# MOMENTUM UNLOAD MANEUVER PLANNING FOR A LUNAR NAVIGATION SATELLITE

**Mark Hartigan,[*] Noble Hatten,[†] and Sun Hur-Diaz[‡]**

NASA is developing an infrastructure at the moon called LunaNet to provide position, navigation, and timing (PNT) service to orbiting and surface users on the moon. One reference orbit that has been considered for a Lunar Navigation Node (LNN) is a 12-hour frozen orbit. The impact of regularly scheduled momentum unload maneuvers on such an orbit and its PNT service availability was analyzed and an approach is established to minimize the disturbances. Goddard's General Mission Analysis Tool (GMAT) was used to survey the effects of maneuver timing and direction on orbit stability and find an appropriate solution. For a LNN satellite autonomously performing its orbit determination (OD), the impact of timing and direction of the momentum unloads on PNT service availability was analyzed using a combination of Monte-Carlo techniques and linear covariance analysis with Goddard's Orbit Determination Toolbox (ODTBX). For the reference frozen orbit, performing momentum unloads near apoapsis and in the orbit-normal direction was found to strike the best balance between service availability and orbit perturbation. Adopting this approach will improve service uptime of the LNN by reducing outages from momentum unloads, as well as save fuel and extend mission life by minimizing the need for corrective maneuvers.

## INTRODUCTION

Recent years have brought a growing interest in establishing a presence in cislunar space as technology has matured and research interests have turned towards unexplored areas of the moon. Prominent among recent plans is NASA's Artemis program to establish a sustainable human presence on the lunar surface and in cislunar space. Maintaining this human presence will require unprecedented communications, navigation, and networking capabilities: enter LunaNet, an architecture specification developed by NASA's Space Communications and Navigation program to rapidly develop these capabilities at the moon.[1]

The LunaNet architecture includes a constellation of relay satellites that will allow communication between the lunar surface and Earth, as well as provide a position, navigation, and timing (PNT) service to surface users – initial plans target the lunar south pole as an area of scientific interest. These relay satellites are also referred to as Lunar Navigation Nodes (LNN).

[*] Graduate Research Assistant, Department of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA. hartigan@gatech.edu
[†] Aerospace engineer, Navigation and Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, MD.
[‡‡] Aerospace engineer, Navigation and Mission Design Branch, NASA Goddard Space Flight Center, Greenbelt, MD.

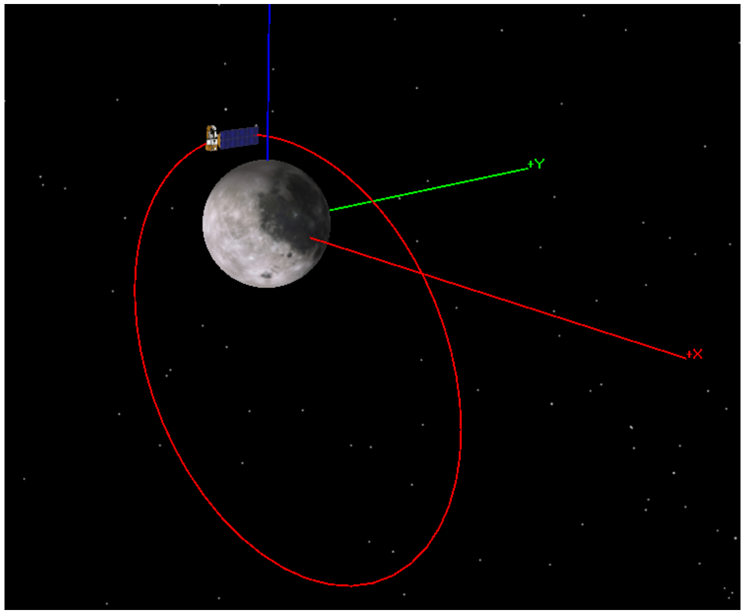


**Figure 1. Graphical depiction of a sample LNN satellite orbit about the moon.**

A candidate orbit for the LNN is an elliptical lunar frozen orbit with a semi-major axis of ~6000 km and a period of 12 hours, shown in Figure 1.[2] At these altitudes, the satellite orbit is kept stable by third (Earth) and fourth (Sun) body perturbations, which helps to minimize station-keeping maneuver requirements. However, torques from external sources such as solar radiation pressure combined with internal sources like antenna pointing requirements mean that reaction wheels will need to be desaturated regularly in order to maintain attitude control authority. Depending on thruster configuration, performing these regularly scheduled momentum unloads can result in an added translational velocity.

Users of the LNN PNT service derive their state estimate from the provider satellites' own orbit determination (OD) – which, unlike GPS, isn't provided by a ground segment. Rather, each LNN satellite will perform its own OD using a combination of weak-signal GNSS and optical navigation (OpNav) ranging to the moon.[3] $\Delta v$ maneuvers like those resulting from momentum unloads negatively impact both the orbit stability and the satellite OD knowledge, the former of which could necessitate an additional maneuver to maintain orbital requirements, and the latter of which may cause a PNT service outage if the mission requirements for maximum OD uncertainty are violated. This paper will provide a detailed analysis of resulting orbit stability based on maneuver location and direction, followed by a similar analysis from the navigation perspective. A recommendation specific to the reference frozen orbit is generated, but results provide more general insight into the effects of $\Delta v$ maneuvers on lunar frozen orbit stability and satellite navigation uncertainty.

## ORBIT STABILITY

Orbit stability performance after a maneuver is based on the goal of maintaining the unperturbed frozen orbit. A sensitivity analysis was conducted using maneuver location and direction as the independent variables. Periapsis, apoapsis, and the descending node were chosen as locations of interest, with the ascending node not included for brevity and its similarity with the descending node. The velocity, orbit-normal, and binormal directions (Figure 2) were chosen primarily because of these directions' relevance to efficiency in changing various orbital parameters. For example, a maneuver in the velocity direction is most efficient for performing an orbit-raising maneuver.

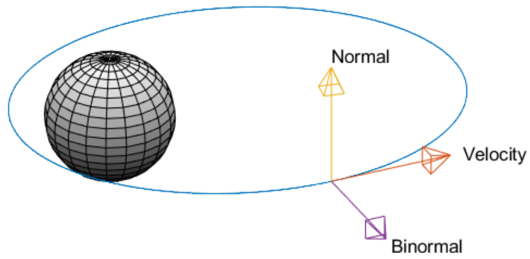


**Figure 2. The Velocity-Normal-Binormal (VNB) frame.**

### Unperturbed Case

Certain lunar orbits with specific values of orbital elements such as inclination, $i$, eccentricity, $e$, semi-major axis, $a$, and argument of periapsis, $\omega$, can lead to stable orbits where the drift of orbital parameters is mitigated or eliminated completely.[4] Figure 3 plots orbital elements for a 12-hour frozen orbit over one year, with the spacecraft conducting no maneuvers. For these propagations, forces from the moon, Earth, Sun, drag, and solar radiation pressure were included. To analyze the impact of maneuvers on the stability of these orbits, the behavior of $e$ versus $\omega$ can be observed. The long-period oscillations of this plot (Figure 3, left) should form a closed circle, indicating it repeats. Periapsis is plotted on the right to check for surface impaction and adherence to the unperturbed case.

### Maneuver Impacts

To emphasize the effects of maneuvers on orbit stability, a 100-m/s $\Delta v$ is first performed and overlaid on the unperturbed data in FiguresFigure 4 andFigure 5. This $\Delta v$ is much larger than a momentum unload, but is helpful for visualizing the different effects produced by maneuvers in different directions. In these propagations and throughout the paper, $\Delta v$ maneuvers are modelled as impulsive. Figure 4 shows the resulting orbital elements for the first year after performing the maneuver in the velocity direction at the descending node. This is an example of a poor direction for maintaining orbit stability; the velocity direction is optimal for performing coplanar orbit changes, resulting in large changes to semimajor axis and eccentricity. This is obviously undesirable for minimizing changes to eccentricity. The descending node proves to be a suboptimal location as well; the goal of this exercise is to minimize changes in both magnitude and direction of the velocity vector pre- and post-maneuver, so it logically follows that starting with the largest velocity magnitude (i.e. at periapsis) will minimize the relative change in vector magnitude, regardless of maneuver direction. The binormal direction is also suboptimal, as it drastically shifts argument of periapsis.

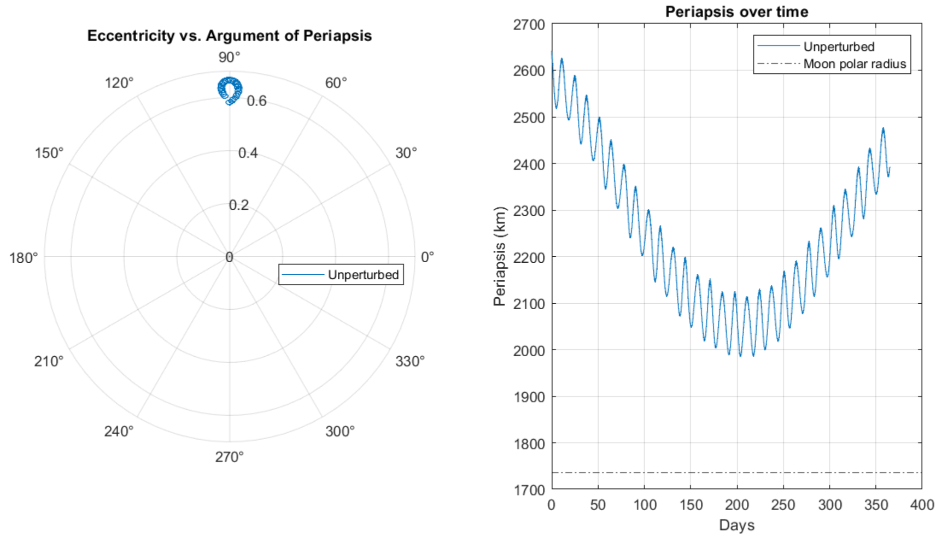


**Figure 3. Orbital elements (OE) over one year in a lunar frozen orbit**

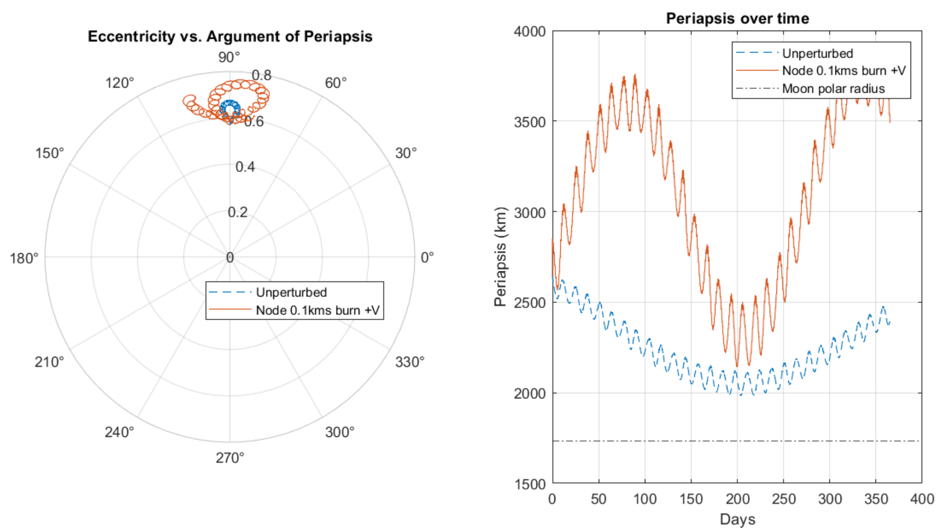


**Figure 4. OE over one year after a 100 m/s burn in the velocity direction at the descending node.**

What remains is performing the momentum unload maneuver at periapsis in the orbit-normal direction, the results of which can be seen in Figure 5. Firing in the orbit-normal direction at periapsis primarily changes the right ascension of the ascending node, but rather inefficiently, so it adheres to the unperturbed case the best of any of these large maneuvers.

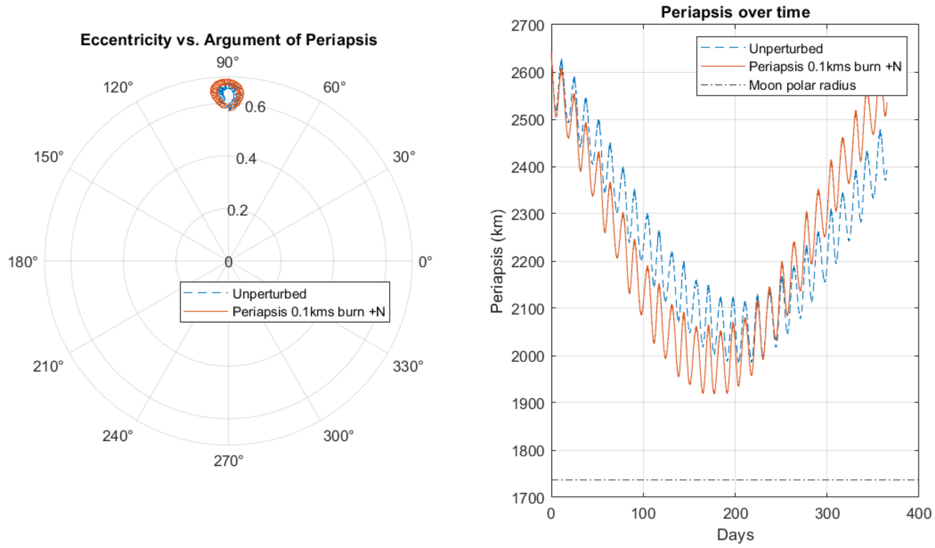


**Figure 5. OE over one year after a 100 m/s burn in the orbit-normal direction at periapsis.**

For a sample thruster configuration and bus design, we assume regular momentum unload maneuvers impart a $\Delta v$ on the order of 10 cm/s at a cadence of once every two weeks. In Figure 6, the results of a momentum unload scenario with these parameters are shown. A $\Delta v$ is performed every two weeks along the orbit-normal direction at periapsis. Maneuvers are alternated between the positive and negative directions, which effectively stops any drift of orbital elements caused by the previous maneuver. This permits the satellite to maintain its natural orbit stability while performing these momentum unload maneuvers.

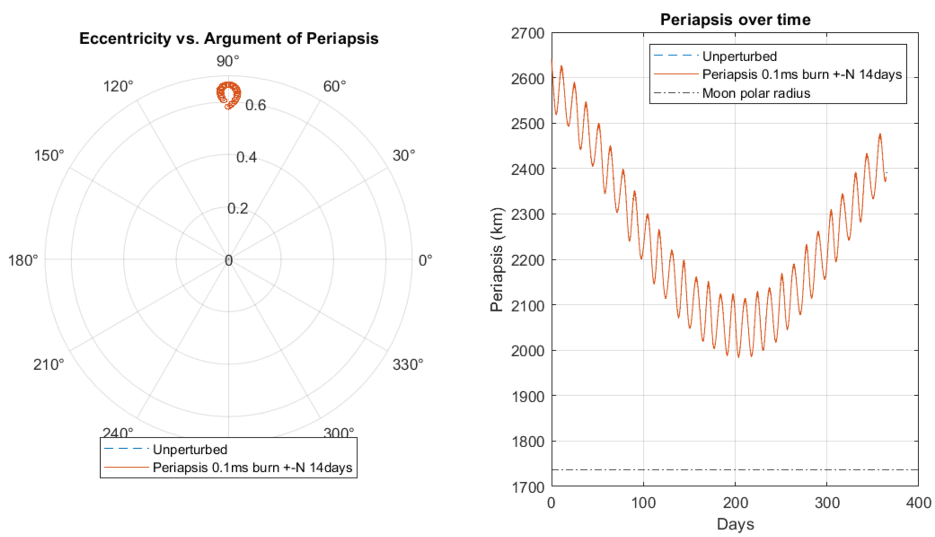


**Figure 6. OE over one year with 10 cm/s burns every 14 days along the orbit-normal axis at periapsis, alternating positive and negative directions.**

## NAVIGATION ANALYSIS

$\Delta v$ maneuvers negatively impact the satellite OD accuracy for a period after the maneuver occurs, so finding the best direction and location to perform a maneuver to maximize service availability is critical to the mission.

### Analysis Setup

Orbit Determination Toolbox (ODTBX)* is a MATLAB toolbox developed by NASA Goddard Space Flight Center (GSFC) for early-mission-phase navigation analysis. ODTBX is a generalized and well-featured tool, but in this context will primarily be used for Monte-Carlo simulations, linear covariance analysis, and measurement processing. Using this tool, an approximation of LNN navigation can be established and covariance analysis performed. To reduce computational complexity, navigation measurements and processing are simplified. The primary purpose of this analysis is to compare relative changes in navigation performance between maneuvers – analysis using more realistic models has also been performed by GSFC to assess the performance of a system of lunar relay satellites.**Error! Bookmark not defined.**

We assume navigation based on weak-signal GNSS and OpNav ranging to the moon, with the OD resolved using an extended Kalman filter (EKF). Weak-signal GNSS and OpNav measurements were approximated as ranging to the Earth and moon, respectively, as shown in Equations (1) and (2) – the satellite's current position given as $r$.

$$h_{GNSS}(r,t) = \left\| r(t) - r_{Earth}(t) \right\|_2 \tag{1}$$

$$h_{OpNav}(r,t) = \left\| r(t) - r_{Moon}(t) \right\|_2 \tag{2}$$

The measurement noise covariance was assumed to be constant for weak GNSS, since the changes in satellite position relative to the Earth are small compared to the Earth-Moon distance. Measurement noise covariance for OpNav was scaled with the square of satellite altitude above the lunar surface because the spacecraft's optical navigation is based on shape recognition of the moon. The baselined accelerometer for this mission has a resolution of 3 mm/s$^2$, and the error introduced by each maneuver is assumed to have a standard deviation of half the resolution multiplied by a 1-second duration of the maneuver (~1.5 mm/s for the momentum unload). This error was applied in all 3 axes, as would be outputted from a 3-axis accelerometer.

Each simulation was propagated for 48 hours, or 4 orbits, to allow the navigation filter to settle and converge to a steady state. A maneuver is performed after this point. Then, the simulation is propagated for another 48 hours to allow the filter to fully return to its pre-maneuver state. To aid this process, the EKF was adjusted by increasing process noise for a finite amount of time post-maneuver. The process noise spectral density matrix associated with the EKF dynamics function can be represented by the formula in Equation (3):

$$Q(t) = \begin{bmatrix} 0_{3\times3} & & 0_{3\times3} & \\ & 10^{-9} & 0 & 0 \\ 0_{3\times3} & 0 & 10^{-9} & 0 \\ & 0 & 0 & 10^{-9} \end{bmatrix} * Q_{scale}(t) \tag{2}$$

$Q_{scale}$ is generally constant but is increased for a period of time, $\tau_{scale}$, after the maneuver.

* https://opensource.gsfc.nasa.gov/projects/ODTBX/

### Unperturbed Case

Figure 7 is a plot of the root-sum-of-squares (RSS) position error in the unperturbed case in which the navigation filter is propagated – beginning at periapsis – for 96 hours without maneuver. The true error lines are based on ten Monte-Carlo simulations, while the three-sigma line is derived from the EKF time-dependent linear covariance matrix. Since the covariance is linearized, the Monte-Carlo cases were used to validate that assumption. From the data, it is evident that error reaches a minimum just after periapsis and a maximum just after apoapsis. For the remaining figures in this paper, Monte-Carlo runs will be omitted for readability and only three-sigma RSS position errors will be considered; however, all linear covariances were validated against a minimum of five Monte-Carlo simulations. After three orbits, the RSS error settles to just under 20 meters $3\sigma$ positional.

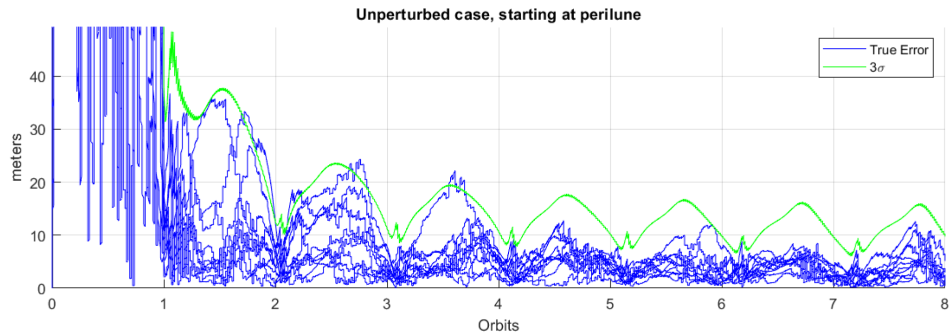


**Figure 7. 96-hour simulation of LNN navigation uncertainty.**

### Post-Maneuver Filter Performance

Since the goal of LNN is to provide a PNT service to users, the performance of different maneuver locations is quantified by the percent service availability for four orbits (or 48 hours) after the maneuver is performed. The steady-state performance of 20 meters is used as the baseline requirement for service in these simulations, since it lies just above the maximum error seen during nominal operations.

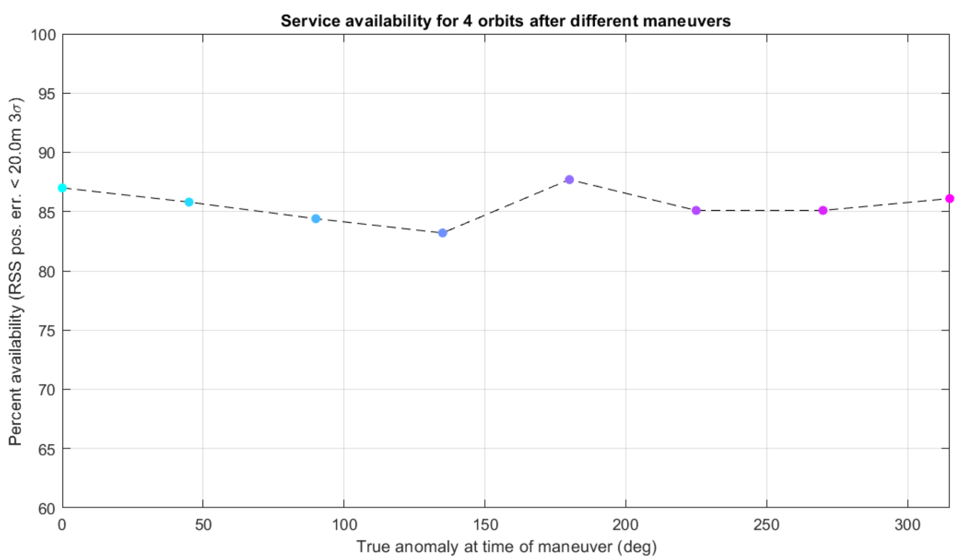


**Figure 8. Service availability for four orbits after a maneuver at different true anomalies.**

Figure 8 shows percent availability for maneuvers being performed at different true anomalies. In this plot, performing the maneuver at apoapsis yields the best availability, at 88 percent. However, the worst performing true anomaly is just before at 135°, with an availability of 83 percent. This is a maximum range from best to worst performance across the orbit of just 5 percentage points, which is likely within the tolerance of this simulation accuracy and filter tuning.

In fact, filter tuning post-maneuver was found to have a much greater impact on navigation performance than either maneuver direction or location. The tuning parameters for Figure 8 can be found in Figure 9. A very noticeable trend is that required process noise and duration reach a minimum around periapsis and a maximum around apoapsis. This also matches the behavior of filter covariance at the time of the maneuver, suggesting the two may be linked.

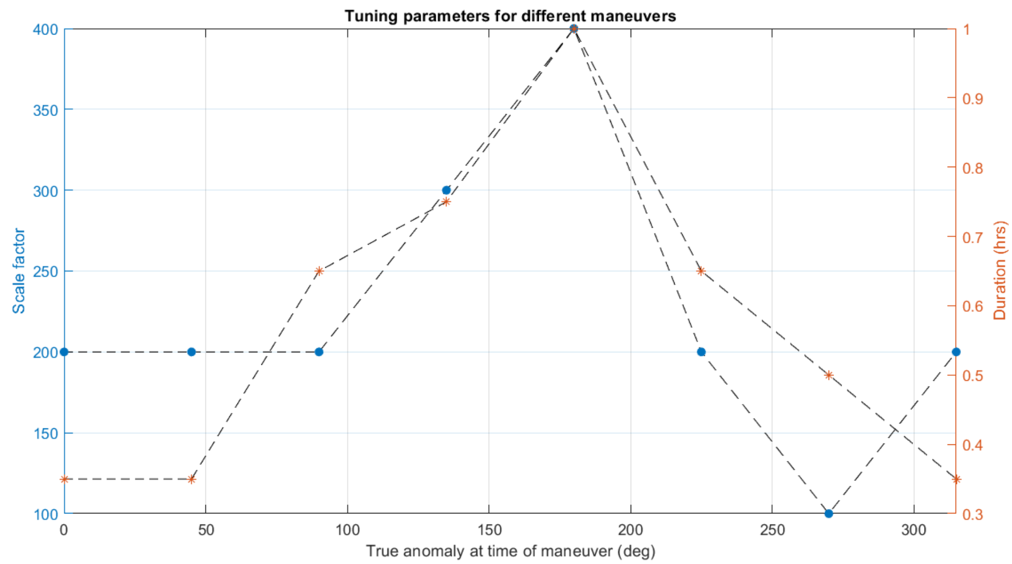


**Figure 9. Process noise scale factor and duration post-maneuver for different true anomalies.**

To further stress the importance of proper tuning for optimal navigation performance, two separate tunings for the same maneuver are displayed in Figure 10. Here, a 10 cm/s maneuver was performed at periapsis and the $3\sigma$ RSS error is shown. The first case is poorly tuned, with a scale factor of 500 applied for 2 hours post-maneuver. This case has a much higher peak than the well-tuned variant ($Q_{scale} = 200$ and $\tau = 0.35$ hours), and it takes three orbits to settle down below the 20-meter service threshold. The well-tuned case performs much better – it has an availability for the four orbits post-maneuver of 86.5 percent, compared to just 47.7 percent in the worse-performing case.

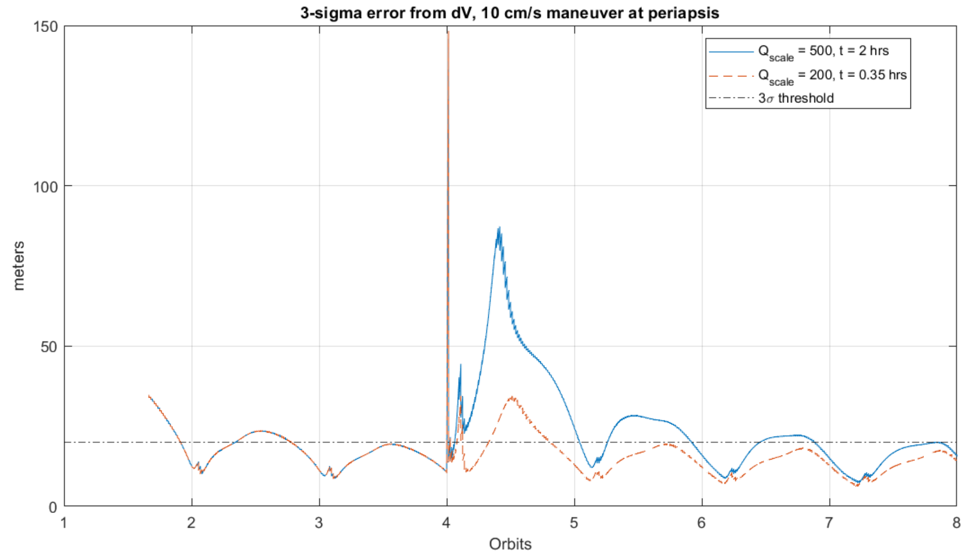


**Figure 10. Error for 10 cm/s maneuver at periapsis with poorly tuned versus well-tuned filters.**

One final consideration for navigation is the satellite service volume. Currently, initial plans target the lunar south pole – hence placing apoapsis in the southern hemisphere as opposed to the northern. Ultimately, there will be a defined service volume for LNN, outside of which each satellite will not be providing PNT to users. This will correspond to a range of true anomalies for each orbit, generally centered around the south pole. Figure 11 shows $3\sigma$ errors resulting from maneuvers at different locations, with each simulation starting at periapsis (here, the midpoint in the orbit is apoapsis). With the simulations aligned in this way, it becomes clearer that true anomalies near periapsis spend the majority of time in violation of the 20-meter OD knowledge requirement around apoapsis. This would mean the satellite would experience downtime when most needed, above the south pole of the moon. Conversely, performing the maneuver at apoapsis results in a slightly larger error peak, but spends more time in violation of the OD knowledge requirement around periapsis, where the satellite would be outside of the service volume. This provides stronger motivation for using apoapsis as the momentum unloading maneuver location of choice, though future work would be to quantify this once a service volume is solidified.

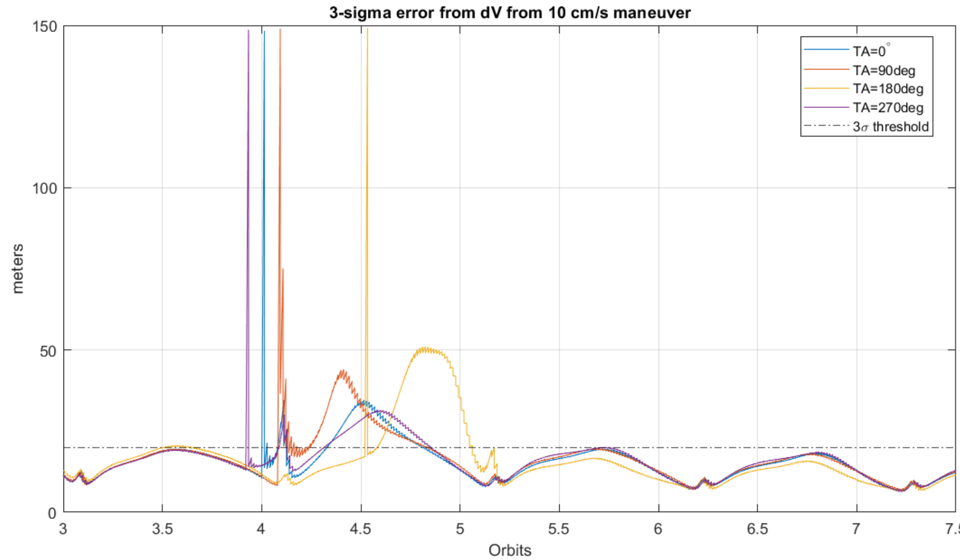


**Figure 11. Comparison of maneuvers at different true anomalies, aligned by orbit position.**

## Orbit Stability at Apoapsis

LunaNet will be providing a critical service for Artemis and human surface users, so service availability will likely be prioritized over orbit stability. As a result, apoapsis is deemed a preferable location over periapsis for momentum unloads based on the two analyses described here. Nevertheless, sending the satellite into an unstable orbit is still undesirable, so orbit stability while performing momentum unloads at apoapsis (rather than periapsis, as shown in Figure 6) was investigated and is shown in Figure 12.

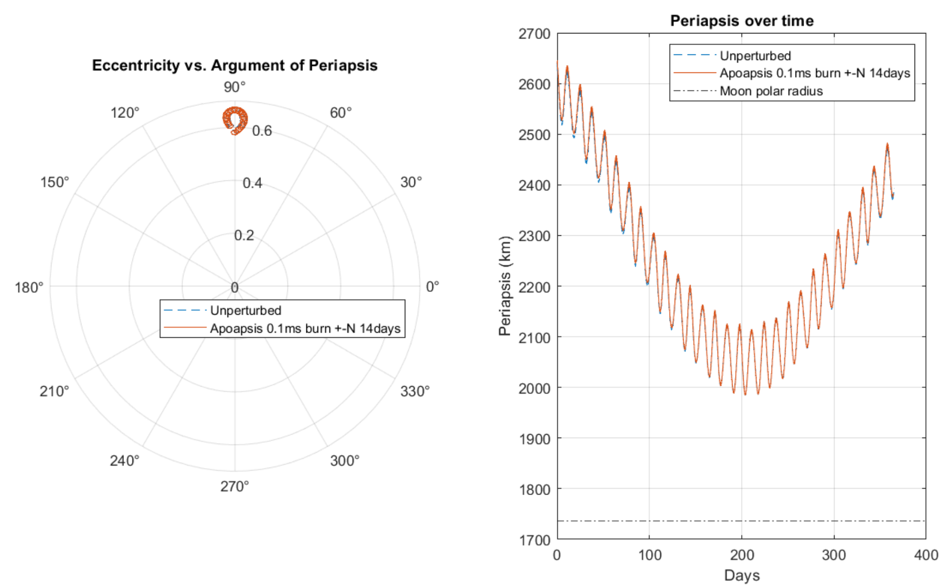


**Figure 12. OE over one year with 10 cm/s burns every 14 days along the normal axis at apoapsis.**

In this simulation, momentum unloads follow the same scheme where they are performed every 14 days and the resultant $\Delta v$ is directed along the orbit-normal axis – alternating directions each time. Performance is slightly worse than the optimal case since they are being performed at apoapsis rather than periapsis, but the orbit remains stable and follows the trend of the unperturbed case closely.

## CONCLUSION

In this paper, the problem of appropriate placement and direction of momentum unload maneuvers for lunar navigation satellites was considered. A strategy was developed to minimize the negative effect of momentum unloads on position, navigation, and timing service availability and orbit maintenance, based on analysis of long-term orbit propagations and navigation simulations following momentum unloads. For the Lunar Navigation Node (LNN) scenario considered in this paper, performing momentum unloads near apoapsis and in the orbit-normal direction achieves the best service availability while maintaining orbit stability. Adopting this approach will improve service uptime of LNN satellites by reducing outages from momentum unloads, as well as save fuel and extend mission life by minimizing the need for orbit-maintenance maneuvers.

## ACKNOWLEDGMENTS

Mark Hartigan's work was performed while participating in the Space Communications and Navigation (SCaN) Internship Program through the Office of STEM Engagement at NASA GSFC.

Special thanks to Jose Rosales and Jeff Small in the Navigation and Mission Design branch at GSFC for providing a strong foundation off which this work was based.

## REFERENCES

[1] Israel, D. J., Mauldin, K. D., Roberts, C. J., Mitchell, J. W., Pulkkinen, A. A., La Vida, D. C., Johnson, M. A., Christe, S. D., and Gramling, C. J., "LunaNet: a flexible and extensible lunar exploration communications and navigation infrastructure", IEEE Aerospace Conference, 2020, pp. 1-14.

[2] Small, Jeffrey L., Mann, Laurie M., Crenshaw, Juan M., Gramling, Cheryl J., Rosales, Jose J., Winternitz, Luke B., Hassouneh, Munther A., Baker, Dahlia A., Hur-Diaz, Sun, Liounis, Andrew J., "Lunar Relay Onboard Navigation Performance and Effects on Lander Descent to Surface," *Proceedings of the 2022 International Technical Meeting of The Institute of Navigation*, Long Beach, California, January 2022, pp. 587-601. https://doi.org/10.33012/2022.18221

[3] Silva, P.F., Lopes, H.D., Peres, T.R., Silva, J.S., Ospina, J., Cichocki, F., Dovis, F., Musumeci, L., Serant, D., Calmettes, T., Pessina, I., Perelló, J.V., "Weak GNSS Signal Navigation to the Moon," *Proceedings of the 26th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2013)*, Nashville, TN, September 2013, pp. 3357-3367.

[4] Folta, D. and Quinn, D., "Lunar Frozen Orbits," AIAA Paper 2006-6749, August 2006. https://doi.org/10.2514/6.2006-6749.