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CONTROL OF THE LUNAR RECONNAISSANCE ORBITER REACTION WHEEL ANGULAR MOMENTUM USING ATTITUDE SLEWS

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The Lunar Reconnaissance Orbiter (LRO) makes use of four Reaction Wheel Assemblies (RWA) for the purpose of adjusting and maintaining the spacecraft attitude. Reduction of RWA angular momentum through the use of propulsive momentum unloads is the principal source of fuel use. Nominally, LRO maintains a nadir orientation but frequently slews off-nadir for science observations. Off-nadir attitude slews can reduce RWA angular momentum by changing the direction of the external torques in the spacecraft body frame. Control of RWA angular momentum using momentum attitude slews has the potential to significantly reduce fuel expenditure. The momentum slew planning process requires careful evaluation of spacecraft constraints, ground constraints, and science observations. Momentum slews are projected to extend LRO fuel lifetime by several years.

INTRODUCTION

LRO was launched in 2009 into a Lunar elliptical orbit with a three-year mission to study the Moon and is still operating 15 years later. It has the following instruments: Cosmic Ray Telescope for the Effects of Radiation (CRaTER), Diviner Lunar Radiometer (DLRE), Lyman Alpha Mapping Project (LAMP), Lunar Exploration Neutron Detector (LEND), Lunar Orbiter Laser Altimeter (LOLA), Lunar Reconnaissance Orbiter Camera (LROC), and the mini-RF technology demonstration. LRO is currently in its fifth mission extension (ESM-5) slated to end October 2025. Momentum unloads account for most of LRO's fuel usage. To extend LRO's fuel lifetime, various efforts have been made to optimize the execution of momentum unloads. With the additional fuel saved using momentum lowering slews, planning is underway for a full three year ESM-6 to end October 2028.

This paper focuses on the development of a process for planning momentum slews in order to control RWA angular momentum. An overview of earlier conceptional work on finding slews to optimize momentum change is presented. The LRO high fidelity (HiFi) simulator is introduced, and corrections to the LRO HiFi momentum, to match the actual spacecraft momentum, are discussed. Including the momentum lowering slews in the daily operational schedule is subject to multiple spacecraft constraints, operational constraints and planned science instrument observations. The slew planning process evaluates the momentum changes for a large number of potential slews which are subsequently down selected. Results of momentum slew planning since May 2023 are presented, along with updates to the forecast fuel lifetime. Future work will make the process more efficient and transition from an analysis effort to an operational process.

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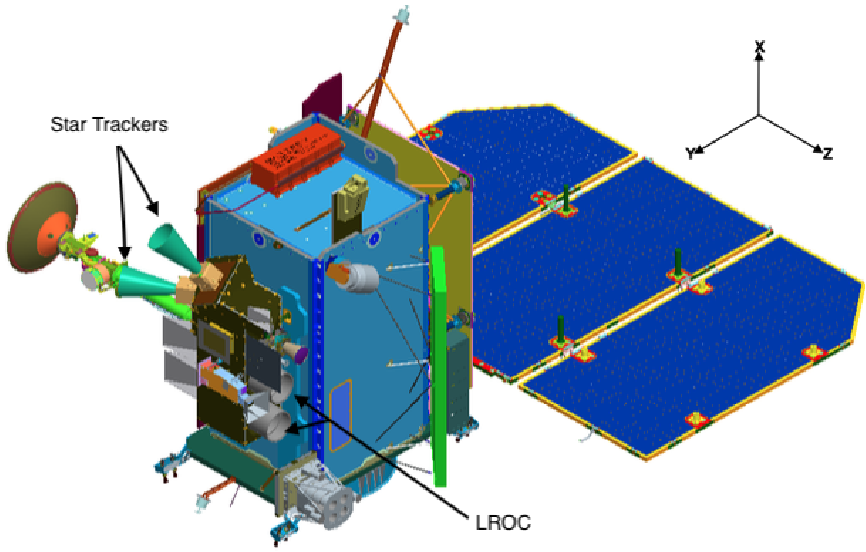

Figure 1. LRO Spacecraft and Body Coordinate System

GRAVITY GRADIENT ANGULAR MOMENTUM MANAGEMENT

LRO momentum management using attitude holds dates back to 2014, when a conceptional plan was developed on the basis of examining angular momentum trends, gravity gradient torques, and solar radiation pressure torques.[1] The goal was to eliminate the need for propulsive angular momentum unloads by lowering the rates of momentum growth within the orbit plane and perpendicular to the plane.

RWA angular momentum growth was observed to be dependent on solar beta angle and solar array configuration. LRO has single solar array with two axis gimbal. The configuration of the LRO solar array gimbal actuators varies by solar beta angle to manage the gimbal thermal environment to prevent lubricant evaporation (Table 1). RWA momentums are reported in the Body Coordinate System (BCS). The X and Z axes momentums (Hx and Hz) oscillate, but the root-sum-square of these momentums (Hxz) evolves secularly. The Y-axis momentum (Hy) also evolves secularly. During Low Beta configurations, when the solar array is tracking the Sun, Hy increases at about 5 Nms/day and Hxz increases at about 4 Nms/day. During configurations where the solar array remains in a fixed orientation, Hy decreases at about -1 Nms/day and Hxz increases at about 2 Nms/day. The differences in these natural momentum rates between low and high beta angle help establish targets for planning slews.

Table 1. Solar Array Configurations

Solar Beta Configuration	Solar Beta Angle (degrees)	Inner Gimbal (degrees)	Outer Gimbal (degrees)
Low, Offset +30	$< \|30\|$	Tracking	Tracking Offset +30
Low, Offset -30	$< \|42\|$	Tracking	Tracking Offset -30
Moderate	$< \|55\|$	Fixed -90	Fixed +45
High	$< \|75\|$	Fixed -90	Fixed +15
Extreme	$> \|75\|$	Fixed -90	Fixed +5

Gravity gradient torques act throughout the entire orbit but were found to peak at about 3 x10^{-4} Nm. The gravity gradient approximately averages out over the course of an orbit for the orbit plane momentum (Hxz), but does not equalize for the out-of-plane momentum (Hy). Solar radiation pressure torques act only during daylight portions of the orbit with magnitudes of 1.4 x10^{-4} Nm at orbit noon. The solar radiation pressure torque acts primarily on the solar array, which has an area of 12 meter^2 and is offset from the spacecraft center of gravity by 2.6 meters in Y-axis and 0.79 meters in X-axis. Solar radiation pressure torques switch signs at solar beta = 0 and 90 degrees. During portions of the orbit that are entirely in daylight, the effect of solar radiation pressure torque averages out.

This earlier analysis examined the effect of using Pitch and Roll slews placed throughout the orbit to effect momentum control. Analytic predictions of momentum changes were compared with actual flight data. The telemetry reflects momentum changes due to secular rates, oscillations, and slews. To estimate the momentum change, the secular rate was subtracted using a linear estimate of the momentum rate prior to the slew. Executed slews were found to have momentum changes appreciably larger than the analytic prediction, pointing to the need for more flight testing and eventually for a high-fidelity momentum simulation.

HIGH FIDELITY MOMENTUM SIMULATION

A high-fidelity (HiFi) Simulink model was created during development of LRO to test the Guidance, Navigation, and Control (GNC) system. In 2018, the Miniature Inertial Measurement Unit (MIMU) began to degrade in the X-axis and was powered off to preserve usage for recovery from anomalies. Onboard software was updated with a gyroless algorithm that relies on differentiated star tracker quaternions and integrated control torques for rate estimation. The HiFi model was also updated with the gyroless algorithm.[2] The implementation of this algorithm onboard allows LRO to conduct off-nadir slews but with restrictions on occultation of the star trackers since they are necessary to provide the onboard rate estimate.

The HiFi model is used for momentum forecasting to target momentum unloads and to plan momentum slews. The predicted HiFi RWA momentum diverges from telemetry at approximately a linear rate. To accurately forecast RWA momentum seven days ahead or more, an algorithm was developed to calculate the linear correction for the Hxz and Hy momentums.

SLEW CONSTRAINTS

Momentum slews must meet both spacecraft operational constraints and avoid conflicts with science observations. Operational constraints include star tracker occultations, +Z-axis interference, thermal constraints, power constraints, and ground communications contacts. Conflicts with science slews, nadir science observations, and other spacecraft events also must be considered. There are limits on the number of slews that can be conducted per day and per orbit.

Star Trackers

LRO has two star trackers mounted on the +Y-axis face of the spacecraft. With the star trackers in the critical path for attitude control, constraints were put in place to avoid occulting the star trackers during attitude slews. Evaluation of these constraints includes checking the Sun, Earth, and Moon angles with respect to the star tracker boresights against limits for these angles. For slews whose angular magnitude is less than 20 degrees, the constraint is relaxed to allow occultation on one star tracker.

Z-Axis Sun Angle

The LRO instruments are located on the +Z body axis. The Sun angle with respect to the +Z-axis is required to be above 60 degrees during orbit day to protect the LROC from sunlight impingement.

Thermal

LRO subsystems must be kept within thermal limits. Angular constraints on Sun and Moon angles are evaluated for thermal constraints (Table 2). For slews that exceed these angular constraints or have a total duration greater than one-half orbit, further evaluation of the slews is required prior to implementation.

Table 2. Thermal Angular Constraints for $\beta < 55$

Body Axis	With Respect To	Angular Constraint (deg)	Duration (minutes)
+Y	Sun	< 60	15
+X	Moon	< 45	57.5
+Y	Moon	< 60	10
+Z	Moon	> 45	57.5

Power

The Slew Verification Tool (SVT) models solar array power generation, system load, and power storage. The power generation routine calculates solar array gimbal angles and tracking configuration based on solar beta angle for the given Sun vector. The routine estimates array power output at each time step. The system load is based on observed total load and considers transmitter usage during ground contacts and other operational activities that would change the load profile. SVT models the battery capacity and issues a warning if the battery voltage drops too low for any given activity.

To maintain the battery charge, slews within 20 minutes of an orbit day/night transition are evaluated for total time that the solar array points away from the Sun. The combination of the slew duration during orbit day and eclipse duration is required to be less than 70 minutes.

Ground Site Passes

The LRO Mission Operations Team (MOT) uses S-band and Ka-band ground passes for the uplink and downlink of data. Slews are to be avoided during the Ka-band passes. S-band ground passes between 12:00 and 5:00 PM Eastern are reserved for uplinking of the daily command load, ephemerides, and other loads. Instrument teams can also reserve ground passes. The Diviner instrument team requests S-band passes for uplink. The LOLA instrument team will request an extension of certain S-band passes for the purposes of radio occultation observations.

Instrument Slews

Instrument slews are documented in the operational slew plan, which is released seven days prior to execution. Requested slews should avoid overlaps within 11.5 minutes of another slew to allow for reconfigurations and battery recharging. Other constraints can occur which need to avoid slews, such as a long lunar eclipse or a special instrument or spacecraft operation.

LROC Nadir Observations

When LRO is not performing instrument slews, the +Z-axis points nadir toward the Lunar surface. The LROC team employs +Z-axis nadir pointing to image targets of opportunity using the Narrow Aperture Cameras (NAC). The LROC team provides a list of these planned observations, which forecasts out seven days from the current day. Opportunities prioritized 1 or 2 are considered mandatory while those prioritized 3 or 4 are considered optional.

SLEW PLANNING PROCESS

The momentum slew planning processing consists of estimating momentum changes over a range of potential slews, evaluating constraints to exclude non-viable slews, and selecting slews based on momentum rates and momentum targets (Figure 8). Slews are planned seven days prior to execution. Owing to the required processing time, some steps are performed at the beginning of the planning day (slew definition, slew ΔH estimation, evaluation of star tracker, +Z-axis, and thermal constraints, as well as extrapolation/interpolation). The remainder of the steps are performed after receipt of the operational slew plan, which contains science instrument observation requests.

Slew Definition

Potential momentum slews are defined by on-target time, attitude angles (pitch, roll, yaw) and duration (Table 3). Argument of latitude, the sum of true anomaly and the argument of periapsis, is used to define the timing of the slew. Each argument of latitude reoccurs about twelve times each execution day. The benefits of using argument of latitude will be discussed in the extrapolation/interpolation section. Attitude angles define the slew for single-axis and two-axis slews; three-axis slews are excluded from consideration due to processing limitations. Duration defines the amount of time at attitude. For single-axis slews, duration is from the on-target time until the spacecraft begins to maneuver back to the nadir attitude. For two-axis slews, the duration applies to the second axis only; the first leg has a duration of one minute after the on-target time. Each slew definition is translated into a slew request. The slew request consists of on-Target time, duration, angle and settle time. For daily planning, approximately 4.5 million potential slews are considered. Due to processing limitations, a larger step size is used for estimation than for planning. As a result, only about 18,000 potential slews are evaluated for momentum change.

Table 3. Slew Definition Parameters

		Step Size	
Slew parameter	**Range**	**Planning**	**Estimation**
argument of latitude (deg)	0 to 360	10	30
attitude angles (pitch, yaw, roll) (deg)	-90 to +90	15	15
duration (minutes)	10 to 40	1	10

Momentum Change Estimation

Estimation of the momentum change associated with a slew (or sequence of slews) requires taking into account the natural secular and oscillatory momentum trends. To perform this chararacterization, two HiFi runs are required, one with the slews and one without them (Figure 2). By subtracting the no-slew run momentums from the slew run momentums (Figure 3), the effects of the secular and oscillatory trends are removed, leaving only the momentum change due to the slew(s). The differenced momentums are then smoothed using a five-minute moving average. The momentum changes (ΔHy and ΔHxz) for each individual slew can be obtained by subtracting points before and after the slew.

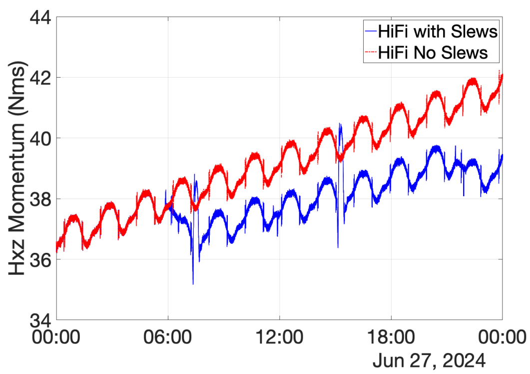

Figure 2. HiFi Hxz Momentum

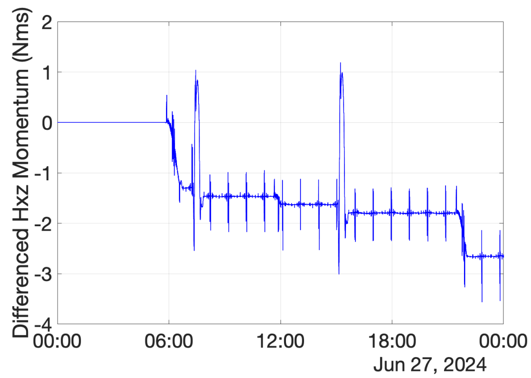

Figure 3. HiFi Hxz Differenced Momentum

For the range of potential slews, estimation is performed at least on a weekly basis. HiFi is run with baseline configurations without any slews. These baseline runs set up the initial conditions for HiFi runs with the potential slews. For each potential slew, the initial conditions from the baseline are modified to incorporate the slew. HiFi is run in parallel with the potential slews using the MATLAB Parallel Computing Toolbox. Momentums from the HiFi run with the slew and the baseline run are differenced to estimate the momentum change. For the approximately 18,000 potential slew cases, approximately 30 hours of processing time is required.

Extrapolation and Interpolation of Momentum Changes

Processing time limits the number of slews for which momentum change can be estimated. Once constraints are evaluated, a significant number of slews are excluded. Extrapolation and interpolation are used to expand the number of potential slews. Defining the slew in terms of argument of latitude allows for momentum changes to be estimated for a single orbit and then extrapolated to subsequent orbits. For slews with arguments of latitude between the estimated points, interpolation by argument of latitude is used. Additionally, slews are interpolated by duration.

Early in the development of this process, momentum changes for each slew attitude and duration were observed to be periodic, with the largest changes occurring near apoapsis (Figure 4). Argument of latitude was found to line up with the momentum changes from various orbits. The momentum changes estimated from this single orbit have shown reasonable consistency when applied over an entire day, approximately 12 orbits. Furthermore, these estimations have been extrapolated up to a week after the orbit used for estimation. Momentum change for a given slew does evolve over time as the solar beta angle changes, thus requiring frequent re-estimations.

Momentum change as a function of duration was found to be almost linear. However, a quadratic function was found to provide better agreement with the HiFi runs. For each argument of latitude and each slew attitude (pitch, roll, yaw), the momentum changes for ΔHy and ΔHxz were fit to a quadratic function of duration. For each slew attitude, duration interpolation has allowed expansion from three slews (10, 20, 30 minutes) to thirty slews (10 to 40 minutes in one-minute step size).

For fixed slew attitude and duration, momentum changes as a function of argument of latitude are continuous (Figure 5). Linear interpolation between argument of latitude points is performed using a step size of 10 degrees. This provides a three-fold expansion of the number of slews that were estimated using 30-degree step size.

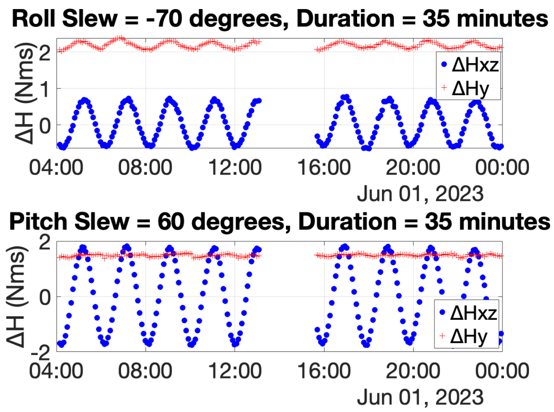

Figure 4. ΔH for Roll and Pitch slews by time

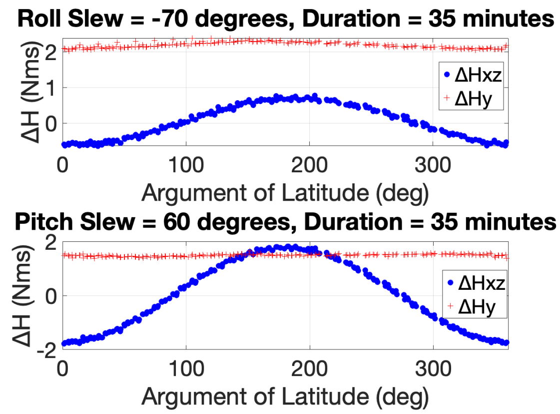

Figure 5. ΔH for Roll and Pitch slews by ArgLat

Constraints Evaluation

For the set of potential slews, the constraints are evaluated at the beginning of the planning day, after receipt of the daily operational slew plan. Constraints evaluated at the beginning of the planning day are: star tracker occultations, +Z-axis interference, thermal constraints, eclipse power constraints, and the slew duration constraint. Constraints evaluated after receipt of the operational slew plan are: ground site pass constraints, instrument slew conflicts, additional slew constraints, and LROC nadir opportunities conflicts and thermal issues. The battery voltage power constraint is only evaluated after slew selection.

Evaluation of star tracker occultations, +Z-axis interference, and thermal constraints requires the generation the predicted attitude over the span of the slew. Due to the processing time required, this evaluation is performed at the beginning of the planning day in conjunction with slew definition and extrapolation/interpolation of momentum changes.

Total slew duration is constrained to less than one-half orbit as an additional thermal constraint. This constraint is evaluated as part of slew definition.

Eclipse constraint evaluation is dependent on predicted eclipse times which are generated from the ephemeris and are evaluated at the beginning of the planning day. For slews that occur within ten minutes of orbit night (within twenty minutes when solar beta is less than $|\ 30\ |$ degrees), the time of the slew during orbit day plus the duration of orbit night must remain under seventy minutes. Slews with a total eclipse time greater than seventy minutes are excluded.

Momentum slew planning uses the latest operational schedule to evaluate ground pass conflicts. The first, second, and last Ka-band passes are marked as mandatory, as are S-band passes between 12:00 and 5:00 PM Eastern and passes requested by Diviner. Slew planning aims to avoid nonmandatory ground passes, unless doing so would exclude slews that prevent reaching momentum targets. Conflicts exist if any part of the slew overlaps the ground pass or if the end of the slew is within eight minutes of the start of a ground pass. The eight minute buffer is needed to allow LRO to reconfigure after the slew.

Conflicts with instrument slews and additional slew constraints are evaluated after receipt of the operational slew plan. The initial version of this plan is usually released around mid-morning and finalized in the early afternoon. To avoid conflicts, the evaluation needs to use the latest version the operational slew plan, since instrument teams may submit slew requests after the initial version of the operational slew plan. Momentum slews within 16 minutes of an instrument slew or an additional slew constraint are excluded.

After receipt of the daily operational slew plan, slews are evaluated against LROC nadir imaging opportunities for conflicts and thermal issues. Any slew within five minutes of an opportunity is flagged as conflicting. Slews are marked as having potential thermal issues if they occur during orbit day and have priority 1 or 2 opportunities within one orbit after slew end. Slews with conflicts with priority 1 or 2 opportunities or thermal issues are excluded from selection. The option remains whether or not to exclude slews that have conflicts with priority 3 or higher opportunities.

Momentum Forecast

HiFi is used to forecast momentum from the current day to the execution day. To provide an accurate momentum forecast, the HiFi momentum is corrected for divergence from telemetry. Then, the LRO Angular Momentum Unload Planning Tool (LAMUPT),[34] predicts momentum from the execution day to the next 60 Nms threshold crossing using regression equations.

The correction between HiFi and telemetry requires a quiet period with no slews, as significant momentum perturbations can affect the linear correction fit. To consistently provide such a period, momentum slews are not scheduled on Sundays. The start and end times of the fit period can be adjusted to avoid momentum perturbations. Generally, the HiFi/telemetry correction changes across solar array transitions. If the correction is estimated prior to the transition, a static correction is used after transition. If sufficient telemetry exists after transition, the period after the transition is used as the quiet period.

To predict the next 60 Nms threshold crossing, the momentum forecast must be generated out beyond the execution day. Running HiFi for long spans requires significant processing time. Instead, the end conditions of the HiFi run serve as initial conditions for the regression equations used in LAMUPT. These regression equations were previously estimated from telemetry between 2013 and 2014. The regression equations generally agree with HiFi, with the exception being the period after peak solar beta angle. A future study is to determine if the HiFi could be used to improve the regression equations for such cases.

Momentum targets used for slew selection are established using the momentum forecast. From the HiFi run without slews, an estimate of the daily momentum rates (dH_{xz}/dt, dH_y/dt) is made. If only maintaining momentum at current levels, these rates set the momentum change targets to be achieved by slews. Using LAMUPT, momentum is forecast out to solar array configuration changes. Differences in momentum rates between solar array configurations, such as when dHy/dt switches from negative to positive, can be beneficial in managing momentum. To best take advantage of these rate changes, momentum targets are set at the solar array configuration transition, which then guide the momentum change required of slews.

Slew Selection

Slews are selected from those that have passed constraint evaluation to meet momentum targets. The number of momentum slews that can be selected is dependent on the number of requested instrument slews. Manual and automatic methods were developed for selecting slews.

The MOT constrains the total number of large slews that can be planned within a 24-hour period. The reason for this constraint is to manage the workload associated with processing slew requests. Large slews are constrained to a maximum of 11 per day. The maximum for instruments is seven large slews. Thus, the number of possible momentum slews varies between four and eleven, depending on the number of instrument slews that are planned.

Manual selection uses plots of ΔHy versus ΔHxz for pitch, roll, yaw, pitch-roll, pitch-yaw, and roll-yaw slews that are not excluded by constraints (Figure 6). From these plots, individual points that correspond to a slew are manually selected on the basis of momentum change targets. The plots are updated to remove the selected slew and any slews that conflict with it. The user may continue to select slews from the plots until desired momentum targets are reached or the maximum number of slews is reached.

Automatic selection uses vector distances between slew momentum changes and target momentum changes to select the optimal slew. To obtain a trade space of possible slew selections, the selection process is performed over a range of momentum change targets and a number of slews. For each set of targets, the slews are iteratively selected. The iteration cycle begins by calculating the vector distance between slew and target momentum changes. The slew with the minimum distance is selected. Each time a slew is added to the slew request, any of the remaining slews that conflict will be excluded from selection. The momentum change targets are adjusted to account for the selected slew. The iteration continues until the number of slews is reached. The resultant sequence of slews may not meet the original momentum change targets, but rather shows what is feasible given the available slews (Figure 7).

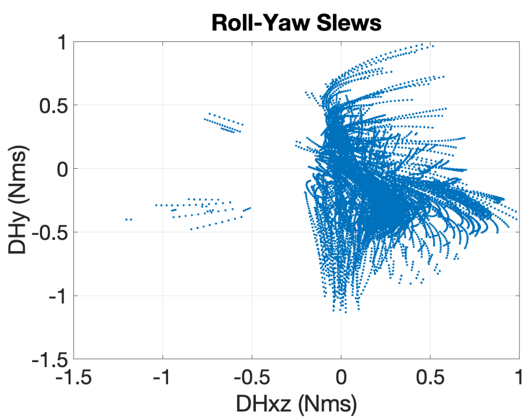

Figure 6. Roll-Yaw Slews ΔHxz/ΔHy

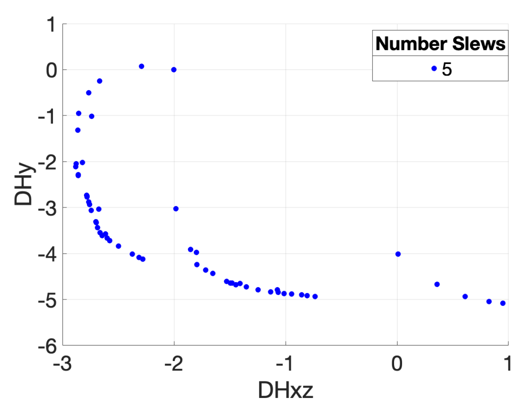

Figure 7. ΔHxz/ΔHy for Sequences of 5 Slews

Final Verification

The selected momentum slews, combined with the requested instrument slews is evaluated for constraint violations. Specifically, this verification checks star tracker occultations, +Z-axis interference, thermal constraints, power constraints, and conflicts between momentum slews and instruments slews. Conflicts with ground passes and LROC nadir observations are not checked in this step.

HiFi is run to simulate the momentum changes of the selected slews. These forecast momentum changes confirm that selected slews meet the momentum targets. Reductions in slew duration due to power constraints often result in reduced momentum changes.

Request Submittal

The selected slews are requested using an Operational Action Request (OAR) for each slew. These OARs are sent to the MOT and instrument teams to review for conflicts and constraints as well as for incorporation into the operational slew plan. Instrument teams help identify conflicts since their requests have priority. In cases where constraint issues or conflicts are identified after submittal, the slew requests must be replanned.

The MOT evaluates requested slews for conflicts with other planned slews, conflicts with ground passes, and checks star tracker, +Z-Axis, thermal and power constraints. Issues with the requested momentum slew may require modifications or cancellation, requiring the submittal of a new OAR. Power constraint issues can arise because of the combination of instrument slews, momentum slews, and ground passes. These issues can be resolved by decreasing slew duration at the expense of achieved momentum change. Conflicts with mandatory ground passes result in the cancellation of the momentum slew. For conflicts with instrument slews, the slew cancellation is negotiated with the instrument team, because instruments slews have the higher priority. In cases of canceled momentum slews, the strategy has been to make up for the momentum change on a subsequent day rather than try to replace the canceled slew.

Replanning is a manual process and imposes additional workload, thus every effort is made to identify constraints and conflicts prior to submitting the slew request. Momentum slews are only planned for the 24-hour period from midnight UTC seven days in the future. Planning momentum slews beyond this period risks conflicting with instrument slews. The planning process begins after the MOT has built the spacecraft commanding load to allow instrument teams to submit slews for the execution day. Occasionally, an instrument team may submit slew requests after the daily slew plan has been released. Those slew requests are added to the Additional Events file so that the momentum slew planning process can take that request into account.

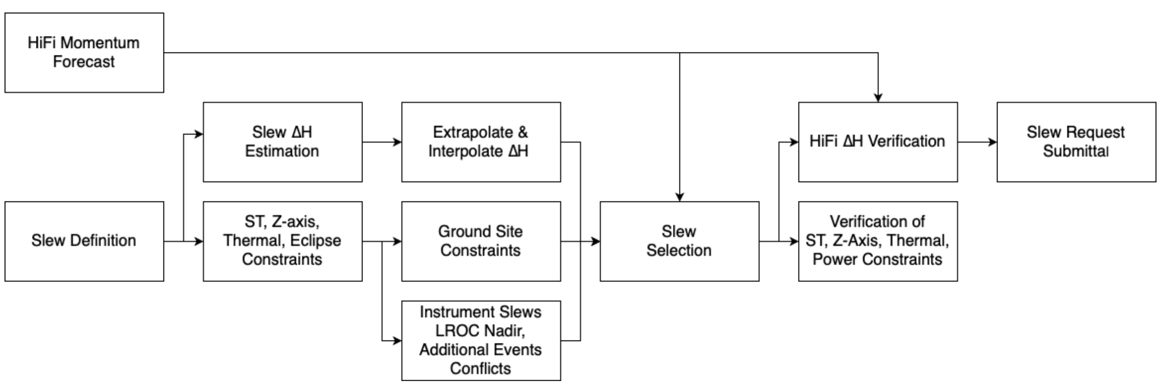

Figure 8. Slew Planning Process

MOMENTUM SLEW IMPLEMENTATION

Momentum slews executed by LRO have been planned using predicted momentum changes from HiFi. The first onboard test occurred in 2016, which resulted in delaying the need for a momentum unload by 42 days. In 2022 and 2023, individual slews were executed to validate the momentum changes predicted by HiFi and develop the process for integrating slews into the operational plan. LRO has been performing momentum slews to manage RWA angular momentum since 22 May 2023, during which the solar beta angle has proceeded through one full cycle. Momentum management using slews across all solar beta configurations has improved over time. The impact of these slews has led to a reduction in unloads and fuel usage, extending fuel lifetime. The process for planning momentum slews continues to evolve.

Momentum Management

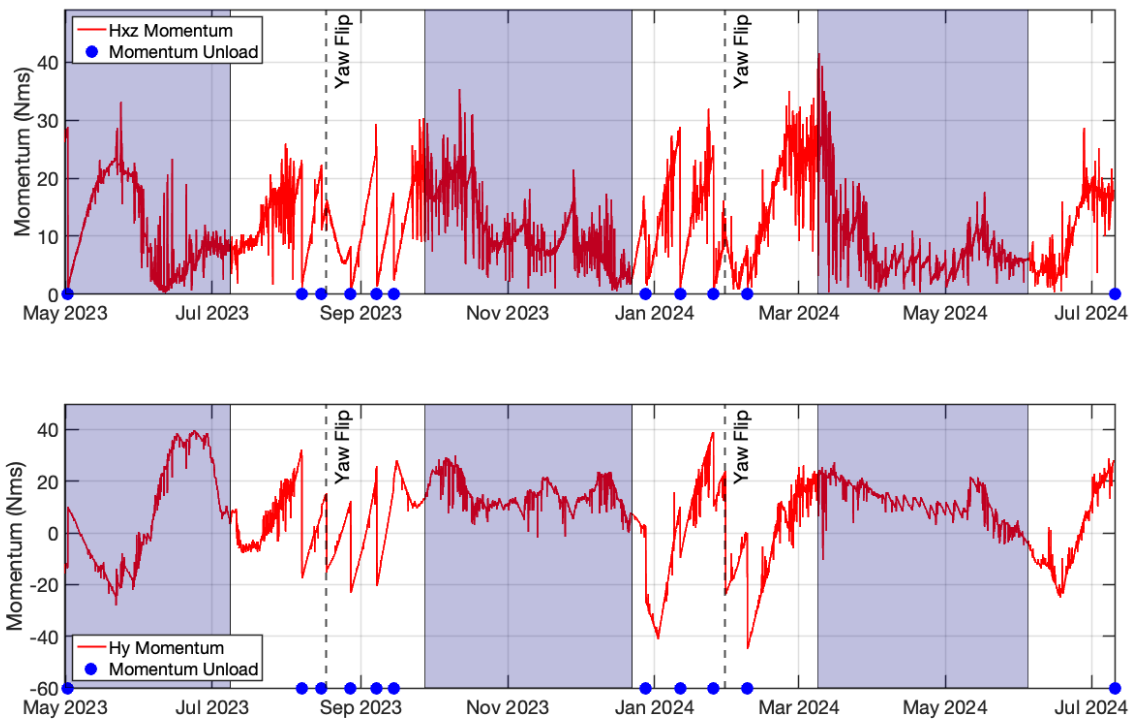

Figure 9. LRO Hxz and Hy Momentums

Momentum slews executed during Extreme, High, and Moderate Beta configuratons (Figure 9, shaded) have allowed for control of both Hxy and Hy. In these configurations the solar array remains in a fixed orientation. Without slews, Hy decreases while the solar array is in a fixed orientation with a maximum rate of -2.2 Nms/day (Figure 10). Hxz increases during these configurations at rates between 1 to 4 Nms/day. Typically, the maximum momentum change achievable by a single slew is about 2 Nms. Slews where ΔHxz is negative while ΔHy is positive appear to be more feasible than when both ΔHxz and ΔHy are negative. During the fixed solar array configurations, a sufficient number of slews were planned not only to match daily momentum rates but also to achieve momentum targets. Slews were able to lower Hxz from a peak of about 23 Nms to under 10 Nms during fixed solar array configurations. Beginning 22 May 2023, slews raised Hy from -24 Nms to +39 to

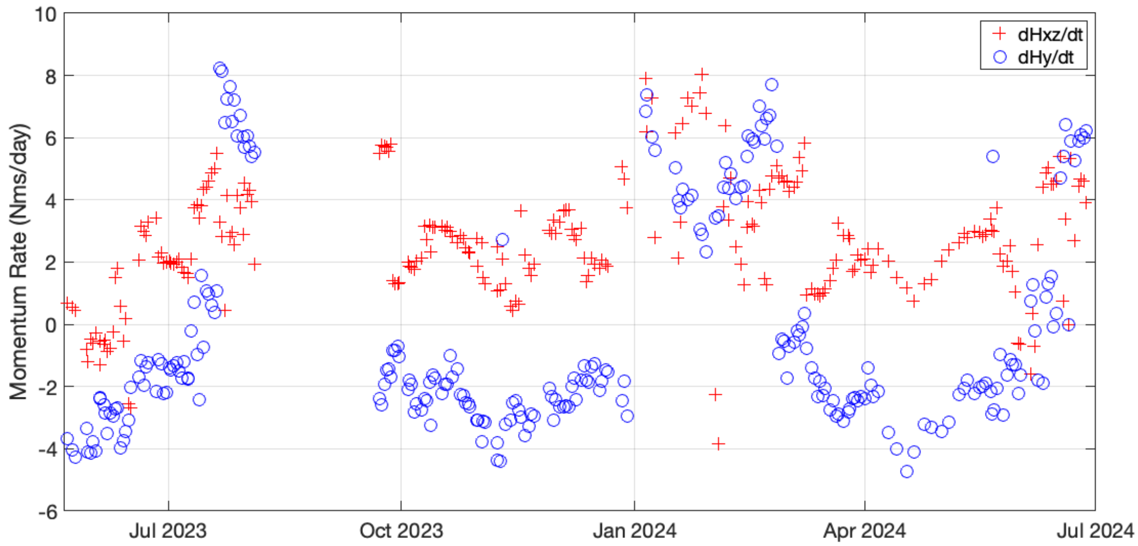

Figure 10. Daily Momentum Rates

take advantage of the negative dHy/dt. In subsequent fixed solar array configurations that began in October 2023 and March 2024, Hy was maintained between 0 and 30 Nms. In November 2023, the Extreme Beta configuration was instantiated to deal with elevated solar gimbal temperatures; the first full instance of this configuration occurred in April 2024. This new configuration did not adversely affect momentum slews. Overall, when the solar array is in a fixed orientation, momentum rates are low enough that sufficient slews can be planned to control momentum.

During the short periods of Low Beta Offset -30 configuration (generally less than a week), momentum slews have generally been able to match daily momentum rates but not achieve significant shifts in Hxz and Hy. The solar array tracks the Sun in this configuration with the outer gimbal offset by -30 degrees. Hy continues to decrease during these configurations, but rates can reach maximums of -4 Nms/day. Hxz increases with rates reaching up to 5.5 Nms/day. Star tracker occultations, thermal constraints, and power constraints can limit the potential momentum change during this configuration. Compensating for daily momentum rates and achieving momentum targets has improved over time.

Momentum management using slews becomes more challenging during the Low Beta Offset +30 configuration prior to crossing zero solar beta angle. The solar array continues to track the Sun but with an offset of +30 degrees. Both Hxz and Hy increase with rates sometimes as high as 6 Nms/day, though typically around +4 Nms. Additionally, spacecraft constraints, particular the power constraint, severely limits the achievable momentum change by slews. Slews often had to be shortened by 50% or more to stay within power constraints. Sufficient Hxz momentum change only appears to be possible with orbit day slews. Additionally, achieving large negative momentum changes in both Hxz and Hy is problematic. To offset the large Hy momentum rates during the Offset +30 configuration, Hy is targeted to -40 Nms prior to this configuration. This target is reached by a combination of natural momentum rates and slews. By achieving this target, the Hy momentum change required by slews is reduced. Since May 2023, there have been three periods in this configuration, which will be further discussed in the section on reductions in momentum unloads.

During the Offset +30 configuration, when the solar beta angle crosses zero degrees, the spacecraft performs a 180-degree yaw flip. This results in LRO switching from the +X body axis flying in the velocity direction to the -X body axis (or vice versa). After the yaw flip, Hy changes sign, resulting in essentially a free unload if Hy was positive. The magnitude of Hxz is unchanged after the yaw flip, but decreases for a period of time. Slews have not yet entirely eliminated the need for momentum unloads after the Yaw Flip.

Reductions in Momentum Unloads and Fuel Usage

Historically, LRO typically performed approximately 20 momentum unloads per year at a cadence of approximately 18 days. Using momentum slews, LRO has performed only 10 momentum unloads between 1 May 2023 and 15 July 2024. All these unloads occurred during Low Beta configurations. The process for planning momentum slews during Low Beta has evolved considerably during this period. During the first Low Beta configuration in August 2023, momentum slews were suspended and five momentum unloads were performed. During the second Low Beta configuration in January 2024, four unloads were performed, though two of these unloads could have been avoided with better momentum forecasting. During the third Low Beta configuration in June 2024, control of Hxz and Hy via momentum slews was significantly improved, resulting in only one momentum unload being performed prior to the Yaw Flip.

A comparison of the solar beta cycles that began in 2021 and 2023 illustrates the potential fuel savings from momentum slews. From peak solar beta in July 2021 to the next peak solar beta in July 2022, 23 momentum unloads were performed, resulting in a fuel usage of approximately 1.67 kg. In contrast, during the solar beta cycle from May 2023 to April 2024, 840 momentum slews were performed, resulting in 9 momentum unloads being performed, reducing fuel usage to 0.62 kg of fuel. Thus, the use of momentum slews reduced fuel usage by 62% when comparing 2021 and 2023 solar beta cycles.

Fuel Lifetime

LRO mission lifetime is impacted by fuel availability (Table 4). On average, a momentum unload uses about 0.09 kg of fuel. Phasing maneuvers are performed to manage power in preparation for Lunar eclipses. For planning purposes, one or two phasing maneuvers are bookkept per year, with each maneuver using about 0.3 kg of fuel. Fuel saved since May 2023 has already shifted the fuel lifetime date from October 2027 to March 2029. This shift alone has allowed for planning to begin for a full 3 year Extended Science Mission 6 (ESM-6) to begin in October 2025. If momentum slews are only used during fixed solar array configurations (Moderate, High, Extreme), the projected number of unloads is cut in half, resulting in a fuel lifetime date of December 2032. Further, if momentum slews are used during Low Beta configurations, and allowing for the possibility for one unload prior to each Yaw Flip, the fuel lifetime date shifts to December 2035. Thus, the use of slews to control momentum can virtually eliminate fuel constraints as a limiting factor for LRO mission lifetime.

FUTURE WORK

The momentum slew planning process is constantly evolving. Future work has been identified to further optimize the selection of slews and transition the method into an operational process. In the area of momentum forecast, the goals are to eliminate the need to correct HiFi forecast momentum for divergence from telemetry and to use HiFi to estimate regression equations for long-term forecasts. For momentum slew estimation, the goal is to reduce the number of cases that need to

Table 4. Projected Fuel Lifetime

Scenario	Momentum Slews	Fuel Lifetime Date	DH per Year	DV per Year
Nominal Rate of Unloads Oct. 2022	No	Oct. 2027	20	1.2
Nominal Rate of Unloads Feb. 2024	No	Mar. 2029	20	1.2
Unloads during Low Beta only	Yes	Dec. 2032	10	1
Single unload prior to Yaw Flip	Yes	Oct. 2035	2	2

be evaluated in order to reduce processing time. Possible avenues for this reduction include consolidating momentum changes based on similar attitudes and investigation of gravity gradient and solar torques for characterizing momentum change. Constraint evaluation could be accelerated by excluding slews with larger durations once a star tracker occultation or +Z-axis interference had been found for a shorter duration of the same attitude. Slew selection during Low Beta configurations would benefit from the ability to automatically evaluate power constraints for individual slews and sequences of slews. Verification of momentum changes has found differences between estimated and forecast momentum changes, the resolution of which could guide how often estimation of slew momentum changes needs to be performed. To achieve that resolution, estimated, forecast, and actual momentum changes need to be assessed. Slew planning must be transitioned into an operational process that the MOT can use, including improving how slew requests are submitted to reduce MOT workload. Lastly, the process needs to be generalized so that other missions can make use of slews for momentum management.

CONCLUSION

Control of LRO RWA angular momentum using attitude holds has been a long-standing goal of NASA Space Science Mission Operations (SSMO) which manages LRO. The realization of this goal began with the implementation of the HiFi simulation. Analysis of a wide range of attitude holds revealed that momentum management would necessitate performing momentum slews on a daily basis. The planning of these momentum slews requires considering spacecraft and operations constraints and science instruments observations. Through the use of momentum slews, LRO potentially could extend its fuel lifetime into the 2030's.

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