Goddard Space Flight Center
Greenbelt, Maryland

National Aeronautics and Space Administration

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Lunar Reconnaissance Orbiter (LRO) Project

LRO Gyroless Slew Requirements between the LRO Mission Operations Center (MOC) and the LRO Science Operations Centers (SOCs)

CM Forward

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LUNAR RECONNAISSANCE ORBITER PROJECT

DOCUMENT CHANGE RECORD

|  |  |  |  |
| --- | --- | --- | --- |
| REV LEVEL | DESCRIPTION OF CHANGE | APPROVED BY | EFFECTIVE DATE |
| Rev- | Initial Release, Released per LRO-451-CCR-nnnn | Francisco Andolz | TBS |

List of TBDs/TBRs

| Item Num | Location | Type | Summary | Ind./Org. | Due Date |
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| 18 |  |  |  |  |  |
| 19 |  |  |  |  |  |
| 20 |  |  |  |  |  |
| 21 |  |  |  |  |  |
| 22 |  |  |  |  |  |
| 23 |  |  |  |  |  |
| 24 |  |  |  |  |  |
| 25 |  |  |  |  |  |
| 26 |  |  |  |  |  |

TABLE OF CONTENTS

[1.0 INTRODUCTION 1-1](#_Toc53557660)

[1.1 Scope 1-1](#_Toc53557661)

[1.2 REFERENCE DOCUMENTS 1-2](#_Toc53557662)

[1.3 OTHER DOCUMENT REFERENCE 1-2](#_Toc53557663)

[1.4 DEFINITIONS 1-2](#_Toc53557664)

[1.5 Document Organization 1-2](#_Toc53557665)

[2.0 LRO Slewing Requirements 2-1](#_Toc53557666)

[APPENDIX A: ABBREVIATIONS AND ACRONYMS APPENDIX A-1](#_Toc53557667)

LIST OF FIGURES

LIST OF TABLES

# INTRODUCTION

The document defines the slew requirements for the spacecraft that takes into account the gyroless state of the spacecraft. Over time the document may change as steps are taken to improve operations or as the state of the spacecraft changes. Please incorporate these rules in planning off nadir operations and operations that affect the solar arrays.

The slew requirements are updates to the Reconnaissance Orbiter Flight Rules and Constraints document.

## Scope

The rules governing special operations of the spacecraft including slews need periodic review and update. The spacecraft is aging making it necessary to manage the operations in a way that reflect this reality while still performing and optimizing science return. LRO has always been a mission with heavy human interaction for slewing and other special operations and while the project has added more automated procedures, this basic character of the mission has not changed. Therefore, management of the spacecraft slews and special observations must reflect both new physical limitations and minimize the possibility of human error. In the latter case, this means giving ample time for review of slew requests using updated tools for modeling the maneuvers.

The specific major drivers of this update to the slewing requirements are the removal of the Miniature Inertial Measurement Unit (MIMU) from the LRO control loop (to preserve its remaining life for emergencies and critical operations, such as eclipses or spacecraft safing) and the degradation of the battery. In the latter case the consequences are easy to understand; a degraded battery means less time with the solar arrays off the sun and the update of this document includes additional restrictions associated with power considerations.

Equally important, but significantly more complicated are considerations related to powering off the MIMU. In place of the MIMU, the attitude control system uses star tracker derived rates combined with integrated torques. The Flight Software Sustaining Engineering group modified the Flight Software (FSW) to use the derived rates in place of the MIMU.

The star trackers on occasion spontaneously reset; the FSW can handle this since both star trackers are used in the Kalman filter. If the Sun, Moon, or Earth causes an eclipse to the second star tracker, during a reset or simultaneous occultation of the first star tracker, then LRO will be without attitude and rate knowledge until a star tracker recovers. Generally, the orbiter will be able to recover from this event but the chances of drifting into an unsafe orientation could trigger (via the coarse sun sensors) a safing condition. This risk increases while slewing, especially at the beginning and end of a slew when the reaction wheels are accelerating or decelerating.

Before implementing and uploading the new FSW in December 2018, it was peer reviewed and extensively tested using LRO simulation tools. Since then, the Mission Operations Team (MOT), project, and science teams have successfully conducted numerous slews onboard for various conditions and project we are confident that LRO can continue to perform science slews if the science community follows the restrictions outlined in this document. The MOT and project personnel will continue to monitor the performance of LRO and seek improvements. .

The LRO project and operations team are committed to optimizing the scientific return of the mission in a manner that maintains a level of safety that assures completion of all extended missions. The following updated rules represent the current assessment of what is needed to accomplish that goal. Some rules are hard and cannot be violated, e.g. we must not simultaneously occult both star trackers, and other rules represent a best estimate based on testing and simulations.

Uncertainty introduced into operations could easily lead to human error and communications breakdown. Nevertheless, for high priority targets given sufficient time, solutions that satisfy safety and operations concerns and science targeting may be found. Early communication is key!

## REFERENCE DOCUMENTS

431-OPS-000309 – Lunar Reconnaissance Orbiter Flight Rules and Constraints

## OTHER DOCUMENT REFERENCE

None

## DEFINITIONS

This document uses the following definitions:

Shall – a hard requirement that is enforced by the project

Will – an expectation

Must – be obliged to meet the necessary requirement or identified deadline

May – a permission perspective; the project/science teams could meet to review or waive an underlying requirement.

Needs – of necessity to meet future mission objectives for spacecraft health and safety or science observations

## Document Organization

Section 1 presents an overview of this MOC to Science Operations Center (SOC) Slew Maneuvers Requirements document.

Section 2 (provides the overall Slew management requirements that the mission/project will levy on the SOC community as a whole and provides the underlying rationale for each of the requirements.

APPENDIX A: (Acronyms and Abbreviations) defines the acronyms and abbreviations used in this document.

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# LRO Slewing Requirements

**LRO-SLEW-1:** Instruments submitting daily files (e.g., Daily Command Sequences (DCS), TARGETS, etc.) shall submit those inputs no later than Noon ET, the day before implementation.

* + Rationale –
		- The MOT needs sufficient time to build and upload commands.

**LRO-SLEW-2:** SOCs shall submit routine Operations Activity Requests (OARs) at least 48 hours before implementation.

* + Rationale –
		- These are regular commands that go into the Absolute Time Sequence (ATS) that do not involve slewing the spacecraft.

**LRO-SLEW-3:** SOCs shall submit OARs to the MOT that involve slews > |20°| and other non-routine planning for instrument calibrations 7 days before implementation.

* + Rationale
		- Requires coordination with external entities (Power, Thermal, Guidance, Navigation, Control (GNC), etc.).
		- Confirm that there are no star tracker occultations.
		- Resolve any conflicts and gather ride-along input from other SOCs.
		- Test at Flatsat if additional testing is necessary.
		- Required Command Authorization Meeting, as necessary.
		- Review by Project Science for complex maneuvers or competing requests.

**LRO-SLEW-4:** The LROC SOC shall submit the LROC9 product to provide the slew request for pitch or roll slews to the MOT that involve slews > |20°| and other non-routine planning for instrument calibrations 7 days before implementation.

* + Rationale
		- Requires coordination with external entities (Power, Thermal, Guidance, Navigation, Control (GNC), etc.).
		- Confirm that there are no star tracker occultations.
		- Resolve any conflicts and gather ride-along input from other SOCs.
		- Test at Flatsat if additional testing is necessary.
		- Required Command Authorization Meeting, as necessary.
		- Review by Project Science for complex maneuvers or competing requests.

**LRO-SLEW-5:** The SOCs shall submit their Slew request by using the Data Management System (DMS) system to send the necessary products for the MOT to create the daily command loads. If DMS is down, the SOCs shall send an email as an alternate method to the MOT, using the gsfc-dl-lro-ops@mail.nasa.gov distribution list. The SOCs should also call the MOT to alert them that the SOCs will deliver a product via the email method.

* + Rationale
		- DMS provides a common transfer mechanism by which the SOCs send products to the MOT. The MOT checks each SOCs input directory to pull the set of daily command loads or OARs.
		- Email is an alternative method if the DMS process fails or if the MOC informs the SOCs that the DMS transfer mechanism is down.

**LRO-SLEW-6:** The SOCs shall submit other products directly to the MOT via email, using the gsfc-dl-lro-ops@mail.nasa.gov distribution list if that product does not normally come through DMS. The following list provides the set of SOC products that DMS recognizes and automatically pulls to the MOC’s archive system for processing:

CRATER-1 LRO Activity Request for CRATER

DLRE-1 LRO Activity Request for DLRE

DLRE-2 DLRE Flight Software Loads

DLRE-3 DLRE Spice Files

LAMP-1 LRO Activity Request for LAMP

LAMP-2 LAMP Instrument FSW Loads

LEND-1 LRO Activity Request for LEND

LOLA-1 LRO Activity Request for LOLA

LOLA-3 LOLA Instrument FSW Loads

LOLA-5 LOLA Target Request

LOLA-6 LOLA Processed Laser Ranging Data

LOLA-7 Lunar Retro Reflector Avoidance Data

LOLA-8 Disable/Enable LOLA Laser Pulse

LROC-1 LRO Activity Request for LROC

LROC-2 LROC Instrument Initialization Command Seq

LROC-3 LROC Command Timeline

LROC-4 LROC Target Request

LROC-9 LROC Special Request Slew

MIRF-1 LRO Activity Request for Mini-RF

MIRF-2 Mini-RF Load Files

MIRF-3 Mini-RF Command Timeline

MIRF-4 Mini-RF Target Request

* + Rationale
		- Email is an alternative method for SOC products that are not covered by the DMS transfer process.

**LRO-SLEW-7:** The project shall restrict the total amount of slews allowed each day to a maximum of 7, Counting starts with any type of slew > |5°|

* + Caveat: The MOT will analyze the slew requests; operational impacts will determine the actual number of slews that the MOT can plan and accomplish in a particular date.
	+ Rationale –
		- The additional vigilance needed for slewing requires limitation of total number of slews.
		- This limit is in the latest Lunar Reconnaissance Orbiter Flight Rules and Constraints document, dated Feb 2016.
		- Used as a limit when LRO introduced the new Flight SW Kalman filter.

**LRO-SLEW-8:** The project shall define the day being from 0400 -0400z for the day in question.

* + Rationale –
		- This provides a common starting point for each SOC.
		- It avoids any confusion as to what the start of the day means.

**LRO-SLEW-9:** The project shall limit each slew such that the end of one slew occurs at least 11.5 minutes before the start of next slew.

* + Rationale –
		- Prevents the pre and post large slew configuration from overlapping.
		- Allows the battery to recharge.

**LRO-SLEW-10:** The project shall only allow one large slew per orbit >|20°| with no star tracker occultations. The instrument teams will evaluate their slews when possible using the Attitude Maneuver (AttMan) software.

* + Rationale –
		- Instrument teams may be able to modify a slew before submission or find a work around that achieves their objective without violating constraints.

**LRO-SLEW-11:** The project shall allow slews that are < |20°| with a single star tracker occultation.

* + Rationale –
		- Larger slews are more difficult to recover from in the event of a star tracker reset; this value represents the optimal compromise for science and safety.
		- The project shall not allow any type of slew that has a double star tracker occultation.
		- If the star tracker occultation occurs while on-target, there will be degraded performance with only a single star tracker.

**LRO-SLEW-12:** The project shall not allow any multi-axis slews that have a single or double star tracker occultation.

* + Caveat: Science teams can work with the Naval Postgraduate School to develop or modify slews to avoid star tracker occultations.
	+ Rationale –
		- Complicated to check in AttMan that the slew legs do not result in an offset of more than |20| deg.

**LRO-SLEW-13:** The project shall enforce the following requirements for Motionless Observations (observations that freeze the solar arrays and high gain antenna).

* + Caveat: LROC09 is a dual product used to automate Large Slews >|20°| and Motionless Observations <=|20°|
	+ Rationale –
		- The project shall require that the SOC include at least an 11.5 minute gap or more in timing between each motionless observation; refer to **LRO-SLEW-9**.
		- The project shall enforce all current rules used for slewing as defined in this document.

**LRO-SLEW-14:** The project requests that the SOCs should avoid any slews during weekday ground-station contacts that occur between noon and 5:00PM, Eastern. The MOT uses those ground station contacts to uplink ATS Loads, Ephemeris loads and Diviner Table Loads.

* + Rationale
		- All products that go in the next day’s ATS load must be in by 12:00 ET leaving 5 hours to build the ATS load and upload it to the spacecraft before COB.
		- Generally, there are only two 30 or 50 minute contacts during this time period. The first is scheduled for upload and the second is reserved for backup.
		- Slewing can cause loss of telemetry and commanding during contacts.
		- Slews will cause CCSDS File Delivery Protocol (CFDP) transactions to freeze, so spacecraft loads can’t be uplinked until CFDP unfreezes after the slew.
	+ CAVEAT: When there is a gap in the schedule during this time period, it is sometimes necessary to load earlier in the day.
	+ Rationale
		- In those cases, the SOCs and Flight Dynamics Facility (FDF) will be alerted and requested to deliver products early.
		- On occasion, the contact schedule is managed using two 24 hours loads and autonomous switching following the standard weekend procedures.

**LRO-SLEW-15:** The project shall use the following “Power rules” when slewing or stopping the solar array for motionless observation**s.**

* + The solar array shall not be off the sun for more than 70 minutes.
	+ The MOT shall evaluate the slew request that take the solar array off the sun using AttMan and SVT; the SOCs are encouraged to check slew requests with these tools prior to submission. The SOCs shall submit non-trivial motionless slew 7 days in advance of the motionless observation.
	+ The project shall require 10 minutes between slew end and eclipse to charge the battery.
		- While tracking at low Beta
		- Moderate Beta position with Beta > |50°|
		- High Beta position with Beta > |68°|
	+ The project shall require 20 minutes between slew end and eclipse to charge the battery.
		- Moderate Beta position with Beta between |43°| and |50°|
		- High Beta position with Beta between |64°| and |68°|
	+ The project shall require that the MOT evaluate high priority slews > 30° using SVT; the MOT shall request concurrence by the power engineers for these high-priority slews of > 30°.
		- Moderate Beta position between |37.5°| and |43°| since it takes 20 – 51 minutes to reach commanded battery voltage
		- High Beta position between |59°| and |64°| since it takes 20 – 48 minutes to reach commanded battery voltage
	+ Rationale –
		- Allows the battery to recharge.

**LRO-SLEW-16:** Momentum unloading shall take precedence over science slew request. The MOT shall reevaluate slews planned shortly after the momentum unloading using the updated products from FDF. If there is not adequate time to revalidate the slews following the momentum unload, the MOT may remove slews for safety reasons if there is a potential for a star tracker occultation.

* + Rationale
		- The project needs to perform regularly scheduled momentum dump maneuvers to maintain the spacecraft health and safety.
		- After a momentum dump maneuver, the MOT requires newly created FDF products since the maneuver may have caused a minor shift in the overall orbital geometry.
		- As noted, spacecraft health and safety takes priority and the MOT may need to remove a slew in the event that there isn’t sufficient time to run AttMan or Slew Verification Tool (SVT) and receive power/thermal concurrence or confirm that there will not be any star tracker occulations.

**LRO-SLEW-17:** The MOT shall use the first, second and last WS1 contacts to downlink the science and housekeeping files, which clears the on-board recorder. The SOCs shall avoid slews or OARs that prevent S/Ka-Band communications, which could lead to science data loss.

* + Rationale
		- The MOT must be notified of high priority targets that require this time 7 days in advance.
		- The SOCs, with MOT support, must manage science data collection to prevent over filling the recorder.
		- SOCs can request to receive the strawman (3 week) and forecast (2 week) station contact schedule. Those schedules include all White Sands-1 (WS1) contacts and provide early planning information.

**LRO-SLEW-18:** The project shall enforce an extended slewing blackout window for all long eclipse events; these include the following times before/after the long-duration eclipse:

* + No slews allowed during the one orbit before observatory pre-heating begins.
	+ No slews allowed during pre-heating activities (typically 24 hours before eclipse).
	+ No slews allowed during eclipse.
	+ No slews allowed until observatory recovery is complete.
	+ Rationale
		- The project requires these pre- and post-eclipse slew blackouts to maintain the orbiter health and safety.
		- The project ensures that there is adequate time to heat all internal spacecraft elements prior to the eclipse.
		- The project ensures the spacecraft condition prior to the final turn-off of instruments and other system elements.
		- The project requires the post-eclipse times to recover the spacecraft systems and ensure the overall spacecraft’s health and safety.
		- The project will perform the restart the instruments in an orderly time-ordered fashion per each station contact to ensure that all instruments are returned to a standard configuration and can begin science observations.
		- The project shall enforce all current rules used for slewing as defined in this document.

ABBREVIATIONS AND ACRONYMS

| Acronym | Definition |
| --- | --- |
| AGS | Attitude Ground System |
| ATS | Absolute Time Sequence |
| AttMan | Attitude Maneuver |
| CCB | Configuration Control Board |
| CCR | Configuration Change Request |
| CFDP | CCSDS File Delivery Protocol |
| CM | Configuration Management |
| CMO | Configuration Management Office(r) |
| CRaTER | Cosmic Ray Telescope for Effect of Radiation |
| DCS | Daily Command Sequences |
| DMS | Data Management System  |
| DLRE | Diviner Lunar Radiometer Experiment |
| FSW | Flight Software |
| GNC | Guidance, Navigation, Control |
| GSFC | Goddard Space Flight Center |
| GSMO-2 | Ground System and Mission Operations, second contract |
| LAMP | Lyman-Alpha Mapping Project |
| LEND | Lunar Exploration Neutron Detector |
| LOLA | Lunar Orbiter Laser Altimeter  |
| LRO | Lunar Reconnaissance Orbiter |
| LROC | LRO Camera |
| Mini-RF | Miniature Radio Frequency |
| MIMU | Miniature Inertial Measurement Unit |
| MOC | Mission Operations Center |
| MOT | Mission Operations Team |
| NASA | National Aeronautics and Space Administration |
| OAR | Operations Activity Request |
| RQMT | Requirement |
| SOC | Science Operations Center |
| SSMO | Space Science Mission Operations |
| SVT | Slew Verification Tool |