

LONG-TERM ORBIT OPERATIONS FOR THE LUNAR RECONNAISSANCE ORBITER

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The Lunar Reconnaissance Orbiter (LRO) has been operating for 14 years at the Moon after it was launched on its original one-year mission on June 18, 2009. Along with the unprecedented scientific record, operating LRO has revealed many significant factors related to orbit operations that can be used when designing future low-lunar orbit missions. Among other things, these factors include maintaining a low-lunar orbit, applications of a frozen orbit, observing a drift in the orbit inclination, compensating operations to survive through long lunar eclipses, and developing inventive new ways to execute maneuvers.

INTRODUCTION

The Lunar Reconnaissance Orbiter (LRO) launched on June 18, 2009, as the first step in NASA's return to the Moon. LRO's six instruments were chosen to map the lunar surface, create accurate surface maps, characterize the radiation environment, and map lunar surface temperatures in advance of future human exploration¹. While NASA lunar architecture plans have changed since then, LRO continues to orbit the Moon, collecting science data and increasing our understanding of our nearest planetary body. From a mission design and operations perspective, we've also analyzed the LRO orbit history to help mission designers make intelligent decisions for future low altitude lunar missions.

LRO has now spent over 14 years at the Moon. Initially operated as a mission under NASA's Exploration Office, LRO was transitioned to the Science Mission Directorate (SMD) at the end of its 1-year prime mission. Over its lifetime, the LRO Science Team has submitted several Extended Science Mission (ESM) proposals to extend its science mission efforts. Originally, the ESM proposals covered two-year extensions but in 2018, NASA Headquarters (HQ) changed to awarding three-year extended mission periods. As such, LRO was awarded an extra year (i.e. ESM3') to sync it with other missions on a 3-year cycle. The current ESM5 proposal will extend LRO's operations out through October 2025 (Table 1).

LRO spent over 2 years in its prime 50-km science orbit. After that period, it was transitioned to a frozen orbit^{2,3} to conserve fuel. We maintained different "flavors" of that frozen orbit for over three years before ending the frozen orbit maintenance and allowing the orbit parameters, primarily periselene and aposelene altitude, to drift.

Orbit operations over LRO's lifetime has required the monitoring of fuel usage, analyzing how to survive long lunar eclipse periods, and learning how to deal with an aging spacecraft. By sharing the LRO operational experience, we hope to benefit to the next generation of lunar orbiters.

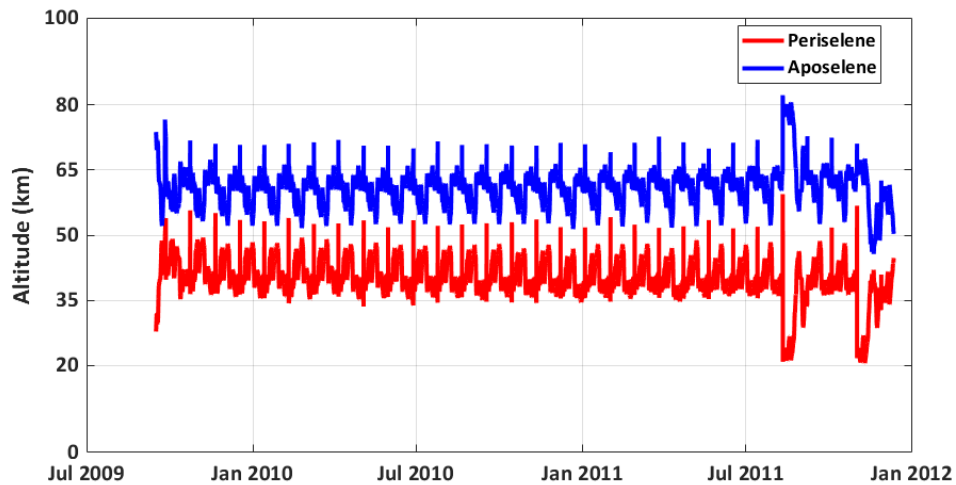
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Table 1: LRO Mission Phases

09/15/2009 – 09/30/2010	Exploration Mission	50-km Science Orbit
10/01/2010 – 09/30/2012	Science Mission	50-km Science Orbit, Frozen Orbit
10/01/2012 – 09/30/2014	ESM1	Frozen Orbit
10/01/2014 – 09/30/2016	ESM2	Frozen Orbit
10/01/2016 – 09/30/2018	ESM3	Orbit Drift
10/01/2018 – 09/30/2019	ESM3'	Orbit Drift
10/01/2018 – 09/30/2022	ESM4	Orbit Drift
10/01/2022 – 09/30/2025	ESM5	Orbit Drift

SCIENCE ORBIT

LRO entered its 50-km science orbit on September 15, 2009 and operated there until December 11, 2011. This low-lunar orbit is unstable without orbit maintenance – the lunar gravity field will perturb the orbit such that the eccentricity will grow, leading to an impact in roughly 40 days^{4,5}. To maintain this orbit at 50 ± 15 km, a pair of stationkeeping (SK) maneuvers were performed roughly every 28 days. The SK maneuver sequence utilized a 2-burn argument of periapsis rotation scheme with a posigrade maneuver followed by a retrograde maneuver, separated by nearly 3 hours^{5,6} (roughly 1.5 orbit revolutions apart). A time history of the LRO periselene and aposelene altitudes (relative to the mean lunar radius) is shown in Figure 1. In this figure, the apsis altitudes mirror each other around the 50 km average value. The aposelene and periselene “spikes” every 28 days represent the intermediate orbit in between the pair of stationkeeping maneuvers.

**Figure 1: LRO Science Orbit Apsis Altitudes**

Another way to look at the LRO stationkeeping cycle is via a polar plot of the periselene motion using the Moon-Fixed argument of periapsis (AOP) and eccentricity (ECC). A single cycle of the orbit is shown on the left side of Figure 2 where the symbol color is mapped to the Longitude of Ascending Node (LAN) of the orbit. For LRO, we started our stationkeeping cycle near a LAN of 270, when the orbit plane is “face-on” to the Earth-Moon line thus ensuring continuous ground coverage from an Earth ground station. This plot at the left shows that over the course of 1 month, the orbit traverses the entire span of LAN values.

There are two deviations in Figure 1 that represent special operations performed by LRO in August and November of 2011. At the request of the LRO Science Team, we altered the LRO stationkeeping cycle for two Apollo Viewing Campaigns (AVCs) to obtain lower altitude passes over the Apollo Lunar Landing sites. Both AVC cycles shifted the typical ECC/AOP pattern to increase the eccentricity at the beginning of the cycle (Figure 2, right). This shift lowered the minimum periselene altitude near 20 km and increased the image resolution of the LRO Camera (LROC) instrument. LROC obtained higher resolution images of

all six Apollo landing locations during these two campaigns and these images can be seen at the LROC website located at http://lroc.sese.asu.edu/featured_sites#ApolloLandingSites.

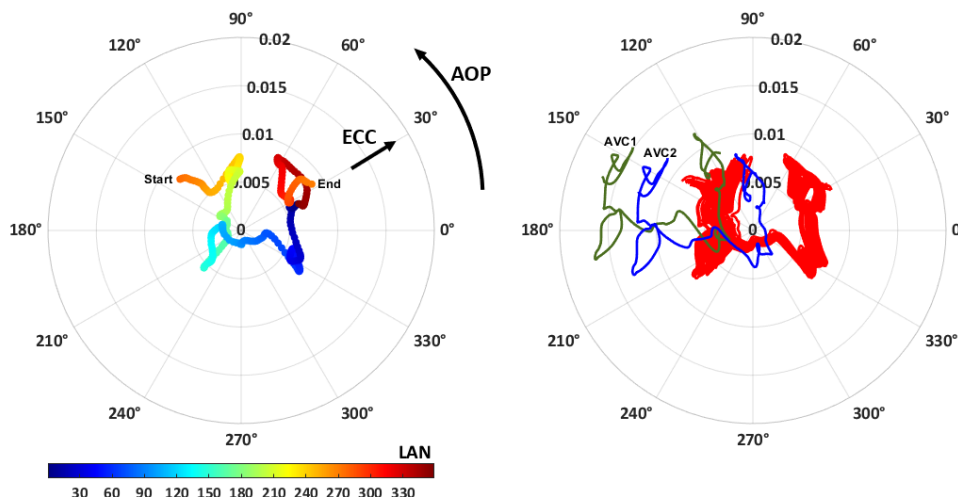


Figure 2: Science Orbit ECC/AOP Polar Plot
Left: Typical cycle shows correlation to orbit LAN
Right: All 30 cycles including two shifted AVC cycles

LRO performed 30 pairs of stationkeeping maneuvers over the next 2+ years in the 50-km science orbit. Except for the maneuvers into and out of the AVCs, the stationkeeping cost was roughly 11 m/s every four weeks.

EXTENDED MISSION ORBITS

LRO was moved from its science orbit into a frozen orbit on December 11, 2011 in order to reduce the fuel needed for orbit maintenance. This move to the frozen orbit reduced LRO's yearly ΔV expenditure from 143 m/s to less than 5 m/s per year. While a 30 x 200 km quasi-frozen orbit was used for LRO's instrument commissioning period, slightly different apsis altitudes were needed in the extended mission periods.⁷ The periselene and aposelene altitude histories for LRO's frozen orbits are shown in Figure 3. There were several different "flavors" of the frozen orbit where the periselene altitude that varied from 20 to 40 km. There were three Frozen Orbit (FO) Reset maneuvers performed on April 29, 2013 (2.7 m/s), April 3, 2014 (3.8 m/s), and May 4, 2015 (5.7 m/s). These maneuvers reset the frozen orbit to bound the periselene altitude within a 20 km band.

An additional maneuver was performed on December 13, 2012 to assist in real-time viewing of the twin impacts of the Gravity Recovery and Interior Laboratory (GRAIL) spacecraft (GRAIL-A and GRAIL-B) as they ended their mission on December 17, 2012. This GRAIL Phasing Maneuver (GPM) is indicated by the aposelene discontinuity in Figure 3. While LRO's orbit plane was serendipitously aligned to go over the GRAIL-A and -B impact locations (75.61° N, 333.41° E and 75.65° N, 333.17° E, respectively) near Philolaus crater, LRO would be over a quarter of an orbit away at the time of impact. To remedy that, a 3.2 m/s retrograde GRAIL Phasing Maneuver (GPM) was performed near periselene on December 13, 2012 to decrease the aposelene and increase the orbit period by 45 seconds. This served to "phase" LRO to along its orbit by 111.9° in over 4 days and allow the LRO instruments to attempt to observe the debris clouds 12 seconds after the GRAIL impacts. The maneuver was executed to within 2 mm/sec of the plan and LRO flew by the impact within 0.5 seconds of the desired time. The LRO instruments measured heating from the impact craters as well as observed Mercury and Hydrogen in the impact ejecta. The LROC instrument was able to find the craters made by the small GRAIL spacecraft as seen in the before/after images of the impact locations shown in Figure 4.

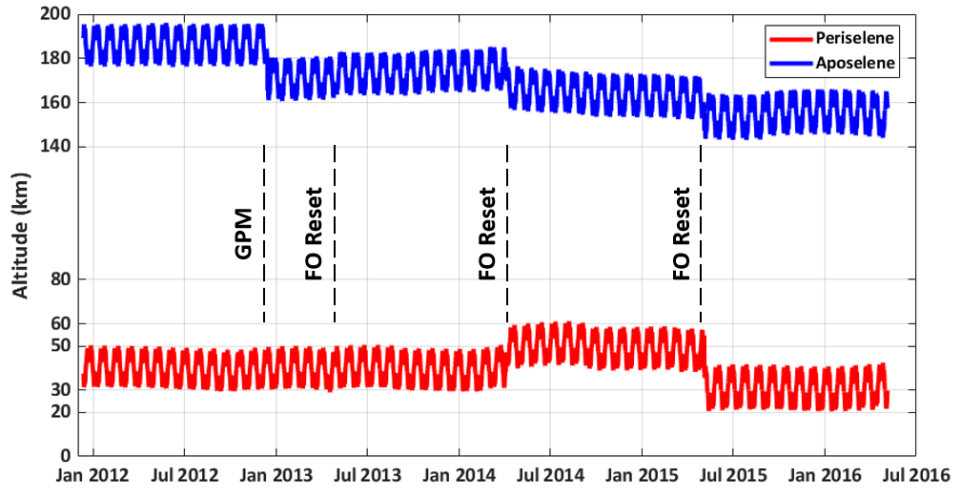


Figure 3: LRO Frozen Orbit Apsis Altitudes Showing GRAIL Phasing Maneuver and Resets

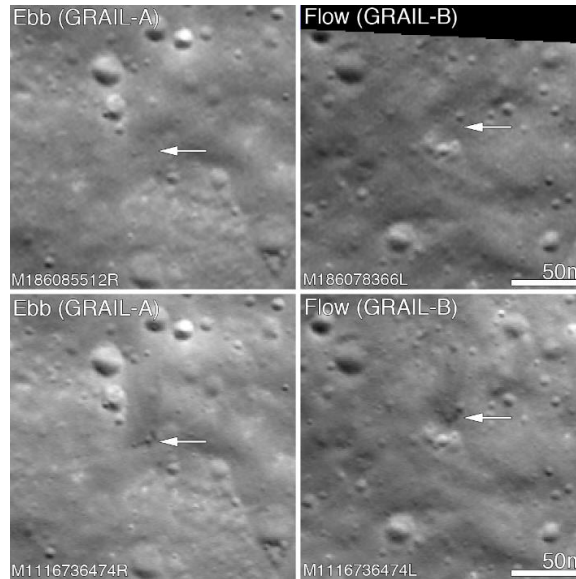


Figure 4: LROC Observation of GRAIL-A (left) and -B (right) Impact Craters Before Impact (top), After Impact (bottom)

[Image Credit: NASA/GSFC/Arizona State University]

The GPM was one of 12 special phasing maneuvers that LRO has performed (see below for further information) but it was over 4 times the size of any of the other 11. The large size is attributed to the short time (only 4 days) available to obtain the large orbit phase change.

The decision was made in 2016 to stop using fuel to maintain a frozen orbit and to allow LRO's orbit to drift. At this point, LRO was in a 90-km average altitude orbit with the eccentricity trending towards zero (i.e. circular). The evolution of the orbit apses from the end of frozen orbit maintenance through July 2023 is shown in Figure 5.

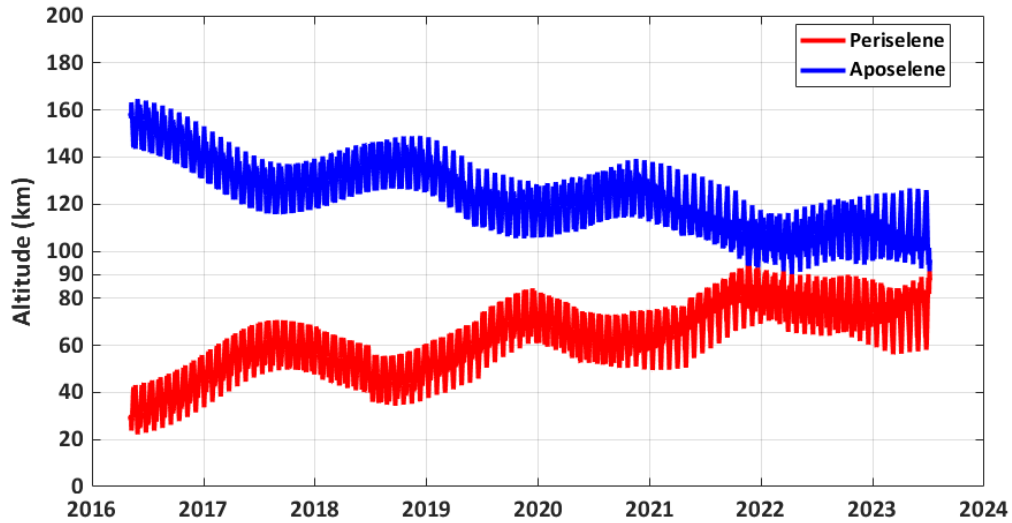


Figure 5: LRO Orbit Evolution Without Frozen Orbit Maintenance

The extended mission phases also revealed a trend in LRO’s orbit inclination evolution. Throughout the mission, it was observed that the orbit inclination wandered from its original Moon-Fixed average near 90° . In addition to a monthly oscillation as LRO flies over the entire lunar surface, a secular decrease in the inclination of approximately 0.4° per year was observed (**Error! Reference source not found.**). Long-term simulations predict the orbit inclination does reach a minimum near 83.5° in mid-2028 before beginning to rise again. Inclination control to keep the orbit polar could have been possible but the ΔV cost (roughly 14 m/s per year) would have prevented LRO from operating as long as it has.

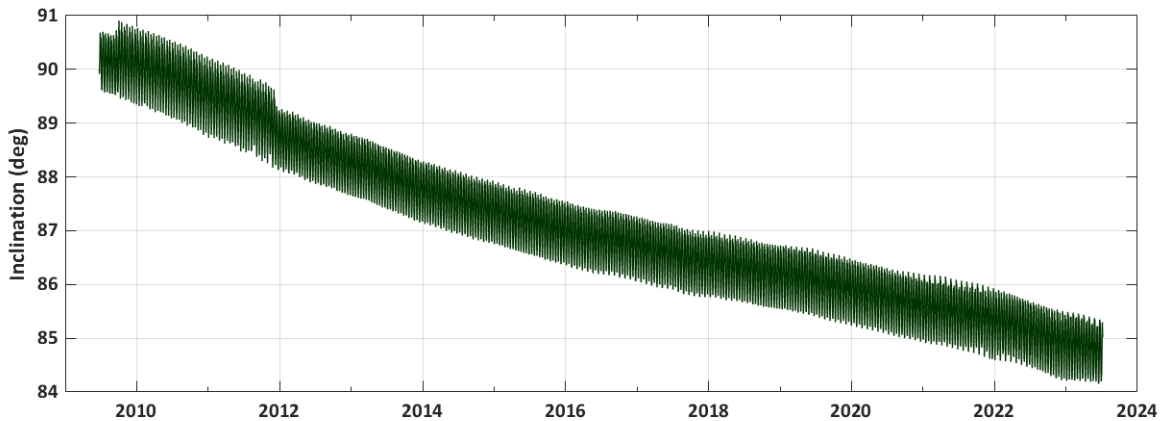


Figure 6: LRO Moon-Fixed Inclination History Since Launch

ECLIPSE OPERATIONS

One important item to consider for long-duration lunar missions is surviving potentially long lunar eclipses where the Earth comes between the Moon and the Sun. This happens usually twice per year but can happen as many as four times. The lunar eclipses come in three flavors – penumbral, partial, and umbral (Figure 7). The penumbral and partial eclipses are relatively benign; however, the total eclipses can last over 5 hours from penumbra entry to exit with as much as 1 hour, 40 minutes spent in the Earth’s umbral cone. During LRO’s mission, we’ve analyzed 33 eclipses to help the Mission Operations Team (MOT) develop command loads for either flying through the eclipse with all instruments on or determining how to load-shed instrument power to minimize battery depth of discharge.

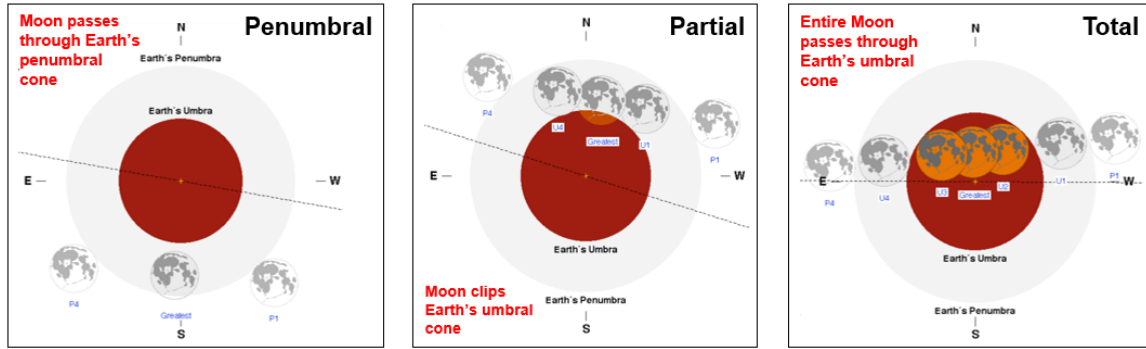


Figure 7: Lunar Eclipse Types*

As an example of eclipse management, consider the total lunar eclipse on May 16, 2022 (Figure 8). Months before the eclipse, we generated a series of solar intensity profiles as a function of LRO's orbit position at the time of maximum eclipse. LRO's Moon-Fixed Argument of Latitude (AOL), the angular location relative to the ascending node, is used as the position metric to differentiate the potential solar intensity profiles. These profiles represent the percentage of solar input that is available to reach the solar array. The LRO Systems Engineers use these solar intensity predictions (see samples in Figure 9) to estimate the power draw through the eclipse.

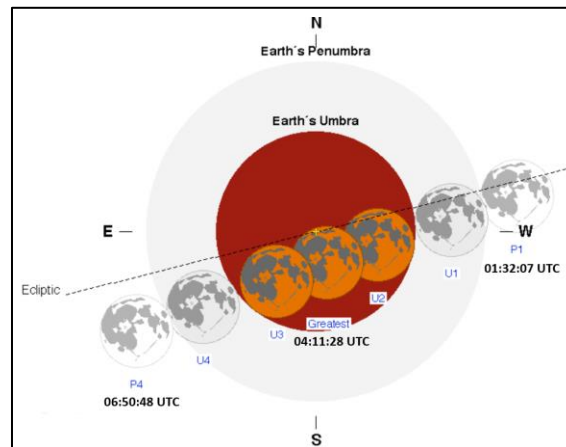


Figure 8: May 16, 2022 Lunar Eclipse Example†

The Systems Engineering team used this data to estimate the battery minimum voltage, ampere-hour (AH) usage, and battery minimum state of charge over the profiles for a specific AOL to determine an acceptable range of AOL values. The May 16, 2022 eclipse analysis determined that there was a generous, 140° range of acceptable AOL values from 180° – 320° (Figure 10).

* Figures courtesy of Fred Espenak, NASA/Goddard Space Flight Center (<https://eclipse.gsfc.nasa.gov>)

† Ibid.

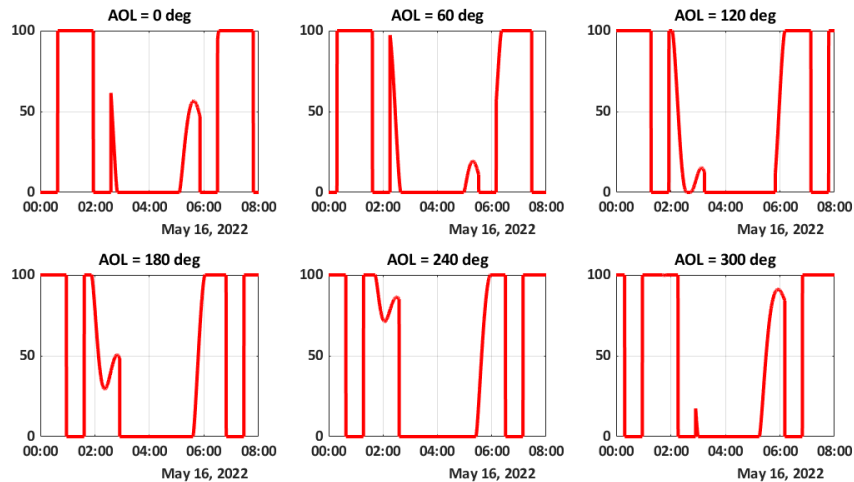


Figure 9: Sample Solar Intensity (%) Profiles for May 16, 2022 Lunar Eclipse

At that point, the focus changed to see how we could get LRO within the acceptable AOL range. Usually, this takes the form of designing a dedicated phasing maneuver to put LRO in the most optimal position during the eclipse. Small Eclipse Phasing Maneuvers (EPMs), typically less than 1 m/s, were performed three weeks ahead of the eclipse event to allow the small period change to translate into a downstream along-track position shift. The size and timing of these eclipses allowed LRO to potentially phase as much as 180° (forward or backward) in its orbit in those 3 weeks.

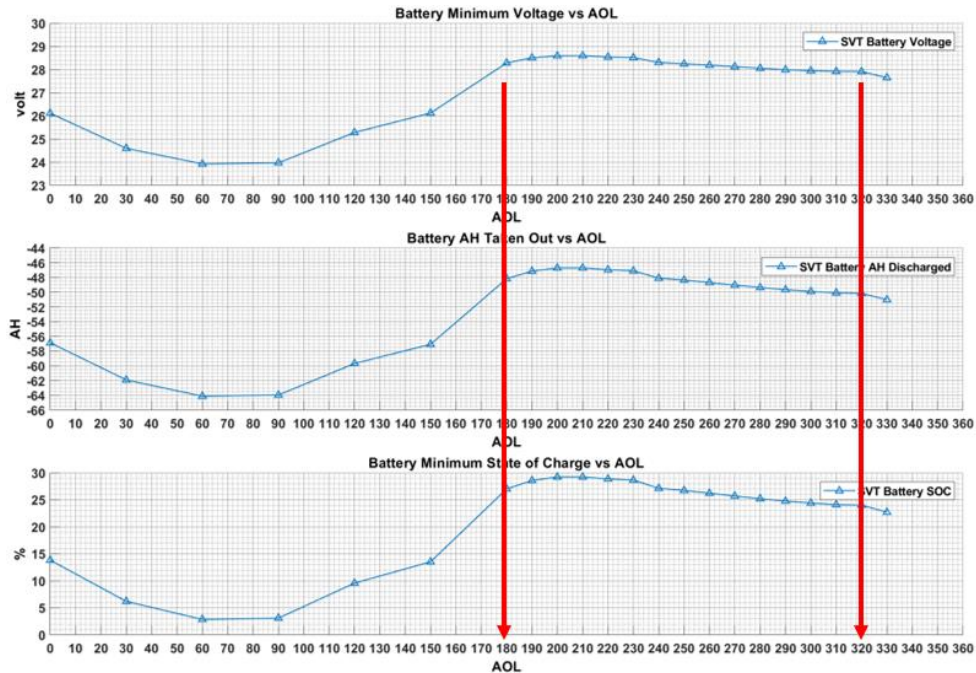


Figure 10: Acceptable AOL (degrees) Range for May 16, 2022 Lunar Eclipse

Over the 33 lunar eclipses, there were nine eclipse events that required dedicated eclipse phasing maneuvers (EPMs) to minimize the battery depth of discharge. The dedicated EPMs occurred beginning in 2014, as eclipse phasing prior to then was accomplished by adjusting required stationkeeping maneuvers to both reset the science orbit and phase for downstream eclipses.

MANEUVER PERFORMANCE

As of July 22, 2023, LRO has completed 391 maneuvers in its 14 years of operations. These maneuvers are detailed below.

- 1 Mid-Course Correction (MCC) to correct for launch vehicle insertion dispersions
- 6 Lunar Orbit Insertion (LOI) maneuvers to capture into lunar orbit and establish the commissioning orbit
- 1 Mission Orbit Insertion (MOI) maneuver to move from the commissioning orbit to the science orbit
- 30 pairs of Stationkeeping (SK) maneuvers to maintain the science orbit
- 4 pairs of SK maneuvers to establish and reset the frozen orbit
- 302 Momentum unloads to off-load system momentum from LRO's reaction wheels
- 3 special phasing maneuvers to coordinate operations with the Chandrayaan, LCROSS (Lunar Crater Observation and Sensing Satellite), and GRAIL orbiters
- 10 EPMS to mitigate the effects of lunar eclipses

Reference 6 contains details on the MCC, LOIs, and MOI maneuvers. The following sections will discuss the stationkeeping, momentum unloading, and phasing maneuvers.

Stationkeeping Maneuvers

As mentioned previously, each stationkeeping sequence involved a pair of maneuvers with the first, the “a” maneuver, being posigrade and the second, the “b” maneuver, being retrograde. Figure 11 shows all the SK a & b maneuver magnitudes for LRO. The typical SKa or SKb individual maneuver magnitudes were near 5.5 m/s but there were some sequence variations, as shown below.

- SK26 initiated the first Apollo Viewing Campaign on August 10, 2011
- SK27 returned LRO to the nominal SK cycle
- SK29 initiated the second Apollo Viewing Campaign on October 31, 2011
- SK30 returned LRO to the nominal SK cycle
- SK31 moved LRO to a frozen orbit on December 11, 2011
- SK32 reset the frozen orbit on April 29, 2013
- SK33 reset the frozen orbit on April 3, 2014
- SK34 reset the frozen orbit on May 4, 2015

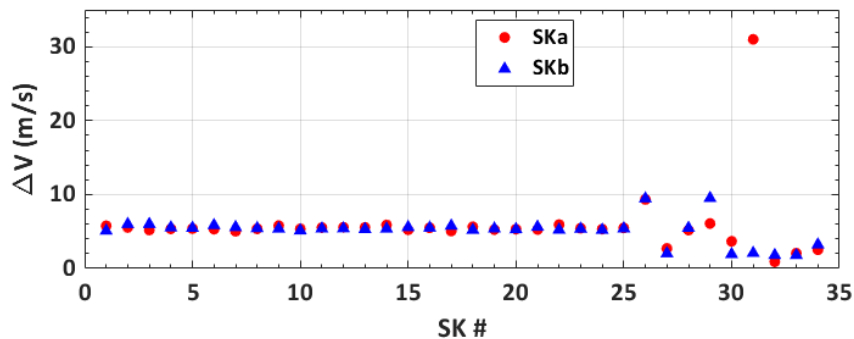


Figure 11: LRO Stationkeeping ΔV History

The individual SK maneuvers were completed to within 12 cm/s of the planned value (Figure 12, top) and the average error magnitude was 2.7 cm/s. Similarly, the SK ΔV errors were typically within 1% of the originally planned size (Figure 12, bottom) with an average error of 0.5%.

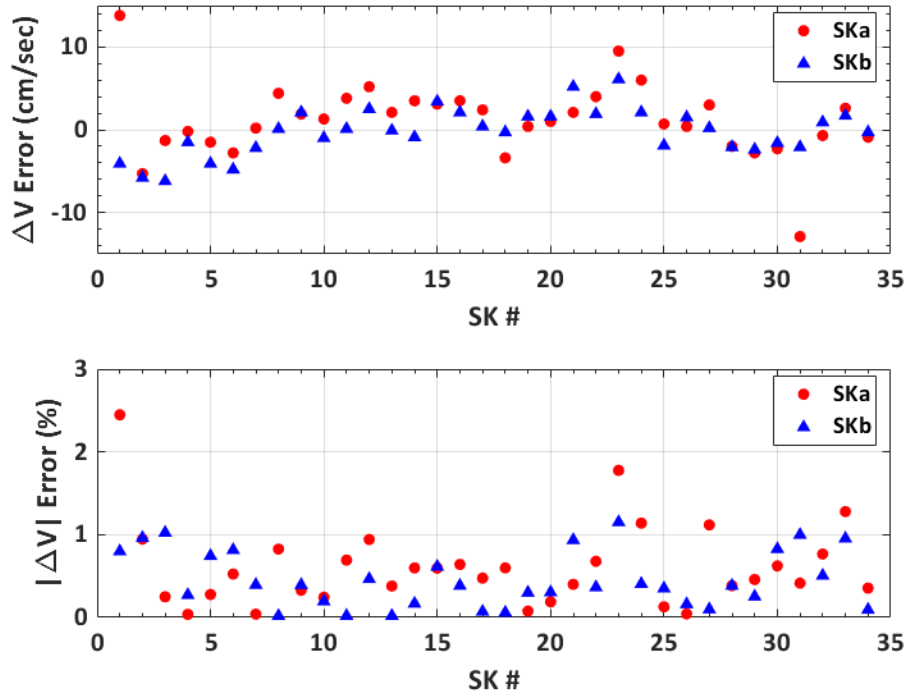


Figure 12: LRO Stationkeeping ΔV Error Magnitude (top) and Percent (bottom)

Momentum Unloads

LRO flies in a Moon-pointed orientation with its +Zbody axis nadir pointed and the +Y body in the plus or minus orbit normal direction such that the Sun vector is on the -Ybody side (i.e., solar array side) of the spacecraft. This orientation places the +Xbody axis in the velocity or anti-velocity direction, depending on the season. Figure 13 shows an example of this attitude with LRO in its “+X backwards” orientation. The Sun vector (orange) is “up” and shows how the Sun in this low-beta angle orientation can induce a solar torque from LRO’s single-wing solar array design. This solar torque is compensated by LRO’s reaction wheels but requires periodic thruster firings to off-load excess system momentum when the momentum storage capacity approaches a limiting value. Since launch, LRO has performed 302 momentum unloading maneuvers where thrusters are fired to reduce the system momentum stored in LRO’s reaction wheels. Momentum unloads typically occur every 2-4 weeks depending on the solar beta angle and spacecraft operations.

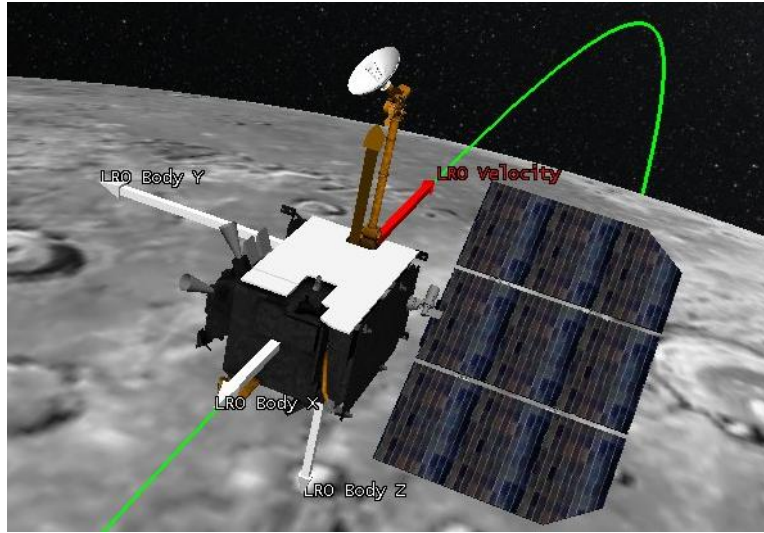


Figure 13: LRO Orientation in Flight

Early in the mission, the momentum unloads were performed in the $\pm$ orbit normal direction to minimize the along-track perturbative effects of firing LRO's attitude control system (ACS) thrusters. The momentum unloading maneuvers were performed in closed-loop DeltaH (H = momentum) mode with LRO's inertial measurement unit (IMU) as the key sensor in the control loop. However, degradation in LRO's IMU led to the decision to turn off the IMU in 2018 to save its remaining lifetime for when it absolutely needed (e.g. safhold mode). A new, open-loop DeltaH mode was developed to perform momentum unloading maneuvers. This new mode is referred to by the LRO team as a 1-shot unload and is monitored in real-time by the Mission Operations Team (MOT). Procedures are used to command single firings (i.e. 1-shots) of the ACS thrusters to offload system momentum. The procedure then waits until attitude disturbances damp out to acceptable levels before commanding another 1-shot. This mode continues until the System Momentum has decreased to an acceptable level. A comparison of the two modes is shown in Figure 14 for the two unload types. Both modes successfully reduce the system momentum but the 1-shot mode requires the controllers to wait until attitude errors damp out before commanding another thruster pulse. The MOT has performed 94 of these 1-shot momentum unloads since the procedure was first implemented in August 2018. The duration of the 1-shot unloads have ranged from 7 to 40 minutes in duration.

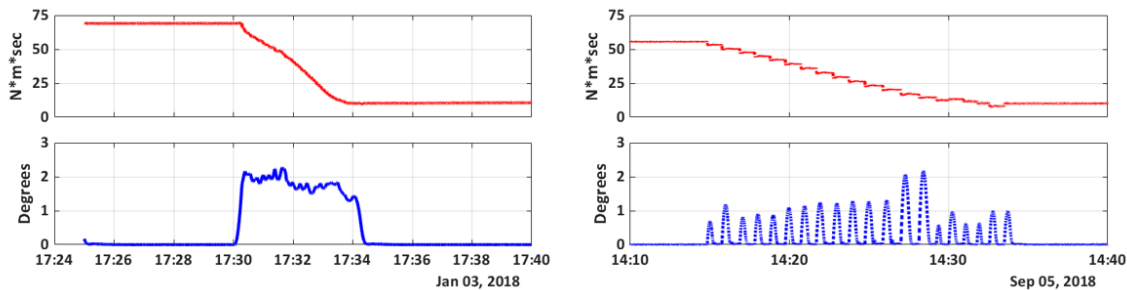


**Figure 14: Example LRO Momentum Unloads
System Momentum (top) and Attitude Error (bottom)
(Left: Closed-Loop | Right: Open-Loop, 1-Shot)**

Careful observation of maneuver performance without the IMU created an opportunity for performing DeltaV maneuvers without using the gyro. The 94 1-shot unloads were calibrated to determine the effective DeltaV caused by the thruster firings. Plotting this data shows a linear relationship between accumulated thruster on-time during the unload and the resultant ΔV (Figure 15).

The MOT developed a procedure using this relationship that keeps track of accumulated thruster on-pulses until the desired ΔV has been met. The new mode was used for EPMs that were performed in November 2021 and May 2022. The use of this new mode has allowed the team to save the IMU for when absolutely needed.

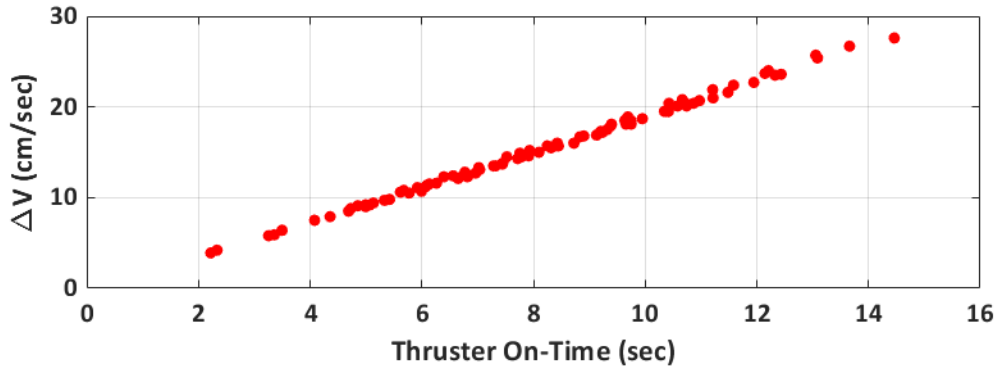


Figure 15: ΔV vs. Accumulated On-Time Based on Momentum Unloads

Phasing Maneuvers

LRO has performed 13 phasing maneuvers – 3 were to coordinate imaging with other lunar assets and 10 were for dedicated EPMs.

The coordinated imaging phasing maneuvers with Chandrayaan (1.382 m/s), LCROSS (0.567 m/s), and GRAIL (3.261 m/s) were executed to within 2 cm/sec of the planned value and satisfied their respective timing constraints.

The 10 EPMs were used to phase LRO for 9 separate eclipses (one EPM used 2 maneuvers). The first seven EPMs were performed in the closed-loop DeltaV mode using the IMU (Table 2). The maneuver magnitude error was less than 2 cm/s and all successfully placed LRO within the desired AOL range during its respective eclipse.

Table 2: EPM Statistics

EPM Date	ΔV (m/s)	ΔV Error (cm/s)
20140915	0.636	-1.6
20150312	0.411	-0.9
20150904	0.403	0.4
20180109	0.273	-0.6
20180703	0.797	1.4
20190624	0.758	0.1
20210503	0.849	0.5

The other two EPMs for lunar eclipses on November 19, 2021 and March 25, 2022 were executing using a new 1-shot ΔV mode derived from the previously discussed 1-shot momentum unloading procedure. There were a pair of maneuvers performed in October of 2021 to help phase LRO for its lunar eclipse on November 19, 2021. These maneuvers were the first to try out the 1-shot ΔV mode described above. Those maneuvers were successful in phasing LRO for the eclipse but some procedure adjustments were needed. The changes were made and the procedure was used again on March 25, 2022 to phase LRO for the lunar eclipse on May 16, 2022. For that eclipse, we determined that we needed 16.224 seconds of accumulated

thruster on-time to provide the desired 0.316 m/s needed for phasing. The results of this unload are seen in Figure 16.

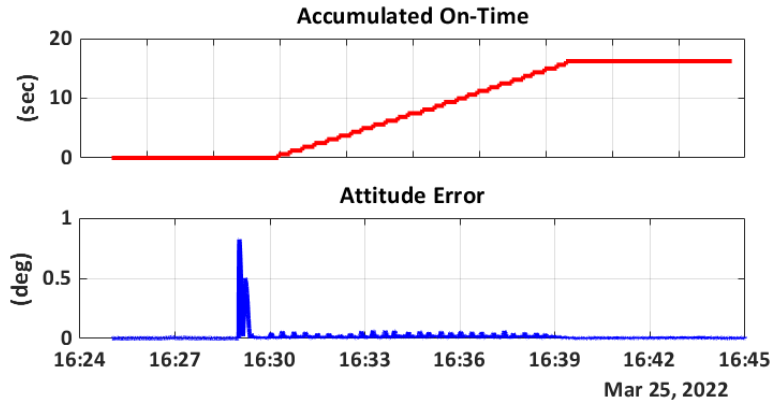


Figure 16: 1-Shot ΔV EPM

The first thing to notice is a large attitude transient before the maneuver began at 16:30 when the LRO attitude source is switched from the Kalman Filter to the star trackers – the filter is disabled during 1-shot maneuvers because of the time needed for reconvergence. The 1-shot ΔV pulses begin after those disturbances are damped out and there are much smaller attitude disturbances than are seen in a 1-shot momentum unload (refer back to Figure 14). The smaller attitude disturbances stem from more-balanced thruster pulses available while firing all 4 thrusters in a DeltaV pulse whereas momentum unloading pulses, by their nature, are unbalanced to create a torque along a particular axis. The 1-shot DeltaV maneuver performed on March 25, 2022 was calibrated at 0.322 m/s, only 6 mm/sec more than planned. This maneuver helped to phase LRO within the desired AOL box for the pending eclipse on May 16, 2022.

THE FUTURE OF LRO

LRO’s tanks were filled to capacity with 894.4 kg of hydrazine at the time of its launch. Over two-thirds of that fuel was used to capture into lunar orbit and maneuver to establish the initial 50 km average-altitude science orbit and an additional 184 kg of fuel was used for stationkeeping and routine momentum unloading in the science orbit (Figure 17). Since the move to the initial frozen orbit in late 2011, LRO has only consumed 33.9 kg of fuel for frozen orbit maintenance, phasing maneuvers, and momentum unloading (Figure 17, inset).

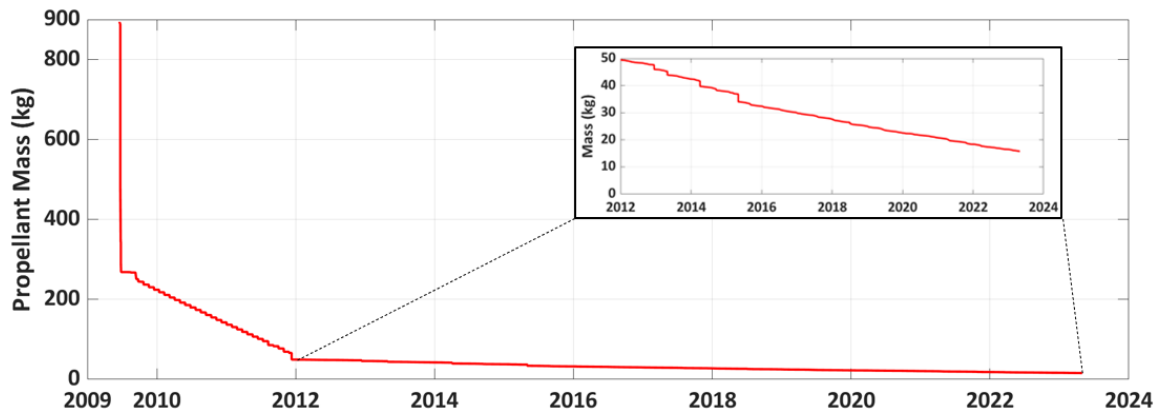


Figure 17: LRO Fuel Mass History

As of July 22, 2023, LRO has 10.7 kg of usable fuel remaining after accounting for 5 kg of “line losses”. LRO’s remaining lifetime, as it relates to fuel usage, depends on the momentum unloading fuel usage rate

and how many EPMs are needed to mitigate the effects of lunar eclipses. LRO's momentum unloading fuel usage rate is roughly 1.8 kg per year, however, the LRO Systems Engineering team has been implementing attitude slews to control momentum buildup. Normally, LRO needs to perform momentum unloads every 2 - 4 weeks. However, a new attitude slew scheme, to be presented in a future paper, has allowed LRO to fly without momentum unloading maneuvers since May 1, 2023 – a period of 12 weeks as of July 22, 2023. LRO's momentum unloading fuel usage rate could be reduced to 1.1 kg per year if this trend holds going forward. Regarding EPM costs, the maximum allowed per phasing maneuver is 0.5 kg but the average of the nine EPMs so far is 0.29 kg. Using those numbers, LRO's estimated lifetime, with respect to fuel usage, is 4.9 – 7.7 years. Over that time, LRO's orbit remains well bounded with respect to its orbit apses Figure 18.

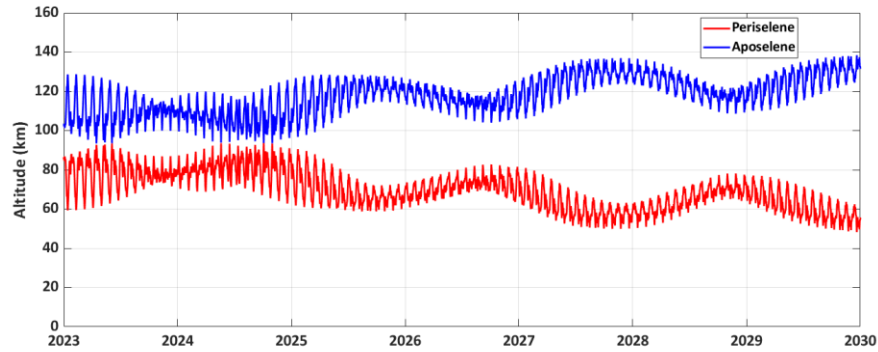


Figure 18: Predicted LRO Apsis Altitudes through 2030

CONCLUSION

LRO has been orbiting the Moon for over 14 years providing a treasure trove of data for the science community. LRO maintained its 50-km science orbit for 2+ years and different flavors of a frozen orbit for 4+ years. Since then, LRO's orbit has been allowed to evolve naturally without maintenance (Figure 19). LRO is in currently in a stable, bounded orbit with sufficient fuel for 5-7 more years of operations.

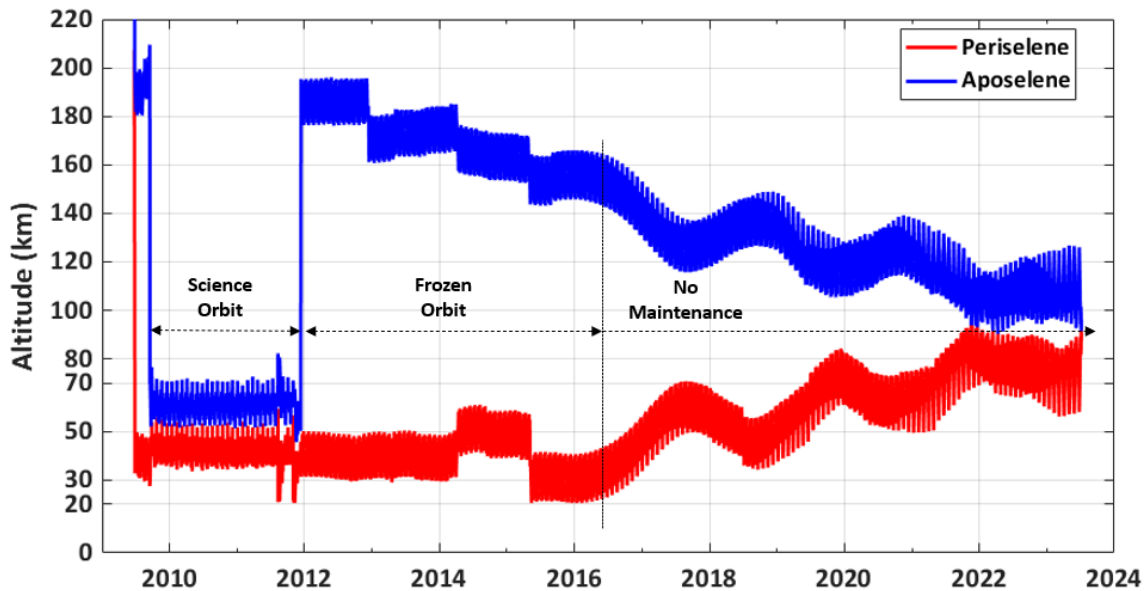


Figure 19: LRO's Orbit Apsis History

Scientifically speaking, LRO data is the source of over 1000 papers by LRO and non-LRO scientists. LRO is the first mission to observe meteorite impacts on an airless body, identify new forms of lunar volcanism, and map permanently shadowed and continuously sunlit areas near the Moon's poles. In a mission enabling sense, LRO data is used by numerous commercial companies and international agencies for designing missions to the lunar surface. For mission designers and operations analysts, LRO presented its own challenges. The team learned how to maneuver LRO to mitigate long-duration lunar eclipses and invented new ways to perform maneuvers to compensate for aging hardware. In all, the experiences learned during LRO operations can be a benefit to the next generation of mission designers when considering future low-lunar orbiting missions.

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