter eclipse durations

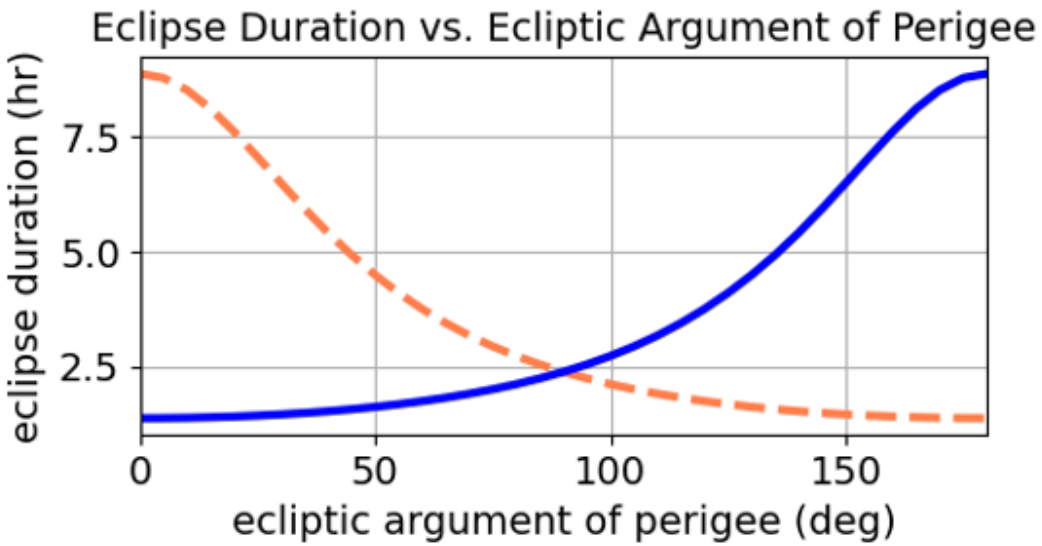


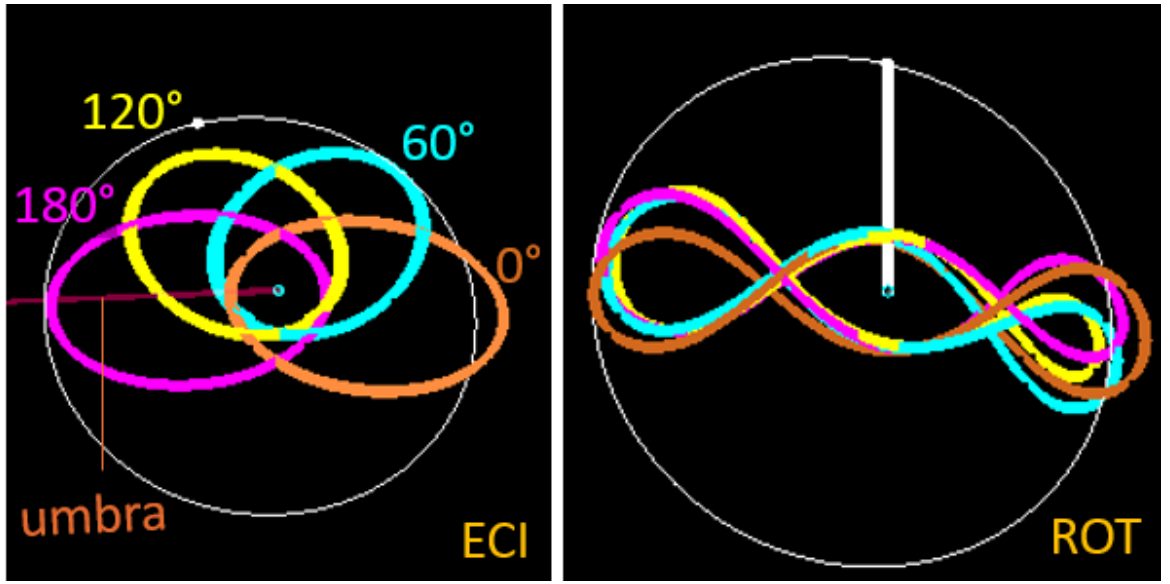


Eclipse duration as a function of ecliptic inclination for an example ecliptic crossing. Trend will vary for different ecliptic crossing geometries.

Ecliptic Argument of Perigee

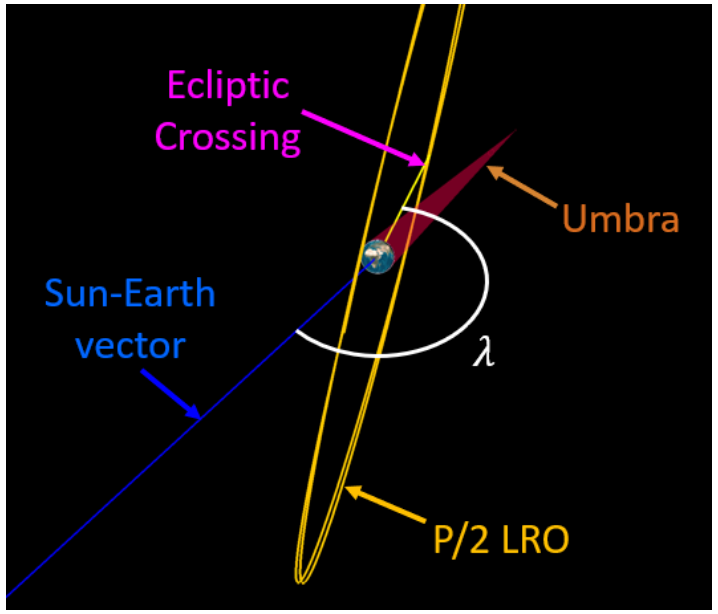
- ω_e values of 90° or 270° rotate apogee as far out of the ecliptic plane as possible, while values of 0° or 180° place apogee in the ecliptic plane
- Values near 90° or 270° provide the best long-term eclipse mitigation

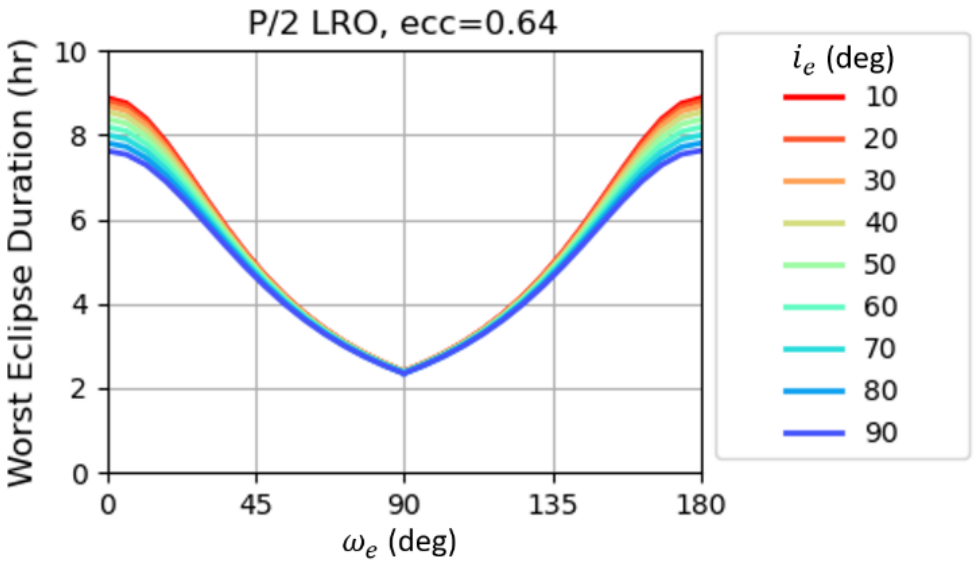




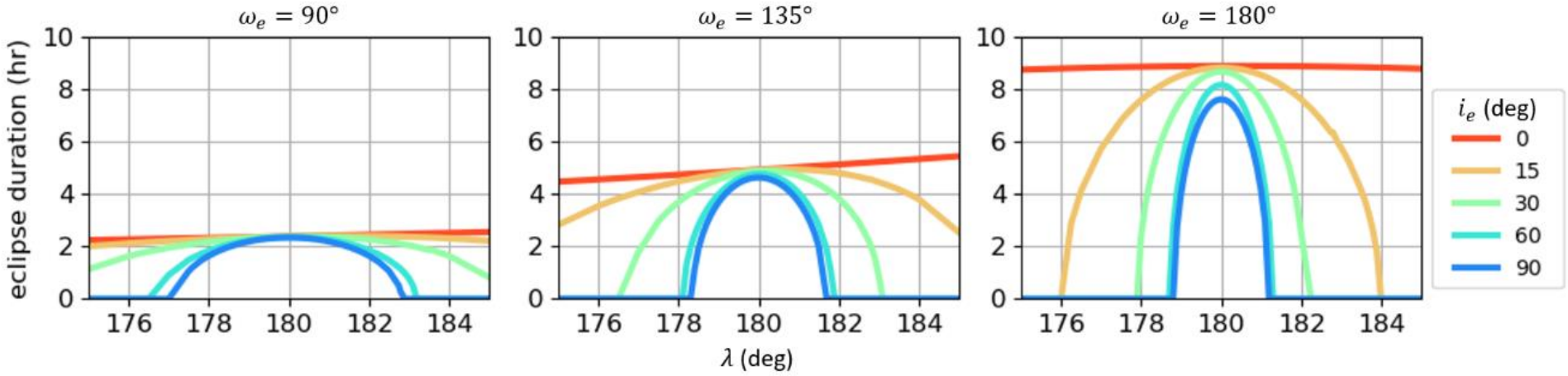
Eclipse duration as a function of ω_e. Ecliptic RAAN, true anomaly, and epoch of each sampled case were adjusted to ensure worst-case eclipse conditions and ideal P/2 lunar resonant alignment.

Combined Effects of Ecliptic Parameters

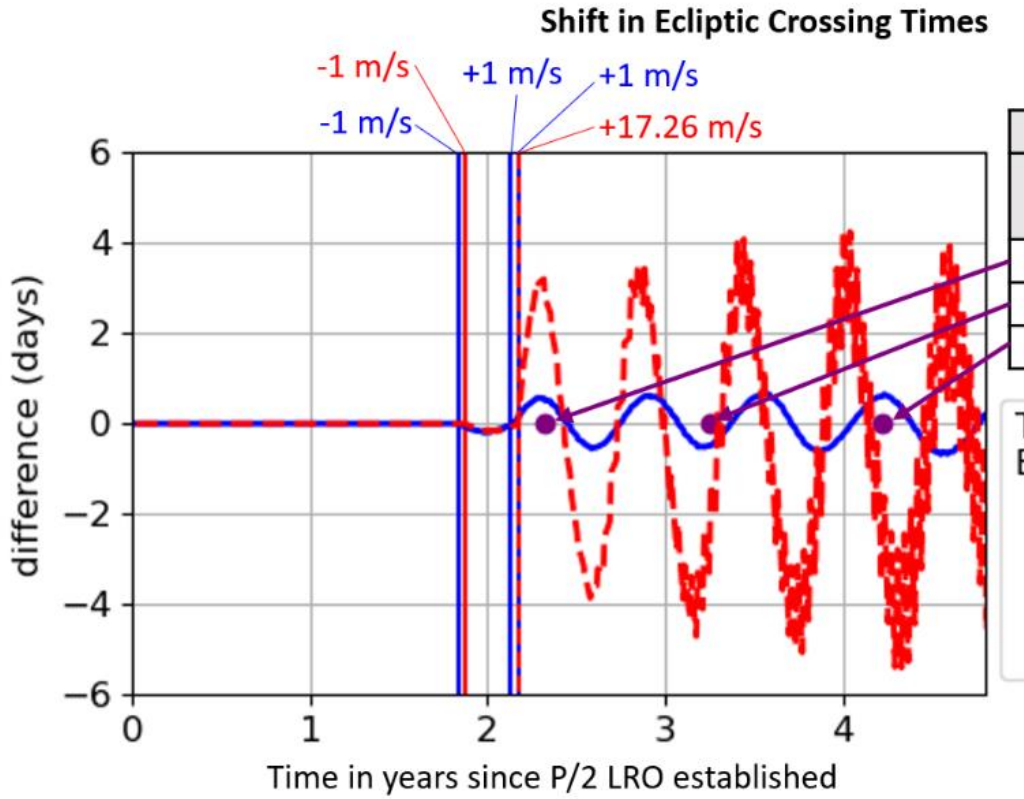




- For worst-case (λ = 180°) eclipse geometries, i_e has limited mitigation effects
- For most eclipse geometries, i_e has a significant effect
- Sun-Earth vector sweeps ~13.5° every 13.7 days; approximate difference in λ for consecutive far-side ecliptic crossings in P/2 LRO



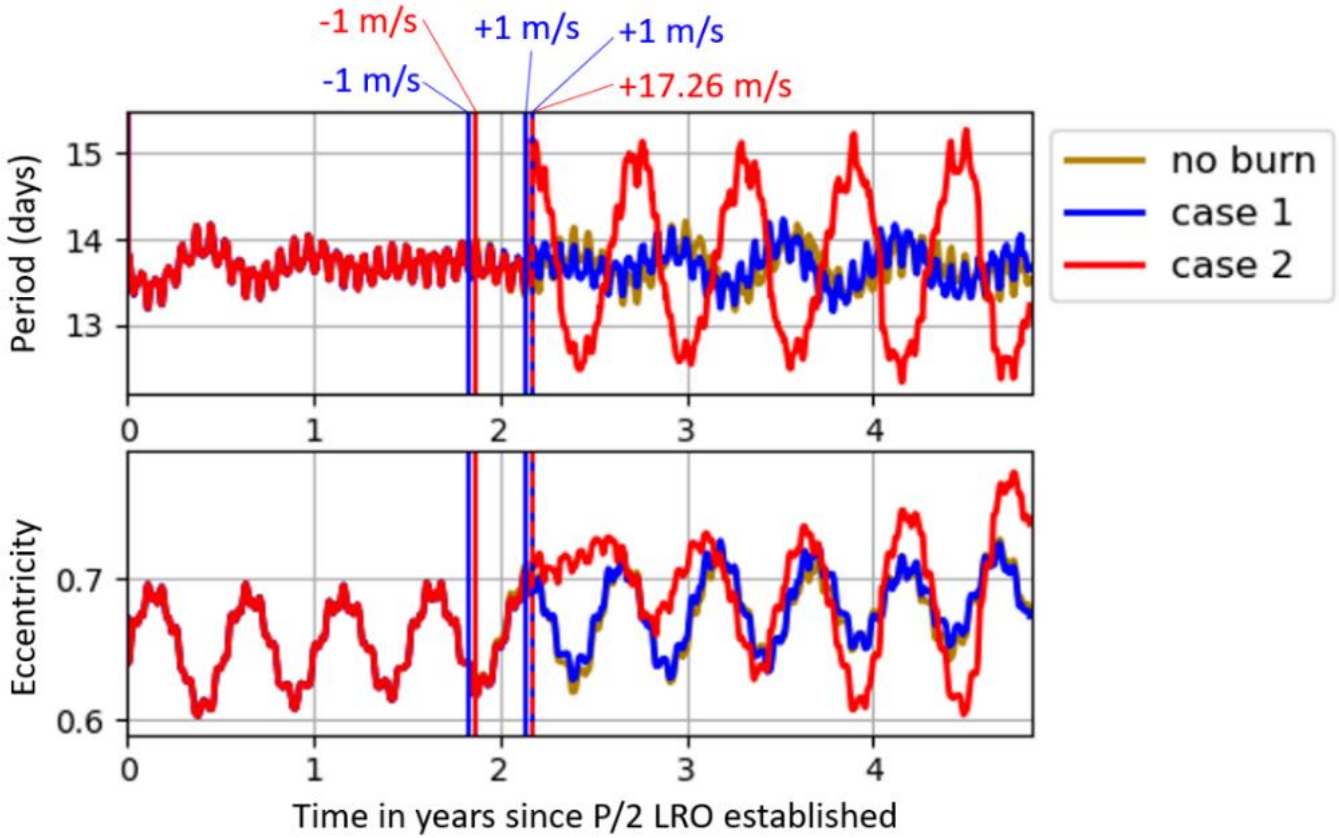
Eclipse Phasing Maneuvers



Eclipse Duration (hr)		
No-burn	Case 1 (3 m/s)	Case 2 (18.26 m/s)
4.09	3.99	-
6.51	6.92	2.95
8.58	7.94	-

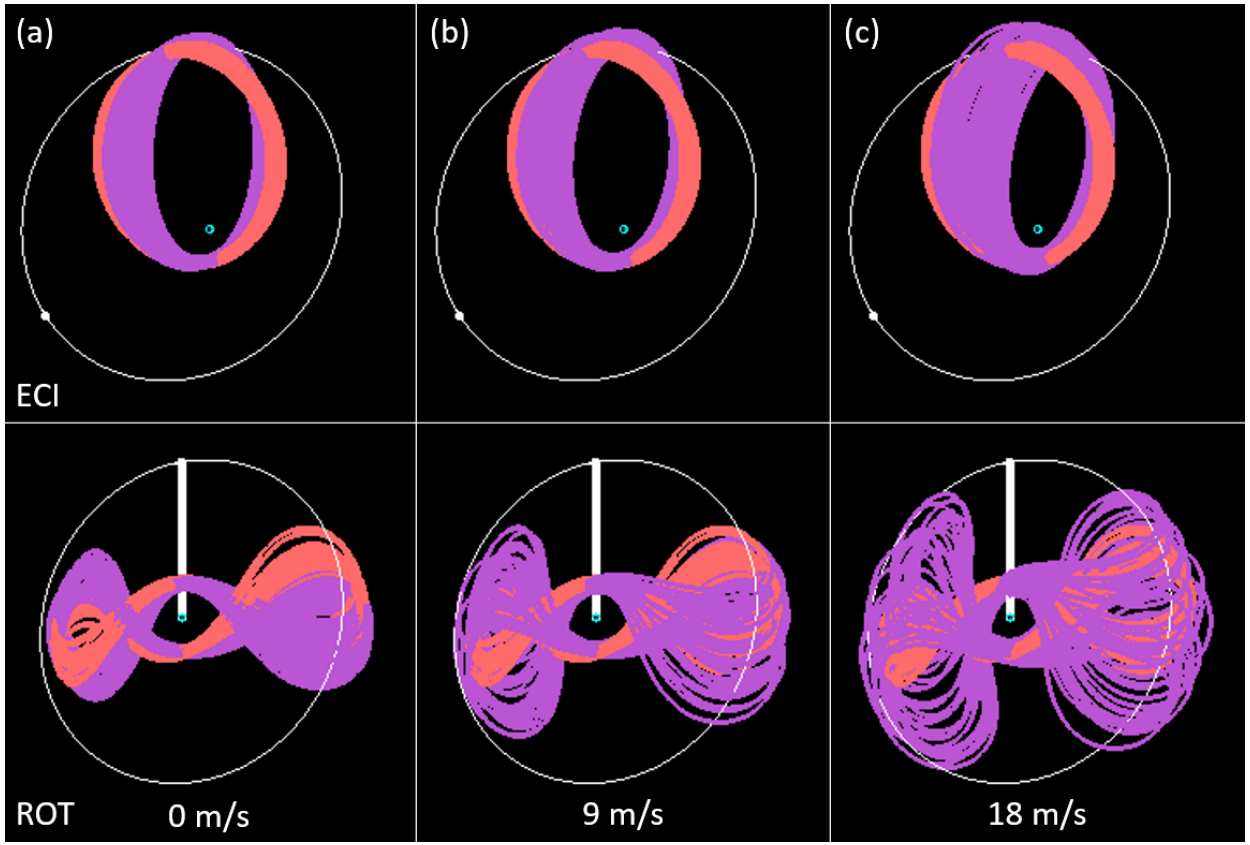
Shift in ecliptic crossing times for mitigation maneuver cases compared to a reference trajectory with no maneuvers. Mitigation maneuvers occur at the times indicated by the vertical lines, and all maneuvers occur in the velocity (+) or anti-velocity (-) direction at perigee. Note that the initial maneuver occurs one perigee earlier for case 1 than for case 2 in order to maximize each case's ecliptic crossing time shift at the first long eclipse epoch.

Eclipse Phasing Maneuvers



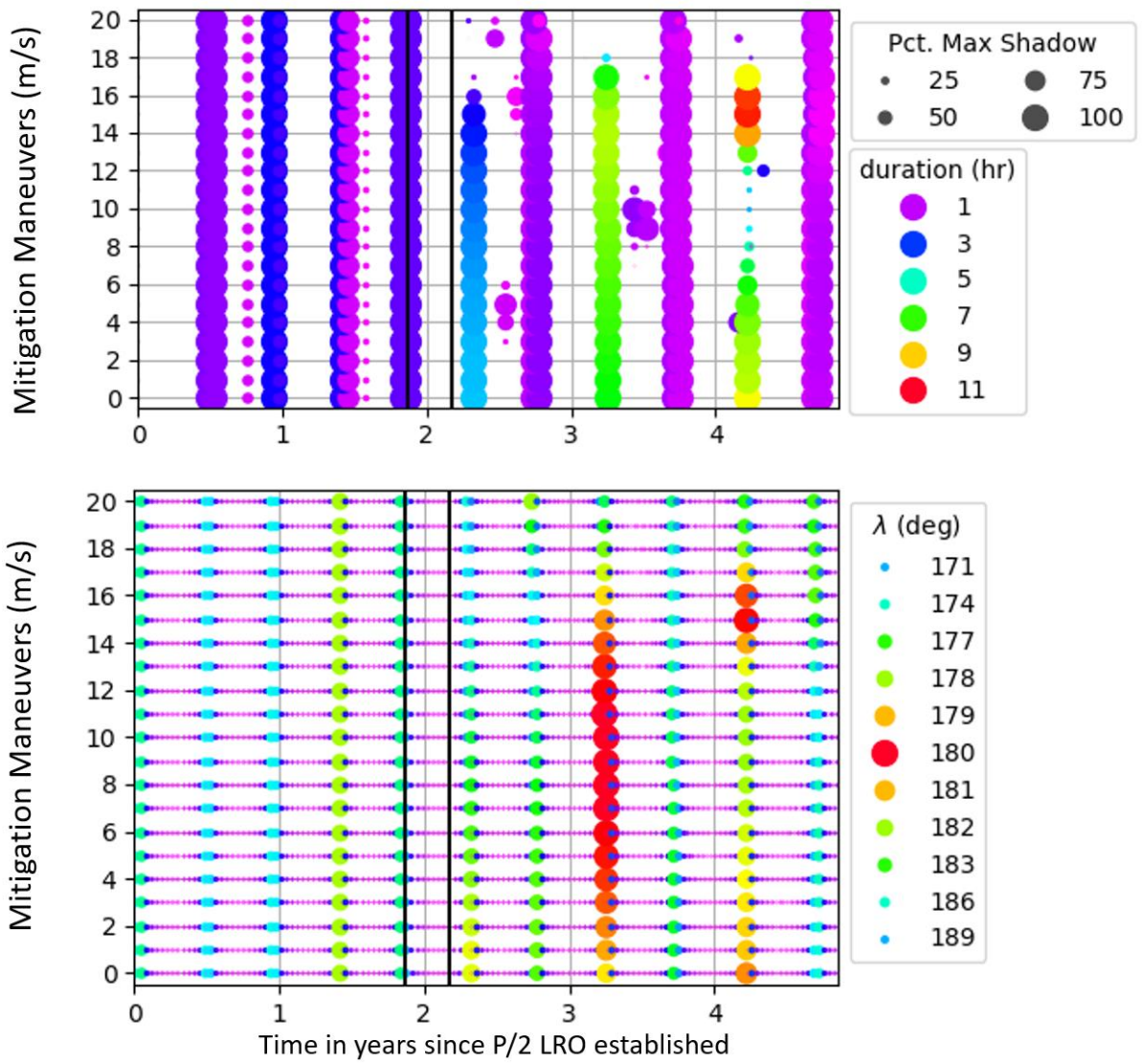
Evolution of orbit period and eccentricity for mitigation maneuver cases and a reference trajectory with no maneuvers. Mitigation maneuvers occur at the times indicated by the vertical lines, and all maneuvers occur in the velocity direction at perigee.

Eclipse Phasing Maneuvers



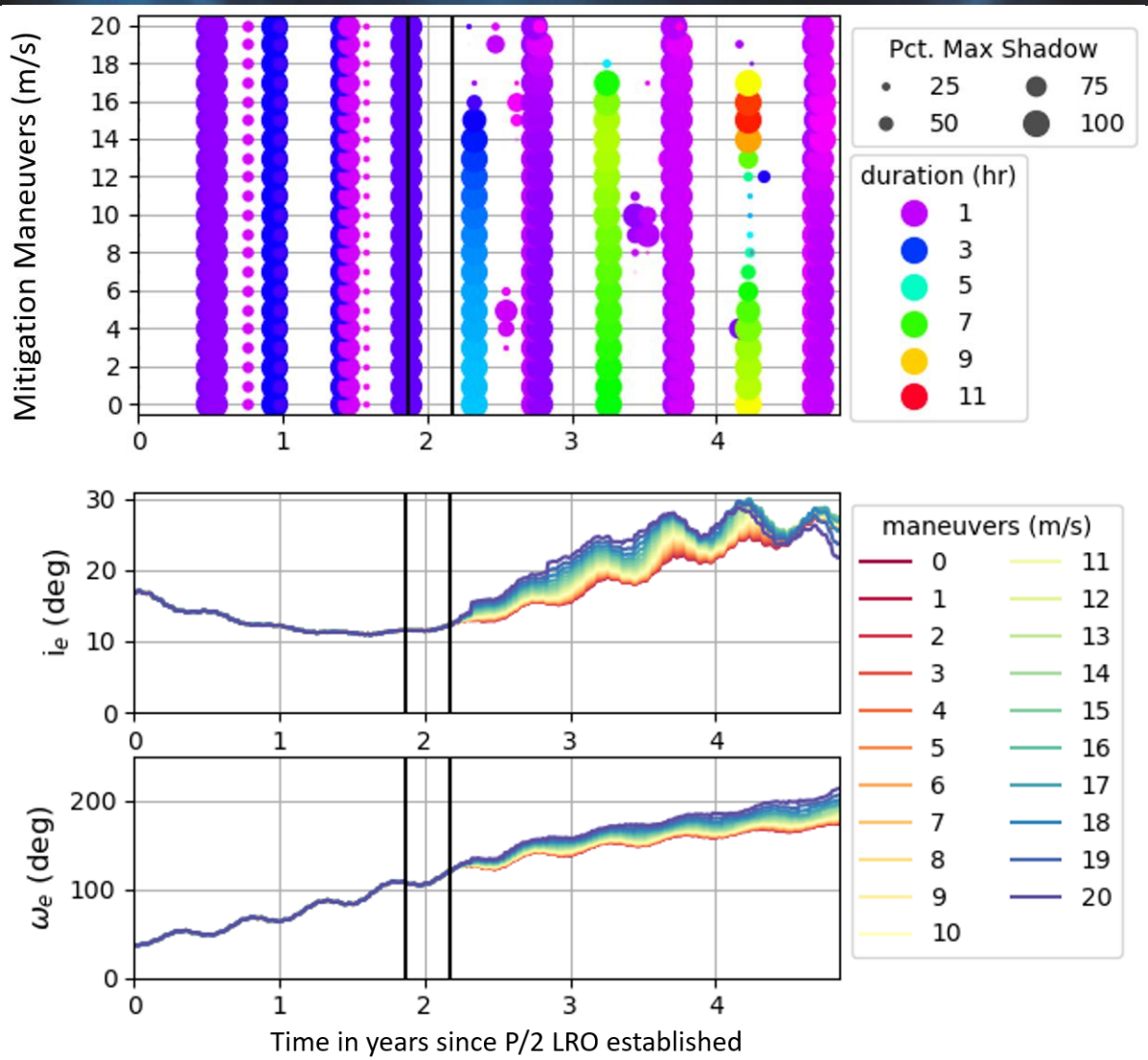
Trajectories shown in the ECI and Earth-Moon rotating frames, with varying magnitudes of mitigation maneuvers. Column (a) shows the trajectory with no mitigation burns, column (b) shows the trajectory with a pair of maneuvers totaling 9 m/s, and column (c) shows the trajectory with a pair of maneuvers totaling 18 m/s. The salmon color shows the pre-maneuver trajectory, extending roughly 2 years; the purple color shows the post-maneuver trajectory, extending roughly 2.8 years.

Eclipse Phasing Maneuvers



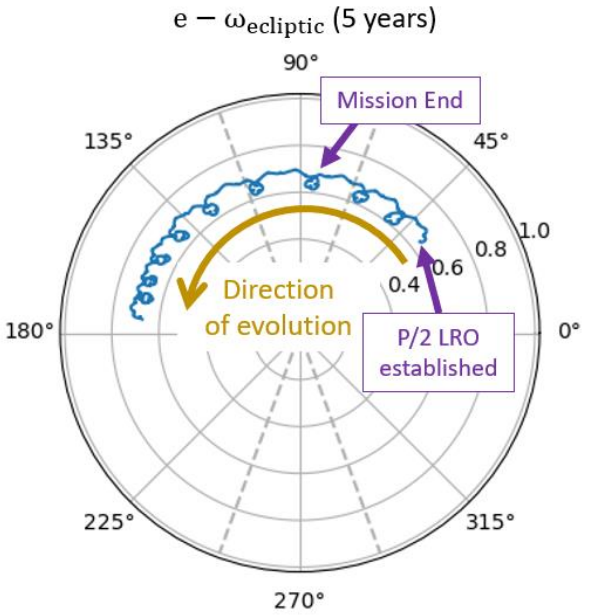
- Profiles of eclipse duration (top) and λ (bottom) over time for varying magnitudes of mitigation maneuver pairs
- Maneuvers occur at perigee at the times indicated by the vertical lines
- The first maneuver is 1 m/s in the anti-velocity direction; the second is in the velocity direction
- The longest eclipse durations correspond to λ values near 180°

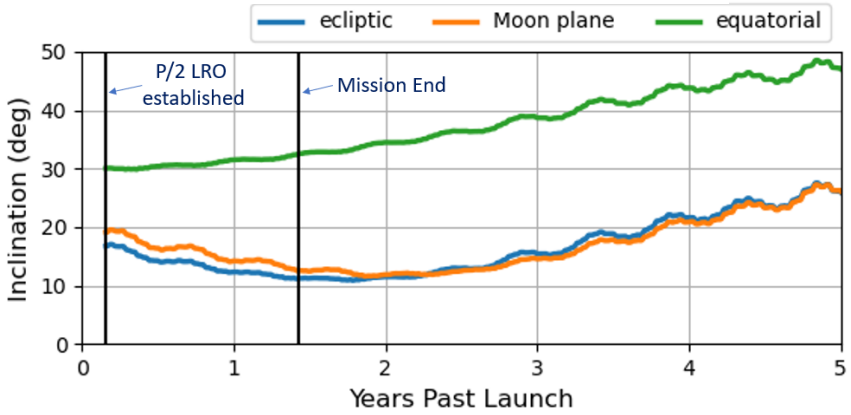
Eclipse Phasing Maneuvers

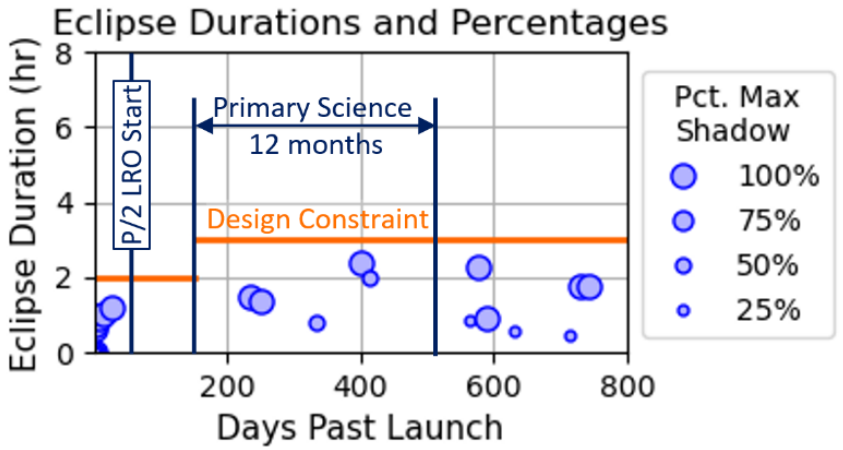


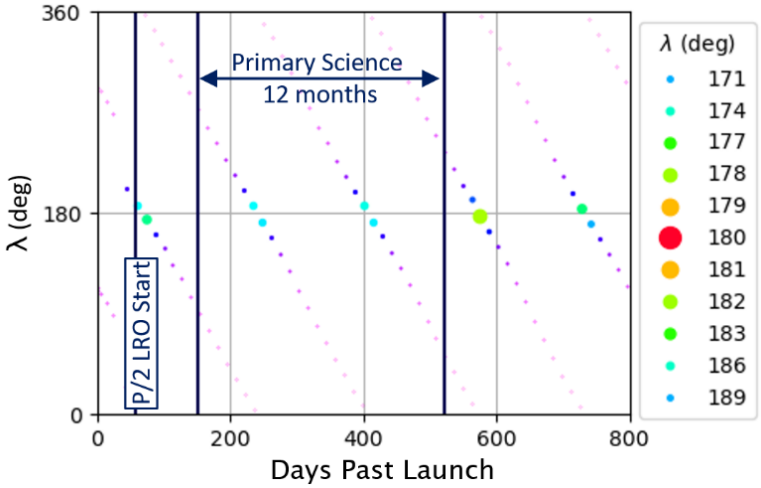
- Profiles of eclipse duration (top), i_e (middle) and ω_e (bottom) over time for varying magnitudes of mitigation maneuver pairs
- Maneuvers occur at perigee at the times indicated by the vertical lines
- The first maneuver is 1 m/s in the anti-velocity direction; the second is in the velocity direction
- Changes to λ have a much stronger effect on the eclipse duration trends for the mitigation maneuvers explored here

Mission Design Applications









- The HelioSwarm mission concept provides an example of eclipse mitigation efforts in a P/2 LRO
- The P/2 LRO's i_e must remain below 30° during the mission
- ω_e circulates, evolving from approximately 36° to 86° during the mission
- The worst ecliptic crossing geometry during the mission has a λ of 175°
- Mission eclipse durations fall below 3 hours for the nominal trajectory and range of expected dispersions

Conclusion

- P/2 LROs enable long-term access to high altitudes in the Earth-Moon system, but require careful planning to mitigate long eclipses
- Mission-specific considerations may make certain mitigation strategies impractical, so an array of strategies are presented
- Selection of i_e and ω_e enable strong eclipse mitigation during trajectory design
- Mitigation maneuvers enable eclipse mitigation after launch; larger maneuvers enable greater reduction in eclipse duration but may affect the lunar resonant alignment

Selected References

(Full reference list in conference proceedings)

- Gangestad, J. W., G. A. Henning, R. Persinger and G. R. Ricker, 2013. “A High Earth, Lunar Resonant Orbit for Lower Cost Space Science Missions”. AAS 13-810.
- Parker, J. J. K., R. L. Lebois, S. Lutz, C. Nickel, K. Ferrant, and A. Michaels, “Transiting Exoplanet Survey Satellite (TESS) Flight Dynamics Commissioning Results and Experiences,” Paper No. 18-408, AAS/AIAA Astrodynamics Specialist Conference, Snowbird, UT, August 2018.
- Plice L., Dono A., West S. “HelioSwarm: Swarm mission design in a highly elliptical orbit”. AIAA/AAS Astrodynamics Specialists Conference, Portland, Maine, 2019.