Lunar Reconnaissance Orbiter
Lunar Orbiter Laser Altimeter
Reduced Data Record and Derived Products
Software Interface Specification

Version 2.6

March 11, 2016

SIGNATURE PAGE

Prepared by:

_____   _____

Gregory A. Neumann   Date

LOLA Instrument co-Investigator

GSFC Code 698

Reviewed by:

_____   _____

David E. Smith   Date

Principal Investigator, LOLA Instrument

GSFC Code 690.5

Approved by:

_____   _____

Stanley R. Scott   Date

LRO Project Science Data Manager

GSFC Code 451

Concurred by:

_____   _____

Susan Slavney   Date

PDS Geosciences Discipline Node

_____   _____

Ed Grayzek   Date

PDS Program Manager, GSFC Code 690.1

TABLE OF CONTENTS

TABLES AND FIGURES

DOCUMENT CHANGE LOG

Change	Date	Affected Portions
GDR and SHADR descriptions added	8/12/08	1.1, 5.2, 5.3
Changes reflecting updated calibrations	9/22/08	2.1
Added Ed Grayzek to signatures	10/26/08	ii
Figure 1 updated	10/26/08	2.1
Applicable Document versions updated	10/26/08	1.3
NASVIEW added as tool to inspect data.	10/26/08	4.1
Selenocentric replaced with planetocentric	10/26/08	5.1
Relationships to NAIF and LRO-LR explained	10/26/08	2.2
Acronyms for timing added, other removed	10/26/08	5.1
Reviewers suggested edits adopted	10/26/08	various
Replaced coordinate system text with LDWG text	10/26/08	2.2, 2.4.3
Added Resolution Date to TBD table	11/17/08	v
Explained rational for binary tables and reprocessing	11/17/08	2.2, 2.3
Revised Figure 1 based on Post-ship survey	4/28/09	2.1
Spares added for Earth ranges and pulsewidths	6/28/09	Appendices
Solar incidence/phase/nadir/emission angles added	8/28/09	Appendices
Geotiff headers added to JPEG2000 GDR products	8/28/09	
Edited for readability, updated	03/01/10	Entire document
Correction to LONGITUDE_1 value in LOLARDR.FMT	03/15/11	Appendices
Addition of RADR dataset and related documentation. Updates. – K. Jha	03/09/16	TBD, 2.2, 2.3, 3, 5.2, 5.3, 5.4

TBD ITEMS

Section	Description	Resolution Date

ACRONYMS AND ABBREVIATIONS

APD	Avalanche Photo Diode
ASCII	American Standard Code for Information Interchange
CODMAC	Committee on Data Management and Computation
DOE	Diffractive Optic Element
DU	Data Unit on LRO
DVD-ROM	Digital Video Disk - Read-Only Memory
EDR	Experiment Data Record
FSW	Flight Software
GB	Giga Byte
GDR	Gridded Data Record
GSFC	Goddard Space Flight Center
HK	Housekeeping
ICD	Interface Control Document
ISO	International Standards Organization
JPL	Jet Propulsion Laboratory
LOLA	Lunar Orbiter Laser Altimeter
LR	Laser Ranging
LRO	Lunar Reconnaissance Orbiter
MB	Mega Byte
MET	Mission Elapsed Time on the LRO spacecraft
MOC	LRO Mission Operations Center, B32, NASA-GSFC
MSB	Most Significant Byte
NASA	National Aeronautics and Space Administration
NAIF	Navigation and Ancillary Information Facility of the PDS
PDS	Planetary Data System
PPS	1 Pulse Per Second signal provided by LRO
RADR	Radiometric Active Data Record
RDR	Reduced Data Record
SC	Spacecraft
SHADR	Spherical Harmonic Analysis Data Record
SIS	Software Interface Specification

SOC	Science Operations Center
STCF	Spacecraft Time Correction Factor
TBD	To Be Determined
UTC	Coordinated Universal Time

GLOSSARY

Archive – An archive consists of one or more data sets along with all the documentation and ancillary information needed to understand and use the data. An archive is a logical construct independent of the medium on which it is stored.

Archive Volume, Archive Volume Set – A volume is a unit of media on which data products are stored; for example, one ISO 9660 CD-ROM or DVD-ROM (Applicable Document #3). An *archive volume* is a volume containing all or part of an archive; that is, data products plus documentation and ancillary files. When an archive spans multiple volumes, they are called an *archive volume set*. Usually the documentation and some ancillary files are repeated on each volume of the set, so that a single volume can be used alone.

Catalog Information – Descriptive information about a data set (e.g. mission description, spacecraft description, instrument description), expressed in Object Description Language (ODL) which is suitable for loading into a PDS catalog.

Data Product – A labeled grouping of data resulting from a scientific observation, usually stored in one file. A product label identifies, describes, and defines the structure of the data. An example of a data product is a planetary image, a spectrum table, or a time series table.

Data Set – An accumulation of data products. A data set together with supporting documentation and ancillary files is an archive.

Geotiff, GeoJPEG – an image format used as a container for raster geospatial data formats such as Gridded Data Records, with header information that complies with the Geospatial Data Abstraction Library (GDAL) specification. See www.gdal.org for more information.

Profile – A time-ordered set of altimetry and allied data.

SPICE – An information system maintained by the PDS NAIF Node to assist scientists in planning and interpreting scientific observations from space-based instruments.

Standard Data Product – A data product generated in a predefined way using well-understood procedures, processed in "pipeline" fashion. (Data products that are generated in a nonstandard way are sometimes called *special data products*.)

1.   Introduction

1.1.   Purpose and Scope

The Lunar Orbiter Laser Altimeter (LOLA) is producing a high-resolution global topographic model and geodetic framework that enables precise targeting, safe landing, and surface mobility to carry out exploratory activities. LOLA characterizes the polar illumination environment, and images permanently shadowed polar regions of the Moon to identify possible locations of surface ice crystals in shadowed polar craters.

This Software Interface Specification document provides users of the Lunar Reconnaissance Orbiter (LRO) LOLA Reduced Data Record (RDR), the Gridded Data Record (GDR) and Spherical Harmonic Data Record (SHADR) data products, with a detailed description of the product and how it was generated, including data sources and destinations.

1.2.   Contents

This Data Product SIS describes how the RDR data product is processed, formatted, labeled, and uniquely identified. The document discusses standards used in generating the product and software that may be used to access the product. The data product structure and organization is described in sufficient detail to enable a user to read the product. Finally, an example of a product label is provided.

1.3.   Applicable Documents and Constraints

This SIS is intended to be consistent with the following documents:

1. *Planetary Science Data Dictionary Document,* JPL D-7116, Rev. E, August 28, 2002.

2. Lunar Reconnaissance Orbiter Project Data Management and Archive Plan, 431-PLAN-00182.

3. ISO 9660-1988, Information Processing - Volume and File Structure of CD-ROM for Information Exchange, April 15, 1988.

4. *Planetary Data System Archive Preparation Guide*, August 29, 2006, Version 1.1, JPL D-31224.

5. *Planetary Data System Standards Reference,* March 20, 2006, Version 3.7, JPL D-7669, Part 2.

6. LRO LOLA Science Team and PDS Geosciences Node ICD, October 9, 2006.

7. Lunar Reconnaissance Orbiter Project LOLA Instrument Team Data Management and Archive Plan, April 1, 2007.

8. LOLA Archive Volume Software Interface Specification, V2, October 26, 2008.

9. Memorandum of Agreement between the PDS Geosciences Node and the LRO LOLA Data Node, Washington University, St. Louis, Missouri, and the LRO LOLA Instrument Team, Goddard Space Flight Center, Greenbelt, Maryland, October 27, 2006.

10. *A Standardized Lunar Coordinate System for the Lunar Reconnaissance Orbiter*, LRO Project White Paper, 451-SCI-000958, Version 3, January 30, 2008.

11. Lunar Reconnaissance Orbiter Lunar Orbiter Laser Altimeter Experiment Data Record Software Interface Specification (LOLA EDRSIS), V.2, October 26, 2008.

12. LOLA Calibration Document, Riris, H., J. Cavanaugh, X. Sun, and P. Liiva, Submitted to Applied Optics, 2010.

1.4. Configuration Management and Relationships with Other Interfaces

The RDR and higher-level products described in this SIS are used in the production of other archived products of the LRO mission. Changes to this specification will require concurrence of the Principal Investigator, the LRO Project Science Data Manager, and the Planetary Data System Geosciences Discipline Node.

2. Data Product Characteristics and Environment

2.1. Instrument Overview

The LOLA instrument, designed, assembled and tested by the NASA Goddard Space Flight Center (GSFC), has two primary objectives. First, to produce a high-resolution global topographic model and geodetic framework that assists with precise targeting, safe landing, and surface mobility for future scientific and exploration activities. Second, to characterize the polar illumination environment and image the Moon's permanently-shadowed regions (PSRs) in order to identify possible locations of surface ice crystals in shadowed polar craters. To achieve these primary objectives, LOLA will make three science measurements:

1) the distance between the surface and the spacecraft,

2) the spreading of the returned laser pulse, and

3) the transmitted and returned laser energies.

LOLA is a pulse-detection time-of-flight altimeter that incorporates a five-spot pattern to measure the precise distance to the lunar surface at 5 spots simultaneously, thus providing 5 profiles across the lunar surface. Figure 1 shows the spot pattern used, where the dots are the transmitted laser footprints, and solid circles are receiver fields-of-view. LOLA fires at a fixed, 28-Hz rate, so that for a nominal 1600 m/s ground track speed there is one shot approximately every 57 m. At a nominal 50-km altitude, each spot within the five-spot pattern has a surface diameter of 5 m while each detector field of view has a diameter of 20 m; the surface spread is 25 meters, and the spots form a cross pattern canted by 26 degrees counterclockwise to provide five adjacent profiles.

The 5-spot pattern determines the surface slope in the along-track and across track directions. LOLA's design is similar to the Mars Orbiter Laser Altimeter (MOLA) and the Mercury Laser Altimeter (MLA), augmented by a novel diffractive optic element (DOE). LOLA has five independent detectors coupled via fiber optics to the receiver telescope and five receiver channels (1-5). Channel 1 is also fiber-optic-coupled through a dichroic beamsplitter to a Laser Ranging (LR) telescope mounted on the High-Gain Antenna. An R-C filter with a decay time constant of 3.4 ns is applied to the detector output for noise suppression.

Figure 1: LOLA ground spot pattern sample of four successive shots, with channels numbered. Spacecraft may fly in either +X or -X direction.
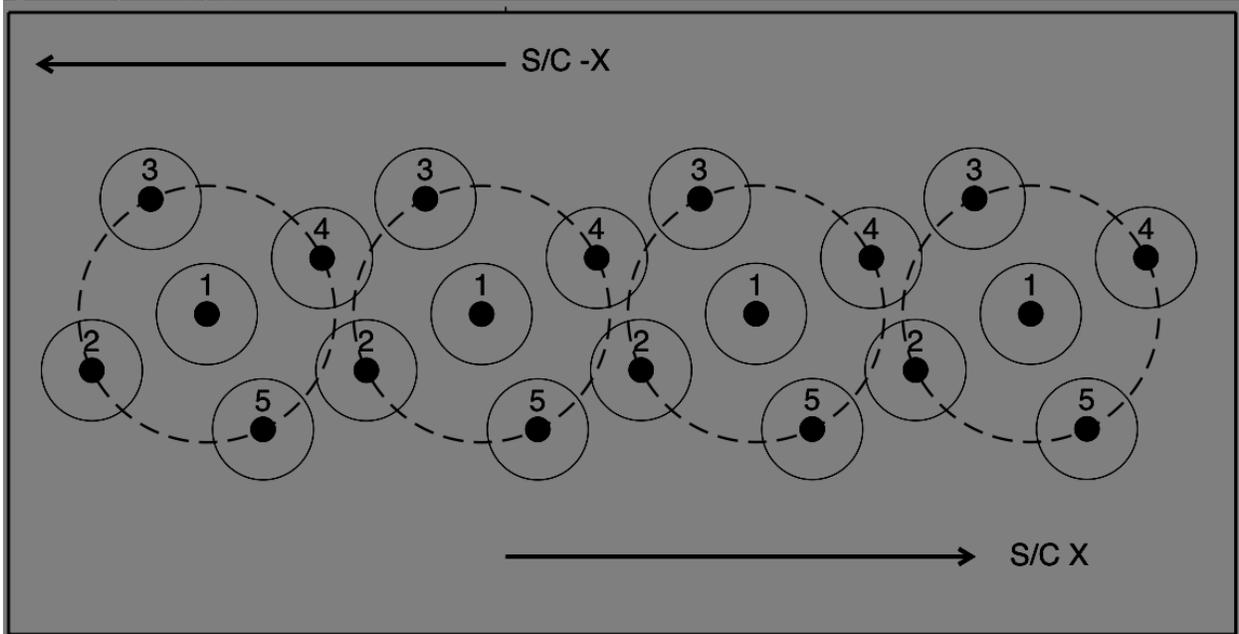
Figure 2: LOLA Optical Transceiver Assembly.
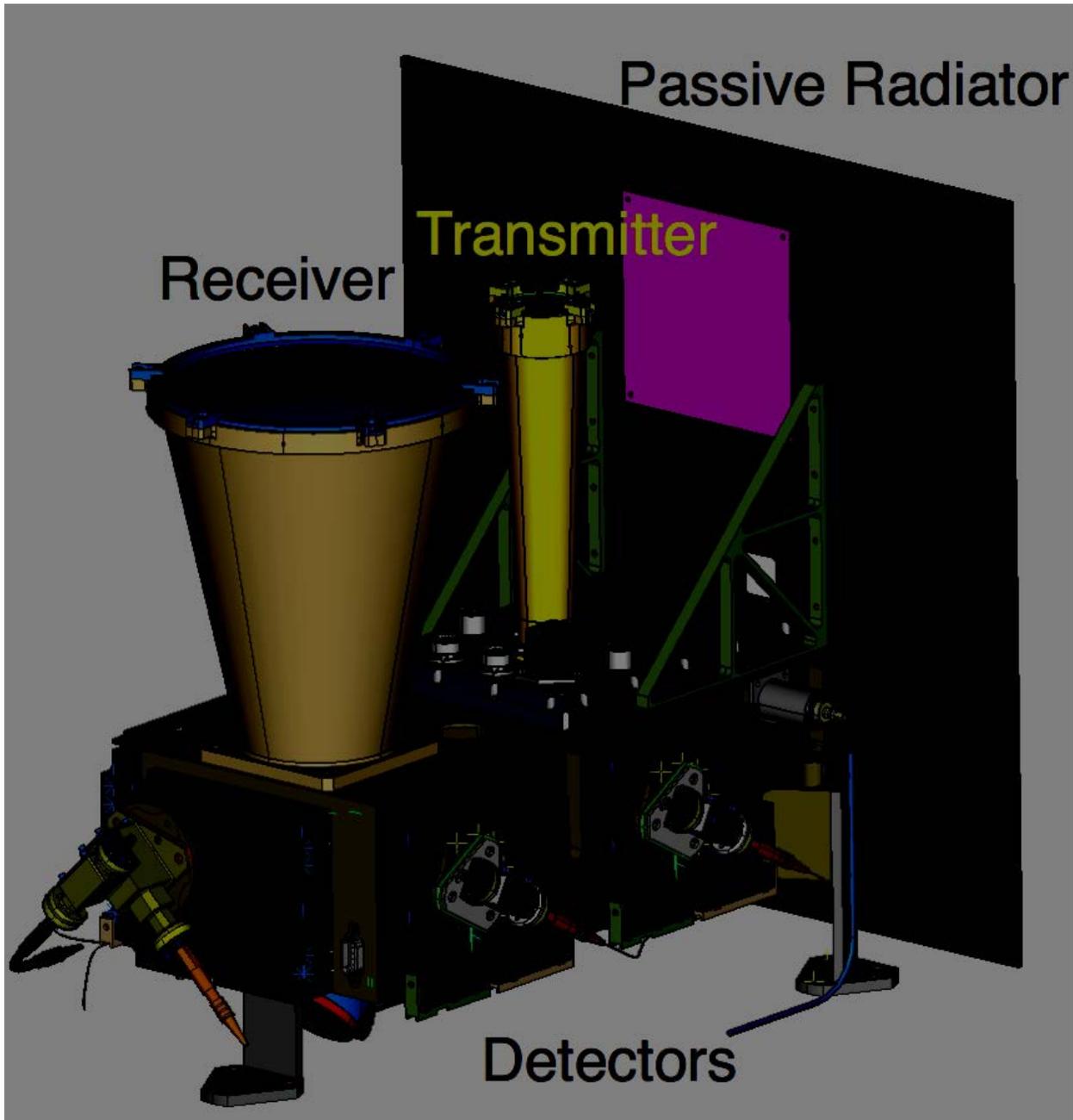
LOLA's altimetry observations are global. Timing of one-way pulses fired from Earth to the LR are employed to improve navigation and lunar gravity determination. The LOLA instrument is a pulsed laser time-of-flight altimeter, operating continuously during mapping orbit to produce altimetric ranges that are stored on the LRO spacecraft (SC) for playback. Its housekeeping (HK) data are also provided in a realtime data stream and contain information regarding the flight software status and the Laser Ranging signals from Earth stations.

The instrument hardware consists of laser transmitters, receivers, and passive radiator subsystems mounted in an Optical Transceiver Assembly (Figure 1), together with a Power Converter Assembly and Digital Unit mounted in the Main Electronics Box. There are two redundant lasers coupled to the transmit optics, selectable by software command. Transmit and receive pulses are measured with independent leading and trailing edge times using ACAM TDC-S1 chips designed for space docking applications (offset by a 5 MHz coarse count.) Energy is monitored via a gated charge-time measurement circuit with digitizer. The instrument is co-boresighted with the LRO Cameras on the spacecraft +Z optical bench. The main technical details regarding the instrument are given in Table 1.

Table 1: LOLA Instrument Technical Details.

Item	Measure	Comment
Mass	13.2 kg	(at Critical Design Review 7/06)
Power	33.5 W	(average)
Data rate	27 kbps	3424 Bytes, 1 packet per second
Lasers	2 (1 cold spare)	Cr:Nd:YAG cross-Porro resonator, TEM00, TEC cooled
Wavelength	1064.3±0.1 nm	
Diode bars	2	60 A, 140-160 μs pump, with passive Cr4+:YAG Q-switch
Pulses	28 Hz, 2.7±0.3 mJ	5.6 ns FWHM
Thermal	passive radiator	Laser operating range: 5°C to 35°C
Detectors	5 Si-APDs	preamp bandwidth 100 Mhz, followed by R-C 3.4 ns filter
Quantum Efficiency	0.4	@1064 nm
Detector noise	0.05 pW/Hz$^{1/2}$	Noise equivalent power
Optics	**Receiver**	**Transmitter after 18x Beam Expander and DOE**
Objective	Sapphire	BK7G18/fused silica DOE
Obj. diameter	14 cm	3.24 cm
Obj. area	0.015 m^2	8.245 cm^2
Transmission	>70%	>95%
Effective F. L.	50.0 cm	16.2 cm
F.O.V. 1/e^2	400 μrad	100 μrad, separation between adjacent beams is 500 μrad
Fiber Optic	200 μm, 0.22NA	LR is a 7x400um core, 0.22NA, step-index, 1.28mm bundle
Bandpass filter	dichroic beamsplitter	Δλ=0.7nm, λ=1064.45 nm; LR λ =532.15 nm, Δλ= 0.3 nm

Instrument modes (Table 2) are controlled by ground command. Independent of these modes, the Flight Software (FSW) may be active or commanded to a reset state. The digital unit outputs data directly to the SC over the 1553 bus in either case. Thresholds, gains, and range gates are normally controlled by the FSW algorithm. The algorithm seeks to maximize the probability of detection within a range window under varying background noise conditions, by utilizing hardware noise counters in a fashion similar to that employed on the MOLA and MLA instruments. There are two separate range windows within the LOLA timing electronics, one for the Earth-based LR pulses, and a second variable lunar range window that only allows triggers during the interval of time when the FSW return histograms predict surface returns. Since only one lunar return is recorded, a separate counter records the number of events within each range window. To accommodate the large dynamic range of lunar return strength, a variable gain amplifier is implemented in hardware prior to the discriminator input. The gain is set according to tables of gain vs. lunar range, one for each detector. Earth laser ranges are recorded by detector 1 during the 8 ms preceding each laser fire, using the same threshold and gain settings as for lunar ranges. Owing to higher background Earth counts, especially during New Moon phases, the detector 1 thresholds are higher than those of the detector 2-5 channels.

Table 2: Instrument Modes.

Mode	Telemetry	Laser	Detector
Measurement	HK, Science	Firing enabled, 28Hz trigger	Active-LR and lunar return
Standby 2	HK, Science	Firing enabled, capacitors charged	Active-LR and noise
Standby 1	HK, Science	Laser TEC active	Active-LR and noise
Off	Analog temps	Survival heaters enabled	Inactive

2.2. Data Product Overview

The LOLA RDR data product consists of time-of-flight ranges to the lunar surface and ancillary data that have been located in a geodetic coordinate frame about the center of mass of the Moon. This planetocentric coordinate frame is described further as the Mean-Earth/polar Axis convention in section 2.4.3 and Applicable Document 10. The EDR data product is the source of the measurement data. After range calibration and orbital processing, the range to each laser spot is located on the surface using the spacecraft trajectory, attitude history, and a lunar orientation model in order to produce an altimetric datum. The range profiles are organized into an RDR product containing calibrated, geolocated pulse returns, radii and energies; and higher-level gridded and transformed data products.

The RDR data product is a binary table with fixed-length records. The binary table is in a PDS standard format that can be stored, managed and reprocessed efficiently without loss of precision. It can be converted to the equivalent engineering and scientific units for import into analysis software by standard formatted output specifications (see Section 4). This choice also maximizes flexibility for users who may wish to handle only selected data values, or who may wish to import

them into geographically-organized databases. Record columns consist of uniform-length, 4-byte integer values, stored in Least-Significant Byte (LSB_INTEGER) order that may be converted to Most-Significant Byte (MSB_INTEGER) order by a single global transformation. Both UNSIGNED and SIGNED INTEGER types are employed.

The RDR product is used to generate derived data products (RADR, GDR, SHADR) that are binned, resampled, and transformed. The RADR product is time-ordered, calibrated and geolocated active radiometry derived from the RDR product using data gathered during the Nominal Mission phases. RADR files are archived as ASCII tables with detached labels, organized by LOLA mission phase.

The primary GDR products are map-projected digital elevation models and related products. Additional GDR products include gridded albedo, slope and roughness maps. Albedo (RADR) products are derived from nominal mission data only, and are further limited – not every return with valid altimetry has a corresponding albedo value, as the energy measurement quality depends on both the laser return and the solar incidence angle. Low data density results in some 'streakiness' seen in the gridded albedo products.

Digital elevation models are transformed into spherical harmonic expansions to produce the SHADR products. Much of the processing of the RDR product may be used to reconstruct and improve the geometric information regarding the spacecraft position, attitude, and clock history. The improved geometry will be archived in the SPICE format through the PDS Navigation and Ancillary Information Facility (NAIF) Node.

Much of this improvement is anticipated to result from the Laser Ranging Experiments on board LRO, for which data are returned through the LOLA instrument. This investigation is separate from that of the altimeter but is intimately coupled. The Laser Ranging data are originated by ground stations under the auspices of the LRO Project and are collated with Earth returns in the LOLA data stream by the LOLA SOC. They are provided to the Flight Dynamics Facility and to the participating stations of the International Laser Ranging Service by the Crustal Dynamics Data Information Service at GSFC. Derived LR products will not be included in this archive.

The LRO SC stores LOLA science data in a file on the SC data recorder in a subdirectory called "SSR/LOLA/". Prior to powering on the instrument, the SC opens the data file and writes the LRO standard file header data. As new data frames are read over the 1553 bus, the SC writes them to the file without modification. The SC closes the file, open a new file, and writes another LRO standard file header when commanded to do so by the ground controllers (this will nominally be scheduled to occur once per lunar orbit at ascending equator crossings, roughly 6,785 seconds apart). Files are always closed on a packet boundary so that packets are not divided between files. During the daily downlink tracking passes these files are transmitted from the SC to the LRO Ground Data System and are pushed by the LRO Mission Operations Center (MOC) to the LOLA Science Operations Center (SOC) computer. Each file is then processed in a pipeline at the SOC.

The orbital period of the LRO spacecraft varies somewhat with mission phase, and is approximately 112-114 minutes in duration. The orbit duration will determine the precise number of RDR files, but they will not exceed 13 per day. The geolocation processing cycle will aggregate the data records into daily batches in order to facilitate analysis. The LRO Project uses an orbital numbering convention whereby the orbit number increments from 0 to 1 on the first ascending node after completion of the LOI-1 lunar insertion maneuver, and increments by 1 on every

ascending node after that. Table 3 summarizes expected sizes and production rates for the Reduced Data and Derived products.

Table 3: Standard Product Sizes and Delivery Rates

Product	Product Size	Production Rate per Day, average	Expected Number of Products for Primary Mission (366 days)	Expected Total Data Volume for Primary Mission
LOLA_RDR	~50 MB	same	4670	225 GB
LOLA_RADR	<10 MB	Same as LOLA_RDR	4162	27 GB
LOLA_GDR	<2 GB	monthly revisions of ~100 data products	100	200 GB
LOLA SHADR	<5 MB	release at ~quarterly intervals	4	<1 GB

2.3. Data Processing

The pipeline data processing begins by generating an EDR product with a detached PDS label, in one-to-one correspondence with the files generated by the instrument on the LRO spacecraft, corrected for transmission errors, gaps and duplicates where possible. The format of the files is identical to that on the spacecraft. LOLA operates continuously, generating one 3,424-byte record each second, with an associated 12-byte telemetry header. The telemetry header information is captured in a detached "PDS3" version ASCII label. During tracking passes, the instrument housekeeping portion of the telemetry is transmitted via a real-time connection for use by the LR ground system, but is not archived since it is duplicated in the EDR product. The aggregate data rate is approximately 300 MB per day.

The EDR products are geolocated using preliminary and definitive orbits produced by the LRO Flight Dynamics Facility in order to determine approximate nodal crossing times. The Data Records are then aggregated by orbit number and geolocated into the RDR products using precision orbit reconstructions and calibration algorithms. Each 1-Hz record of the EDR corresponds to 28 laser shots and produces 28 records in the RDR. Instrument engineering values such as algorithm status, detector status (noise counts, temperatures, etc.) from the EDR are not included in the RDR records.

2.3.1. Data Processing Levels

Table 4 gives descriptions of Committee on Data Management and Computation (CODMAC) product levels.

Table 4: Processing Levels for Science Data Sets.

NASA	CODMAC	Description
Packet data	Raw – Level 1	Telemetry data stream as received at the ground station, with science and engineering data embedded.
Level 0	Edited – Level 2	Instrument science data (e.g., raw voltages, counts) at full resolution, time ordered, with duplicates and transmission errors removed.

Level 1A	Calibrated - Level 3	Level 0 data that have been located in space and may have been transformed (e.g., calibrated, rearranged) in a reversible manner and packaged with needed ancillary and auxiliary data (e.g., radiances with the calibration equations applied).
Level 1B	Resampled - Level 4	Irreversibly transformed (e.g., resampled, remapped, calibrated) values of the instrument measurements (e.g., radiances, magnetic field strength).
Level 1C	Derived- Level 5	Level 1A or 1B data that have been resampled and mapped onto uniform space-time grids. The data are calibrated (i.e., radiometrically corrected) and may have additional corrections applied (e.g., terrain correction).
Level 2	Derived - Level 5	Geophysical parameters, generally derived from Level 1 data, and located in space and time commensurate with instrument location, pointing, and sampling.
Level 3	Derived - Level 5	Geophysical parameters mapped onto uniform space-time grids.

This document is intended to provide enough information to enable planetary scientists to read and understand the format and content of the higher-level LOLA Archive. The specifications in this document apply to all LOLA standard product archive volumes that are generated by the LRO Project. The RDR data product contains the time-ordered LOLA measurement data in reduced, calibrated and geolocated form, one record per laser shot. The altimetric and related measurements generate the GDR and SHADR data products. The GDR data products contain the binned, interpolated altimetric measurements, as well as albedo, roughness, and surface slope both in cylindrical and polar projections. The SHADR products contain the spherical harmonic expansions of the lunar shape.

For geological characterisation, topography is referenced to a non-spherical datum, such as an ellipsoid of revolution, or in the case of Earth, a geoid. The lunar potential derived from satellites provides the equivalent datum for the Moon, referred to as the planetopotential reference surface.

The EDR product is CODMAC level 2 (Table 4), consisting of raw counts, edited to correct transmission errors and eliminate duplicates. In order to be useful for measurement and geological investigations, the data must be classified to determine whether individual laser shots are valid pulses and produce ground returns above the background noise level of detection. These data must be calibrated to engineering and physical units, and located in a center-of-mass coordinate system. The RDR and RADR data products are CODMAC level 3. Binned and interpolated data on a uniformly-spaced grid (GDR) comprise the CODMAC level 4 data products, while transformed spherical harmonic coefficients (SHADR) comprise CODMAC level 5.

2.3.2. Data Product Generation

All data products at CODMAC level 2 and higher are generated by the LOLA SOC. Raw data are not subject to decompression, as the full instrument output counts are stored in the telemetry packets. Following EDR generation, software algorithms perform calibration, geolocation, and editing to eliminate noise. Calibration consists of conversion of raw counts into laser time-of-flight ranges, pulse widths, and energies, using tables and algorithms based on ground test data. Editing consists of generating data quality flags for each laser pulse return, to distinguish between probable

lunar returns and noise triggers, and to flag anomalous measurements. Algorithms and ancillary data used in the RDR processing are described in the LOLA Instrument Calibration Document, Applicable Document #12 (sec. 1.3).

During the primary mission, the LRO spacecraft performs propulsive orbital adjustment maneuvers at monthly intervals. These maneuvers terminated the dynamical orbital solutions and provided a natural breakpoint for altimetric reprocessing. Multiple versions of the RDR and some higher-level products are generated based on a monthly reprocessing and validation step, as orbit knowledge improves and refined crossover adjustments are performed. Each new version of the data products replaces all of the older products and supersedes all previous versions in the electronic archive, and is identified as such in the PRODUCT_VERSION_ID fields of the PDS labels. This approach of periodic reprocessing is in accordance with the cumulative improvement in coverage density and orbital knowledge inherent to laser altimetric missions.

2.3.3. Data Flow

Data are pushed directly from the LRO MOC through the GSFC Internet backbone to the LOLA SOC, where processing occurs. The LOLA SOC serves as a Data Node of the PDS. Data products and catalogs are made available to the PDS via a Query Server connection as well as by other electronic means. Sizes and volumes of all the data products generated over the course of the primary mission are given in Table 3. The data products cover variable time spans according to their processing level. A monthly reprocessing cycle is applied to all CODMAC Level 3 and higher products, following which new versions of current and previous products are redelivered to the Data Node. At 3-month intervals as specified in the Data Management and Archive Plan (Applicable Document 2), validated releases of a cumulative archive will be made. It is anticipated that only the current version of data products will be maintained after the specified releases.

2.3.4. Labeling and Identification

The data set IDs provided by the PDS for the LOLA RDR and higher level data products are:

"LRO-L-LOLA-3-RDR-V1.0", "LRO-L-LOLA-3-RADR-V1.0", "LRO-L-LOLA-4-GDR-V1.0", and "LRO-L-LOLA-5-SHADR-V1.0".

The file naming convention for LOLA RDR files is

LOLARDR_YYDDDHHMM.DAT

in parallel with the EDR product. The LOLA RADR files are similarly named, with a TAB extension corresponding to an ASCII table. PDS detached labels with a suffix of ".LBL" provide information about processing and calibration version. Details about label and header formats are specified in section 6. Labels are subject to revision after monthly reprocessing, but the product filenames will not be modified.

2.4. Standards Used in Generating Data Products

2.4.1. PDS Standards

LOLA data products comply with PDS standards for file formats and labels, as described in the PDS Standards Reference, Applicable Document 5 (sec. 1.3).

2.4.2. Time Standards

All time tags are derived from the LRO internal clock, whose performance is monitored by the Project. The PDS labels for LOLA products use keywords denoting time values, such as start time, stop time, start spacecraft clock count, and stop spacecraft clock count. Each time value standard is defined according to the PDS keyword definitions. Project-supplied conversions from Mission Elapsed Time (MET) to Coordinated Universal Time (UTC) include a Spacecraft Time Correction Factor that is included in the nominal time values. Geolocation software is based rigorously on Barycentric Dynamical Time, a convention that is realized through Terrestrial Dynamical Time (TDT) and orbital theories. The supplied MET-UTC conversions are specified to be accurate within 3 ms, during which time the SC ground track travels approximately 5 meters, or one laser spot diameter. Laser Ranging and orbital analysis are used to reconstruct the observation time to a significantly higher level of accuracy, which is recorded in the RDR data product both in MET seconds and TDT seconds from the J2000 epoch.

2.4.3. Coordinate Systems

Spatial information is applied in conversion of laser altimetric bounce points from inertial coordinates to lunar body-fixed coordinates about the center of mass of the Moon, or planetocentric coordinates. The LRO project adopts the Mean-Earth/polar axis convention, LRO data use lunar planetocentric/body-fixed coordinates and east-positive longitude from 0 to 360 degrees.

The ME reference system is used for all LRO archival data. This LRO standard is documented in Applicable Document 10 (sec. 1.3). Using coordinates in the ME system is consistent with recommendations from the International Astronomical Union (IAU)/International Association of Geodesy (IAG) Working Group on Cartographic Coordinates and Rotational Elements, as implemented by the LRO Data Working Group (LDWG).

The NAIF node of the PDS provides the necessary lunar ephemeris file (SPK) and binary lunar orientation file (PCK) in a Principal Axes (PA) reference frame for use with the SPICE Toolkit. NAIF also provides the frames kernel (FK) used for accessing the PA orientation in the PCK and for transforming from the PA frame to the ME frame.

2.4.4. Data Storage Conventions

The least-significant-byte (LSB) byte order is adopted for archival purposes, consistent with native i386 (PC) storage. Architecture-specific dependencies in the RDR product are mitigated through adoption of a consistent integer byte order and uniform 4-byte word size, with the exception of the last six columns containing solar and Earth information, which are half-words. During intermediate processing, MSB or LSB byte order native to the processing computer may be employed.

2.5. Data Validation

Data validation shall be applied to data products by the LOLA Measurement Team to ensure that their contents and format are free of errors and comply with PDS archive standards (Applicable Document 5). For the RDR product this consists of a combined orbit-determination and crossover residual analysis. The RDR and higher-level products will be re-released at approximately monthly intervals after such analysis is completed.

3. Detailed Data Product Specifications

The LOLA RDR data products are stored as fixed-length, fixed-format binary tables. The LOLA RADR data products are formatted ASCII tables. The detached PDS labels for LOLA RDRs and RADRs are stored as ASCII text in fixed-length records terminated by an ASCII carriage-return and line-feed pair. The product labels point to the corresponding data files, and contain pointers to format files. The GDR data products are stored as binary images and as JPEG-2000 files with GeoTIFF headers, where appropriate. The SHADR data products are Comma-Separated Value (CSV) ASCII text files with attached labels.

3.1. Data Product Structure and Organization

The DATA/LOLA_RDR and DATA/LOLA_RADR directories have subdirectories for each monthly orbital maneuver cycle named LRO_PP_NN, where PP refers to the first two letters of mission phase (CO = Commissioning, NO = Nominal, SM = Science Mission, ES = Extended Science Mission), and NN is refers to the current monthly orbital cycle, ending with Station Keeping Maneuvers, starting with 01. Typical file paths are therefore

 /DATA/LOLA_RDR/LRO_PP_NN/LOLARDR_YYDDDHHMM.DAT and

/DATA/LOLA_RADR/LRO_PP_NN/LOLARDR_YYDDDHHMM.DAT,

where YYDDDHHMM is the time of the ascending node crossing. The orbit numbering convention may also be used for special products. Orbit number is determined by the MOC, incrementing at each ascending equator crossing.

The LOLA_GDR directory has subdirectories for JPEG2000 and IMG files. The LOLA_SHADR directory has no subdirectories.

3.2. Data Format Descriptions

The LOLA RDR table format description is given in Appendix 1. The RDR format file is "LOLARDR.FMT". This column definition file is stored in the /LABEL directory of the LOLA archive. The GDR and SHADR formats are contained in their respective labels.

3.3. Label and Header Descriptions

An example of a detached PDS RDR label follows. The SOURCE_PRODUCT_ID contains information regarding the raw datasets and geometry processed for a given version. The PRODUCT_VERSION_TYPE contains the instrument range calibration, energy calibration, pulse spreading calibration, background illumination calibration (radiometry from noise counts), gravity model, and reprocessing level. The INSTRUMENT_MODE_ID is relevant to the slight offset in alignment of the two redundant lasers, for geolocation, and the timing source for firing. The LRO:STCF_FILE_NAME contains an offset from spacecraft clock counts to Coordinated Universal Time relative to January 1, 2001, 0 hours. The remainder of the parameters are generic and need not be described in detail. Sample PDS RADR, GDR and SHADR labels are given in Appendices.

```
PDS_VERSION_ID                  = "PDS3"

/*** FILE FORMAT ***/
```

```
FILE_NAME                       = "LOLARDR_092000107.DAT"
FILE_RECORDS                    = 200480
RECORD_TYPE                     = FIXED_LENGTH
RECORD_BYTES                    = 256


/*** GENERAL DATA DESCRIPTION PARAMETERS ***/
PRODUCT_ID                      = "LOLARDR_092000107_DAT"
PRODUCT_VERSION_ID              = "V1.01"
PRODUCT_CREATION_TIME           = 2009-08-29T20:28:10
PRODUCT_TYPE                    = "RDR"
STANDARD_DATA_PRODUCT_ID        = "DATA"
SOFTWARE_NAME                   = "LOLA_RDR"
SOFTWARE_VERSION_ID             = "2.45"
SOURCE_PRODUCT_ID               = {"LOLAEDR092000107.DAT", "jgl150q1.sha"}
SPICE_FILE_NAME                 = {
                "moon_pa_de421_1900-2050.bpc",
                "moon_080317.tf",
                "moon_assoc_me.tf",
                "naif0009.tls",
                "de421.bsp",
                "lro_frames.tf",
                "lro_sclk.tsc",
                "fdf29_2009199_2009200_n01.bsp",
                "fdf29_2009200_2009201_n01.bsp",
                "fdf29_2009201_2009202_n01.bsp",
                "moc42_2009199_2009200_v01.bc",
                "moc42_2009200_2009201_v01.bc",
                "moc42_2009201_2009202_v01.bc"}
COORDINATE_SYSTEM_NAME          = "MEAN EARTH/POLAR AXIS OF DE421"
INSTRUMENT_HOST_NAME            = "LUNAR RECONNAISSANCE ORBITER"
INSTRUMENT_NAME                 = "LUNAR ORBITER LASER ALTIMETER"
INSTRUMENT_ID                   = "LOLA"
DATA_SET_ID                     = "LRO-L-LOLA-3-RDR-V1.0"
DATA_SET_NAME                   = "LRO MOON LASER ALTIMETER 3 RDR V1.0"
MISSION_PHASE_NAME              = "COMMISSIONING"
TARGET_NAME                     = "MOON"
PRODUCER_ID                     = LRO_LOLA_TEAM
PRODUCER_FULL_NAME              = "DAVID E. SMITH"
PRODUCER_INSTITUTION_NAME       = "GODDARD SPACE FLIGHT CENTER"
PRODUCT_RELEASE_DATE            = 2009-10-06
ORBIT_NUMBER                    = 295
START_TIME                      = 2009-07-19T01:07:12.928
STOP_TIME                       = 2009-07-19T03:06:31.929
SPACECRAFT_CLOCK_START_COUNT    = "2628408"
SPACECRAFT_CLOCK_STOP_COUNT     = "2635567"
INSTRUMENT_MODE_ID              = {"SC_B",
        "LASER_2 ",
        "ENABLED",
        "FIRING",
        "GAINS_DIS",
        "THRESHOLDS_FSW",
        "RGATES_FSW",
        "SWINPUTS_FSW"}
FILE_NAME                       = "LOLARDR_092000107.DAT"

^TABLE                          = "LOLARDR_092000107.DAT"
```

```
OBJECT                        = TABLE
  COLUMNS                      = 60
  INTERCHANGE_FORMAT           = BINARY
  ROW_BYTES                    = 256
  ROWS                         = 200480
  DESCRIPTION                  = "
    This product contains time-ordered, calibrated, geolocated data
    reduced by the LRO Lunar Orbiter Laser Altimeter (LOLA) Science
    Operations Center at NASA Goddard Space Flight Center. Orbit and
    geometry data describing the observations has been supplied by the
    LRO Flight Dynamics Facility and the LOLA Science Team.
    The complete column definitions are contained in a structure file
    LOLARDR.FMT. Additional details are contained in the RDR SIS document."
    ^STRUCTURE  = "LOLARDR.FMT"
END_OBJECT                    = TABLE
END
```

4.   Applicable Software

Signed and unsigned four-byte integers represent the RDR data values with sufficient precision to avoid roundoff errors. Because the LOLA RDR data products are formatted as binary tables, they must be read by software that understands PDS table formats and can manipulate byte-order-dependent fields. The primary access to the data product is through the table definitions herein described. Software to read and format the data into ASCII text will be maintained by the LOLA Team for commonly used platforms. The PDS Geosciences Node will maintain the most current versions of software for download by users through the Internet, along with the data. The general public may also access the data through geographically-based queries to databases.

4.1.   Utility Programs

A stand-alone utility 'rdr2csv' converts an RDR into a 28-Hz, CSV text file. It is linked with the NAIF SPICE library and requires a table of leap seconds (naif0009.tls). The CSV file may contain up to 200,000 records and may not be supported as a single table by legacy spreadsheet software. Another utility 'rdr2table' will output each valid detector measurement to an ASCII table, with various selection options. Calibrations for energy, surface reflectivity, pulsewidth, and so forth are applied in these programs. They are written in FORTRAN-77 and C and may be easily modified.

For example, to create a spreadsheet table with header:

rdr2csv LOLARDR_100322338.DAT > LOLARDR_100322338.csv

To output height from all 5 detector spots as a table with header:

rdr2table LOLARDR_100322338.DAT a h | head -7

```
  SCLK_LOLA      alt_km id longitudeE  latitudeN range_km  energy noise    thrs    gain  flg   reflect pulsewd
      0.000     -1.3782 1  21.887972   0.188501   42.772   0.3771    3  31.3713 50.2106   0   0.18274   22.15
      0.000     -1.3801 2  21.888284   0.187860   42.773   0.2321    7  28.7125 49.8681   0   0.13246   19.14
      0.000     -1.3799 3  21.887322   0.188194   42.774   0.2630    7  28.6896 49.9720   0   0.15510   16.72
      0.000     -1.3759 4  21.887647   0.189134   42.770   0.2852    5  25.5802 49.2268   0   0.11895   16.88
      0.000     -1.3763 5  21.888602   0.188800   42.769   0.3402    4  30.1136 50.1560   0   0.15275   19.65
      0.036     -1.3712 1  21.887913   0.190412   42.765   0.4207    3  31.3713 50.2106   0   0.21893   21.84
      0.036     -1.3731 2  21.888225   0.189772   42.766   0.2124    9  28.7125 49.8681   0   0.11168   18.66
```

To output geopotential topography on detectors 3 and 4:

rdr2table LOLARDR_100322338.DAT g 3 4 |head -2

```
     0.000    -1.3981 3 21.887322  0.188194   42.774  0.2630    7 28.6896 49.9720  0   0.15510   16.72
     0.000    -1.3941 4 21.887647  0.189134   42.770  0.2852    5 25.5802 49.2268  0   0.11895   16.88
```

To output spacecraft position/attitude, flagged returns, and transmit energy/pulsewidth:

rdr2table LOLARDR_100322338.DAT 0 h f | head -2

```
 SCLK_LOLA      sc_alt 0  sc_longE   sclat_N offnadir emission ifrm  solinc  solphs ngrd   xenrg   xplse
     0.000    41.3700 0  21.934303  0.187423   1.882  1.9280    0 55.3735 57.3015  5   2.67470    8.79
     0.036    41.3701 0  21.934281  0.189339   1.885  1.9309    1 55.3735 57.3044  5   2.63386    8.90
```

Faster binary output is generated by rdr2xyz <RDRFILE> <OUTFILEROOT.xyz> <options>.

4.2. Applicable PDS Software Tools

The PDS-D query software is available to extract metadata from catalogs and download specific data products from a web browser. Software tools are also being developed by the PDS Geosciences Node such as Orbital Data Explorer. NASAVIEW, a generic software reader for PDS-formatted files, can be also be used to inspect the binary RDR data files but is not fully supported on all operating systems.

4.3. Software Distribution and Update Procedures

Software to read the binary tables and output CSV and other tables is provided as source code and stand-alone executable binaries, maintained by the LOLA Team, and distributed by the PDS. Current platforms supported are Intel and PowerPC MacOS X, Linux, and SunOS Sparc. Software will be ported to non-Unix-like systems as time permits. Updates will be made available at the PDS Geosciences Node.

5. Appendix

5.1. Contents of the LOLARDR.FMT file

```
/**************************************************************************/
/* LOLARDR.FMT v. 26 October 2008 with edits 26 March 2009 and May 2009   */
/* Version 2 adds range gate, earth range and pw. 26 June 2009            */
/* Version 2.4 replaces gates w/emission/offnadir/solinc/solphs 26 Aug 2009*/
/* Earth range, Pulse width, energy are packed into the last two spares.  */
/* Version 2.42 puts no_pointing_found into bit 7 of flag 02 Oct 2009     */
/* Each record represents one 28-Hz LOLA minor frame with 5 spots.        */
/* A complete description of the calibrations and algorithms              */
/* is given in RIRISETAL2009, Calibration Document for the LOLA instrument.*/
/* The record length is currently set to 256 bytes, with 16 spare bytes   */
/* Definition of T0:                                                      */
/* Shot reference time, the clock tick starting each 28-Hz minor frame    */
/* relative to the 1 pulse-per-second signal provided by the LRO clock    */
/* Version 2.42 defines enhanced manual editing flags 14 October 200      */
/* 1/26/2010 adds DATA_TYPE and MISSING_CONSTANT for unsigned integers    */
/**************************************************************************/
OBJECT              = COLUMN
 COLUMN_NUMBER      = 1
 BYTES              = 4
 START_BYTE         = 1
```

```
 NAME                  = MET_SECONDS
 DATA_TYPE             = LSB_INTEGER
 MISSING_CONSTANT      = -1
 DESCRIPTION           = "LRO Data Unit (DU) mission elapsed time (MET)
    passed to LOLA at the LRO 1 PPS (one pulse per second) tick."
END_OBJECT             = COLUMN

OBJECT                 = COLUMN
 COLUMN_NUMBER         = 2
 BYTES                 = 4
 START_BYTE            = 5
 NAME                  = SUBSECONDS
 DATA_TYPE             = LSB_UNSIGNED_INTEGER
 DESCRIPTION           = "Laser fire time as fractional seconds of
    MET time, roughly 9.4872 ms after the shot reference time T0.
    If no fire is detected, set to T0, the 28-Hz minor frame start."
END_OBJECT             = COLUMN

OBJECT                 = COLUMN
 COLUMN_NUMBER         = 3
 BYTES                 = 8
 ITEMS                 = 2
 ITEM_BYTES            = 4
 START_BYTE            = 9
 NAME                  = TRANSMIT_TIME
 DATA_TYPE             = LSB_UNSIGNED_INTEGER
 DESCRIPTION           = "Laser fire time in Terrestrial Dynamical Time
    (TDT, aka TT) at the LRO spacecraft, in seconds from the J2000 epoch.
    The LRO Project counts time from 2001-01-01T00:00:00, thus a constant
    offset of 365*86400 + 43200 has been added to match J2000.
    TDT is the independent argument of apparent geocentric ephemerides.
    TDB, barycentric coordinate time, varies from TDT only by periodic
    variations. TDT is related to Coordinated Universal Time (UTC)
    through International Atomic Time (TAI) and leap seconds.
    TDT = TAI + 32.184 seconds.
    TAI = UTC + leap seconds (34 seconds in 2009).
    Time is stored as an integer number of seconds
    and a 32-bit fractional number of seconds, as two unsigned values."
END_OBJECT             = COLUMN

OBJECT                 = COLUMN
 COLUMN_NUMBER         = 4
 BYTES                 = 4
 NAME                  = LASER_ENERGY
 DATA_TYPE             = LSB_INTEGER
 UNIT                  = 'NANOJOULES'
 START_BYTE            = 17
 MISSING_CONSTANT      = -1
 DESCRIPTION           = "Laser transmit energy."
END_OBJECT             = COLUMN

OBJECT                 = COLUMN
 COLUMN_NUMBER         = 5
 BYTES                 = 4
 NAME                  = TRANSMIT_WIDTH
 DATA_TYPE             = LSB_INTEGER
```

```
 UNIT               = 'PICOSECONDS'
 START_BYTE         = 21
 MISSING_CONSTANT   = -1
 DESCRIPTION        = "Laser transmit pulse width."
END_OBJECT          = COLUMN

OBJECT              = COLUMN
 COLUMN_NUMBER      = 6
 BYTES              = 4
 NAME               = SC_LONGITUDE
 DATA_TYPE          = LSB_INTEGER
 UNIT               = 'DEGREES * (10**7)'
 MISSING_CONSTANT   = -2147483648
 START_BYTE         = 25
 DESCRIPTION        = "Spacecraft Center-of-Mass position in Moon-fixed
   coordinates of longitude in the range -180 to 180 degrees."
END_OBJECT          = COLUMN

OBJECT              = COLUMN
 COLUMN_NUMBER      = 7
 BYTES              = 4
 NAME               = SC_LATITUDE
 DATA_TYPE          = LSB_INTEGER
 UNIT               = 'DEGREES * (10**7)'
 MISSING_CONSTANT   = -2147483648
 START_BYTE         = 29
 DESCRIPTION        = "Spacecraft Center-of-Mass position in Moon-fixed
   coordinates of latitude, in the range -90 to 90 degrees."
END_OBJECT          = COLUMN

OBJECT              = COLUMN
 COLUMN_NUMBER      = 8
 BYTES              = 4
 START_BYTE         = 33
 NAME               = SC_RADIUS
 DATA_TYPE          = LSB_UNSIGNED_INTEGER
 UNIT               = 'MILLIMETERS'
 MISSING_CONSTANT   = 4294967295
 DESCRIPTION        = "Spacecraft Center-of-Mass position in Moon-centered
   radial coordinates."
END_OBJECT          = COLUMN

OBJECT              = COLUMN
 COLUMN_NUMBER      = 9
 BYTES              = 4
 START_BYTE         = 37
 NAME               = SELENOID_RADIUS
 DATA_TYPE          = LSB_UNSIGNED_INTEGER
 MISSING_CONSTANT   = 4294967295
 UNIT               = 'MILLIMETERS'
 DESCRIPTION        = "Equipotential radius (geoid) at Spot 1,
   relative to an equipotential surface whose mean equatorial radius is
   1737.4 kilometers."
END_OBJECT          = COLUMN

/* The science shot structure 5x10 fields */
```

```
/* Spot 1, the center spot */

OBJECT              = COLUMN
 COLUMN_NUMBER      = 10
 NAME               = LONGITUDE_1
 DATA_TYPE          = LSB_INTEGER
 BYTES              = 4
 START_BYTE         = 41
 UNIT               = 'DEGREES * (10**7)'
 MISSING_CONSTANT   = -2147483648
 DESCRIPTION        = "The planetocentric longitude of the spot 1 centroid,
   in the range -180 to 180 degrees. Negative values should be adjusted by
   adding 360 degrees to conform with LRO conventions."
END_OBJECT          = COLUMN

OBJECT              = COLUMN
 COLUMN_NUMBER      = 11
 NAME               = LATITUDE_1
 DATA_TYPE          = LSB_INTEGER
 START_BYTE         = 45
 BYTES              = 4
 UNIT               = 'DEGREES * (10**7)'
 MISSING_CONSTANT   = -2147483648
 DESCRIPTION        = "The planetocentric latitude of the spot 1 centroid,
   in the range -90 to 90 degrees."
END_OBJECT          = COLUMN

OBJECT              = COLUMN
 COLUMN_NUMBER      = 12
 NAME               = RADIUS_1
 DATA_TYPE          = LSB_INTEGER
 START_BYTE         = 49
 BYTES              = 4
 UNIT               = 'MILLIMETERS'
 MISSING_CONSTANT   = -1
 DESCRIPTION        = "The distance from the Moon center to the
  Spot 1 centroid."
END_OBJECT          = COLUMN

OBJECT              = COLUMN
 COLUMN_NUMBER      = 13
 NAME               = RANGE_1
 DATA_TYPE          = LSB_UNSIGNED_INTEGER
 START_BYTE         = 53
 BYTES              = 4
 UNIT               = 'MILLIMETERS'
 MISSING_CONSTANT   = 4294967295
 DESCRIPTION        = "LOLA 2-way range (c/2 times time-of-flight)
  to the spot 1 centroid."
END_OBJECT          = COLUMN

OBJECT              = COLUMN
 COLUMN_NUMBER      = 14
 NAME               = PULSE_1
 DATA_TYPE          = LSB_INTEGER
 START_BYTE         = 57
```

```
 BYTES             = 4
 UNIT              = 'PICOSECOND'
 MISSING_CONSTANT  = -1
 DESCRIPTION       = "Pulse width of spot 1 return at THRESHOLD_1."
END_OBJECT         = COLUMN

OBJECT             = COLUMN
 COLUMN_NUMBER     = 15
 NAME              = ENERGY_1
 DATA_TYPE         = LSB_UNSIGNED_INTEGER
 START_BYTE        = 61
 BYTES             = 4
 UNIT              = 'ZEPTOJOULES'
 DESCRIPTION       = "Received Energy of detected return."
END_OBJECT         = COLUMN

OBJECT             = COLUMN
 COLUMN_NUMBER     = 16
 NAME              = BACKGROUND_1
 DATA_TYPE         = LSB_UNSIGNED_INTEGER
 START_BYTE        = 65
 BYTES             = 4
 UNIT              = 'PICOWATTS'
 DESCRIPTION       = "Background noise power at detector 1 using the
   noise counter interval, minus the Earth and lunar events, accounting
   for glitches resulting from the energy measurement, as calibrated by
   the receiver noise model."
END_OBJECT         = COLUMN

OBJECT             = COLUMN
 COLUMN_NUMBER     = 17
 NAME              = THRESHOLD_1
 DATA_TYPE         = LSB_UNSIGNED_INTEGER
 START_BYTE        = 69
 BYTES             = 4
 UNIT              = 'NANOVOLTS'
 DESCRIPTION       = "Threshold at detector 1."
END_OBJECT         = COLUMN

OBJECT             = COLUMN
 COLUMN_NUMBER     = 18
 NAME              = GAIN_1
 DATA_TYPE         = LSB_UNSIGNED_INTEGER
 START_BYTE        = 73
 BYTES             = 4
 DESCRIPTION       = "Gain at detector 1 scaled by 1.E6."
END_OBJECT         = COLUMN

OBJECT             = COLUMN
 COLUMN_NUMBER     = 19
 NAME              = SHOT_FLAG_1
 DATA_TYPE         = LSB_UNSIGNED_INTEGER
 START_BYTE        = 77
 BYTES             = 4
 DESCRIPTION       = "Describes the probability that spot 1 is a lunar range
   and its associated quality using flags in the least significant byte. Any
```

```
  values other than 0 should be regarded as an invalid measurement.
  Abbreviations: TX = transmitted pulse; RX = received pulse
  bit 0 = ground/not ground
  bit 1 = TX LeadingEdge
  bit 2 = TX TrailingEdge
  bit 3 = RX LeadingEdge
  bit 4 = RX TrailingEdge
  bit 5 = TX energy invalid
  bit 6 = automatic edit flag
  bit 7 = Pointing not found from spacecraft C-Kernel

 The next most significant byte gives the Range Measurement Unit (RMU)
  phase status for TX and RX:
  bit 8 = RMU Phase of receive channel, A=0, B=1 (unflipped)
  bit 9 = RMU Phase of transmit pulse, A=0, B=1 (unflipped)
  bit 10= TDC chip status invalid, rare but serious
  bit 11= set to 1 if signal NOT acquired by FSW on last packet
  bits 12-15 are reserved for manual editing and give reasons bit 0 is set
   These are not always recorded by the manual editing software.
  bit 12= failed n-sigma edit criteria on altitude
  bit 13= failed slope edit criteria
  bit 14= just bad
  bit 15= weird
 The succeeding two bytes represent an unsigned 16-bit value.
 Bits 16-31 may be used as a relative indicator of range uncertainty."

END_OBJECT          = COLUMN

/* Spot 2 */

OBJECT              = COLUMN
 COLUMN_NUMBER      = 20
 NAME               = LONGITUDE_2
 DATA_TYPE          = LSB_INTEGER
 START_BYTE         = 81
 BYTES              = 4
 UNIT               = 'DEGREES * (10**7)'
 MISSING_CONSTANT   = -2147483648
 DESCRIPTION        = "The planetocentric longitude of the spot 2 centroid,
   in the range -180 to 180 degrees. Negative values should be adjusted by
   adding 360 degrees to conform with LRO conventions."

END_OBJECT          = COLUMN

OBJECT              = COLUMN
 COLUMN_NUMBER      = 21
 NAME               = LATITUDE_2
 DATA_TYPE          = LSB_INTEGER
 START_BYTE         = 85
 BYTES              = 4
 UNIT               = 'DEGREES * (10**7)'
 MISSING_CONSTANT   = -2147483648
 DESCRIPTION        = "The planetocentric latitude of the spot 2 centroid."
END_OBJECT          = COLUMN

OBJECT              = COLUMN
```

```
 COLUMN_NUMBER         = 22
 NAME                  = RADIUS_2
 DATA_TYPE             = LSB_INTEGER
 START_BYTE            = 89
 BYTES                 = 4
 UNIT                  = 'MILLIMETERS'
 MISSING_CONSTANT      = -1
 DESCRIPTION           = "The distance from the Moon center to the
  Spot 2 centroid."
END_OBJECT             = COLUMN

OBJECT                 = COLUMN
 COLUMN_NUMBER         = 23
 NAME                  = RANGE_2
 DATA_TYPE             = LSB_UNSIGNED_INTEGER
 START_BYTE            = 93
 BYTES                 = 4
 UNIT                  = 'MILLIMETERS'
 DESCRIPTION           = "LOLA range to the spot 2 centroid."
END_OBJECT             = COLUMN

OBJECT                 = COLUMN
 COLUMN_NUMBER         = 24
 NAME                  = PULSE_2
 DATA_TYPE             = LSB_INTEGER
 START_BYTE            = 97
 BYTES                 = 4
 UNIT                  = 'PICOSECOND'
 MISSING_CONSTANT      = -1
 DESCRIPTION           = "Pulse width of spot 2 return at THRESHOLD_2."
END_OBJECT             = COLUMN

OBJECT                 = COLUMN
 COLUMN_NUMBER         = 25
 NAME                  = ENERGY_2
 DATA_TYPE             = LSB_UNSIGNED_INTEGER
 START_BYTE            = 101
 BYTES                 = 4
 UNIT                  = 'ZEPTOJOULES'
 DESCRIPTION           = "Received Energy of detected return."
END_OBJECT             = COLUMN

OBJECT                 = COLUMN
 COLUMN_NUMBER         = 26
 NAME                  = BACKGROUND_2
 DATA_TYPE             = LSB_UNSIGNED_INTEGER
 START_BYTE            = 105
 BYTES                 = 4
 UNIT                  = 'PICOWATTS'
 DESCRIPTION           = "Background noise power at detector 2."
END_OBJECT             = COLUMN

OBJECT                 = COLUMN
 COLUMN_NUMBER         = 27
 NAME                  = THRESHOLD_2
 DATA_TYPE             = LSB_UNSIGNED_INTEGER
```

```
 START_BYTE         = 109
 BYTES              = 4
 UNIT               = 'NANOVOLTS'
 DESCRIPTION        = "Threshold at detector 2."
END_OBJECT          = COLUMN

OBJECT              = COLUMN
 COLUMN_NUMBER      = 28
 NAME               = GAIN_2
 DATA_TYPE          = LSB_UNSIGNED_INTEGER
 START_BYTE         = 113
 BYTES              = 4
 DESCRIPTION        = "Gain at detector 2 scaled by 1.E6."
END_OBJECT          = COLUMN

OBJECT              = COLUMN
 COLUMN_NUMBER      = 29
 NAME               = SHOT_FLAG_2
 DATA_TYPE          = LSB_UNSIGNED_INTEGER
 START_BYTE         = 117
 BYTES              = 4
 DESCRIPTION        = "Describes the probability that spot 2 is a lunar range
   and its associated quality as in SHOT_FLAG_1."
END_OBJECT          = COLUMN

/* Spot 3 */

OBJECT              = COLUMN
 COLUMN_NUMBER      = 30
 NAME               = LONGITUDE_3
 DATA_TYPE          = LSB_INTEGER
 START_BYTE         = 121
 BYTES              = 4
 UNIT               = 'DEGREES * (10**7)'
 MISSING_CONSTANT   = -2147483648
 DESCRIPTION        = "The planetocentric longitude of the spot 3 centroid,
    in the range -180 to 180 degrees. Negative values should be adjusted by
    adding 360 degrees to conform with LRO conventions."
END_OBJECT          = COLUMN

OBJECT              = COLUMN
 COLUMN_NUMBER      = 31
 NAME               = LATITUDE_3
 DATA_TYPE          = LSB_INTEGER
 START_BYTE         = 125
 BYTES              = 4
 UNIT               = 'DEGREES * (10**7)'
 MISSING_CONSTANT   = -2147483648
 DESCRIPTION        = "The planetocentric latitude of the spot 3 centroid."
END_OBJECT          = COLUMN

OBJECT              = COLUMN
 COLUMN_NUMBER      = 32
 NAME               = RADIUS_3
 DATA_TYPE          = LSB_INTEGER
 START_BYTE         = 129
```

```
 BYTES             = 4
 UNIT              = 'MILLIMETERS'
 MISSING_CONSTANT  = -1
 DESCRIPTION       = "The distance from the Moon center to the
  Spot 3 centroid."
END_OBJECT         = COLUMN

OBJECT             = COLUMN
 COLUMN_NUMBER     = 33
 NAME              = RANGE_3
 DATA_TYPE         = LSB_INTEGER
 START_BYTE        = 133
 BYTES             = 4
 UNIT              = 'MILLIMETERS'
 MISSING_CONSTANT  = -1
 DESCRIPTION       = "LOLA range to the spot 3 centroid."
END_OBJECT         = COLUMN

OBJECT             = COLUMN
 COLUMN_NUMBER     = 34
 NAME              = PULSE_3
 DATA_TYPE         = LSB_INTEGER
 START_BYTE        = 137
 BYTES             = 4
 UNIT              = 'PICOSECOND'
 MISSING_CONSTANT  = -1
 DESCRIPTION       = "Pulse width of spot 3 return at THRESHOLD_3."
END_OBJECT         = COLUMN

OBJECT             = COLUMN
 COLUMN_NUMBER     = 35
 NAME              = ENERGY_3
 DATA_TYPE         = LSB_UNSIGNED_INTEGER
 START_BYTE        = 141
 BYTES             = 4
 UNIT              = 'ZEPTOJOULES'
 DESCRIPTION       = "Received Energy of detected return 3."
fEND_OBJECT        = COLUMN

OBJECT             = COLUMN
 COLUMN_NUMBER     = 36
 NAME              = BACKGROUND_3
 DATA_TYPE         = LSB_UNSIGNED_INTEGER
 START_BYTE        = 145
 BYTES             = 4
 UNIT              = 'PICOWATTS'
 DESCRIPTION       = "Background noise power at detector 3."
END_OBJECT         = COLUMN

OBJECT             = COLUMN
 COLUMN_NUMBER     = 37
 NAME              = THRESHOLD_3
 DATA_TYPE         = LSB_UNSIGNED_INTEGER
 START_BYTE        = 149
 BYTES             = 4
 UNIT              = 'NANOVOLTS'
```

```
 DESCRIPTION        = "Threshold at detector 3."
END_OBJECT          = COLUMN

OBJECT              = COLUMN
 COLUMN_NUMBER      = 38
 NAME               = GAIN_3
 DATA_TYPE          = LSB_UNSIGNED_INTEGER
 START_BYTE         = 153
 BYTES              = 4
 DESCRIPTION        = "Gain at detector 3 scaled by 1.E6."
END_OBJECT          = COLUMN

OBJECT              = COLUMN
 COLUMN_NUMBER      = 39
 NAME               = SHOT_FLAG_3
 DATA_TYPE          = LSB_UNSIGNED_INTEGER
 START_BYTE         = 157
 BYTES              = 4
 DESCRIPTION        = "Describes the probability that spot 3 is a lunar range
   and its associated quality as in SHOT_FLAG_1."
END_OBJECT          = COLUMN

/* Spot 4 */

OBJECT              = COLUMN
 COLUMN_NUMBER      = 40
 NAME               = LONGITUDE_4
 DATA_TYPE          = LSB_INTEGER
 START_BYTE         = 161
 BYTES              = 4
 UNIT               = 'DEGREES * (10**7)'
 MISSING_CONSTANT   = -2147483648
 DESCRIPTION        = "The planetocentric longitude of the spot 4 centroid,
   in the range -180 to 180 degrees. Negative values should be adjusted by
   adding 360 degrees to conform with LRO conventions."

END_OBJECT          = COLUMN

OBJECT              = COLUMN
 COLUMN_NUMBER      = 41
 NAME               = LATITUDE_4
 DATA_TYPE          = LSB_INTEGER
 START_BYTE         = 165
 BYTES              = 4
 UNIT               = 'DEGREES * (10**7)'
 MISSING_CONSTANT   = -2147483648
 DESCRIPTION        = "The planetocentric latitude of the spot 4 centroid."
END_OBJECT          = COLUMN

OBJECT              = COLUMN
 COLUMN_NUMBER      = 42
 NAME               = RADIUS_4
 DATA_TYPE          = LSB_INTEGER
 START_BYTE         = 169
 BYTES              = 4
 UNIT               = 'MILLIMETERS'
```

24

```
   MISSING_CONSTANT   = -1
   DESCRIPTION        = "The distance from the Moon center to the
     Spot 4 centroid."
  END_OBJECT          = COLUMN

  OBJECT              = COLUMN
   COLUMN_NUMBER      = 43
   NAME               = RANGE_4
   DATA_TYPE          = LSB_UNSIGNED_INTEGER
   START_BYTE         = 173
   BYTES              = 4
   UNIT               = 'MILLIMETERS'
   MISSING_CONSTANT   = 4294967295
   DESCRIPTION        = "LOLA range to the spot 4 centroid."
  END_OBJECT          = COLUMN

  OBJECT              = COLUMN
   COLUMN_NUMBER      = 44
   NAME               = PULSE_4
   DATA_TYPE          = LSB_INTEGER
   START_BYTE         = 177
   BYTES              = 4
   UNIT               = 'PICOSECOND'
   MISSING_CONSTANT   = -1
   DESCRIPTION        = "Pulse width of spot 4 return at THRESHOLD_4."
  END_OBJECT          = COLUMN

  OBJECT              = COLUMN
   COLUMN_NUMBER      = 45
   NAME               = ENERGY_4
   DATA_TYPE          = LSB_UNSIGNED_INTEGER
   START_BYTE         = 181
   BYTES              = 4
   UNIT               = 'ZEPTOJOULES'
   DESCRIPTION        = "Received Energy of detected return 4."
  END_OBJECT          = COLUMN

  OBJECT              = COLUMN
   COLUMN_NUMBER      = 46
   NAME               = BACKGROUND_4
   DATA_TYPE          = LSB_UNSIGNED_INTEGER
   START_BYTE         = 185
   BYTES              = 4
   UNIT               = 'PICOWATTS'
   DESCRIPTION        = "Background noise power at detector 4."
  END_OBJECT          = COLUMN

  OBJECT              = COLUMN
   COLUMN_NUMBER      = 47
   NAME               = THRESHOLD_4
   DATA_TYPE          = LSB_UNSIGNED_INTEGER
   START_BYTE         = 189
   BYTES              = 4
   UNIT               = 'NANOVOLTS'
   DESCRIPTION        = "Threshold at detector 4."
  END_OBJECT          = COLUMN
```

```
OBJECT              = COLUMN
 COLUMN_NUMBER      = 48
 NAME               = GAIN_4
 DATA_TYPE          = LSB_UNSIGNED_INTEGER
 START_BYTE         = 193
 BYTES              = 4
 DESCRIPTION        = "Gain at detector 4 scaled by 1.E6."
END_OBJECT          = COLUMN

OBJECT              = COLUMN
 COLUMN_NUMBER      = 49
 NAME               = SHOT_FLAG_4
 DATA_TYPE          = LSB_UNSIGNED_INTEGER
 START_BYTE         = 197
 BYTES              = 4
 DESCRIPTION        = "Describes the probability that spot 4 is a lunar range
   and its associated quality as in SHOT_FLAG_1."
END_OBJECT          = COLUMN

/* Spot 5 */

OBJECT              = COLUMN
 COLUMN_NUMBER      = 50
 NAME               = LONGITUDE_5
 DATA_TYPE          = LSB_INTEGER
 START_BYTE         = 201
 BYTES              = 4
 UNIT               = 'DEGREES * (10**7)'
 MISSING_CONSTANT   = -2147483648
 DESCRIPTION        = "The planetocentric longitude of the spot 5 centroid,
    in the range -180 to 180 degrees. Negative values should be adjusted by
    adding 360 degrees to conform with LRO conventions."

END_OBJECT          = COLUMN

OBJECT              = COLUMN
 COLUMN_NUMBER      = 51
 NAME               = LATITUDE_5
 DATA_TYPE          = LSB_INTEGER
 START_BYTE         = 205
 BYTES              = 4
 UNIT               = 'DEGREES * (10**7)'
 MISSING_CONSTANT   = -2147483648
 DESCRIPTION        = "The planetocentric latitude of the spot 5 centroid."
END_OBJECT          = COLUMN

OBJECT              = COLUMN
 COLUMN_NUMBER      = 52
 NAME               = RADIUS_5
 DATA_TYPE          = LSB_INTEGER
 START_BYTE         = 209
 BYTES              = 4
 UNIT               = 'MILLIMETERS'
 MISSING_CONSTANT   = -1
 DESCRIPTION        = "The distance from the Moon center to the
```

26

```
   Spot 5 centroid."
END_OBJECT              = COLUMN

OBJECT                  = COLUMN
 COLUMN_NUMBER          = 53
 NAME                   = RANGE_5
 DATA_TYPE              = LSB_UNSIGNED_INTEGER
 START_BYTE             = 213
 BYTES                  = 4
 MISSING_CONSTANT       = 4294967295
 UNIT                   = 'MILLIMETERS'
 DESCRIPTION            = "LOLA range to the spot 5 centroid."
END_OBJECT              = COLUMN

OBJECT                  = COLUMN
 COLUMN_NUMBER          = 54
 NAME                   = PULSE_5
 DATA_TYPE              = LSB_INTEGER
 START_BYTE             = 217
 BYTES                  = 4
 UNIT                   = 'PICOSECOND'
 MISSING_CONSTANT       = -1
 DESCRIPTION            = "Pulse width of spot 5 return at THRESHOLD_5."
END_OBJECT              = COLUMN

OBJECT                  = COLUMN
 COLUMN_NUMBER          = 55
 NAME                   = ENERGY_5
 DATA_TYPE              = LSB_UNSIGNED_INTEGER
 START_BYTE             = 221
 BYTES                  = 4
 UNIT                   = 'ZEPTOJOULES'
 DESCRIPTION            = "Received Energy of detected return 5."
END_OBJECT              = COLUMN

OBJECT                  = COLUMN
 COLUMN_NUMBER          = 56
 NAME                   = BACKGROUND_5
 DATA_TYPE              = LSB_UNSIGNED_INTEGER
 START_BYTE             = 225
 BYTES                  = 4
 UNIT                   = 'PICOWATTS'
 DESCRIPTION            = "Background noise power at detector 5."
END_OBJECT              = COLUMN

OBJECT                  = COLUMN
 COLUMN_NUMBER          = 57
 NAME                   = THRESHOLD_5
 DATA_TYPE              = LSB_UNSIGNED_INTEGER
 START_BYTE             = 229
 BYTES                  = 4
 UNIT                   = 'NANOVOLTS'
 DESCRIPTION            = "Threshold at detector 5."
END_OBJECT              = COLUMN

OBJECT                  = COLUMN
```

```
 COLUMN_NUMBER       = 58
 NAME                = GAIN_5
 DATA_TYPE           = LSB_UNSIGNED_INTEGER
 START_BYTE          = 233
 BYTES               = 4
 DESCRIPTION         = "Gain at detector 5 scaled by 1.E6."
END_OBJECT           = COLUMN

OBJECT               = COLUMN
 COLUMN_NUMBER       = 59
 NAME                = SHOT_FLAG_5
 DATA_TYPE           = LSB_UNSIGNED_INTEGER
 START_BYTE          = 237
 BYTES               = 4
 DESCRIPTION         = "Describes the probability that spot 5 is a lunar range
   and its associated quality as in SHOT_FLAG_1."
END_OBJECT           = COLUMN

/* pack things into four bytes using short integers */

OBJECT               = COLUMN
 COLUMN_NUMBER       = 60
 BYTES               = 2
 NAME                = OFFNADIR_ANGLE
 DATA_TYPE           = LSB_UNSIGNED_INTEGER
 START_BYTE          = 241
 UNIT                = 'RADIANS * 20,000'
 DESCRIPTION         = "Angle from nadir to detector 1 boresight."
 MISSING_CONSTANT    = 65535
END_OBJECT           = COLUMN

OBJECT               = COLUMN
 COLUMN_NUMBER       = 61
 BYTES               = 2
 NAME                = EMISSION_ANGLE
 DATA_TYPE           = LSB_UNSIGNED_INTEGER
 START_BYTE          = 243
 UNIT                = 'RADIANS * 20,000'
 MISSING_CONSTANT    = 65535
 DESCRIPTION         = "Angle from vertical to detector 1."
END_OBJECT           = COLUMN

OBJECT               = COLUMN
 COLUMN_NUMBER       = 62
 BYTES               = 2
 NAME                = SOLAR_INCIDENCE
 DATA_TYPE           = LSB_UNSIGNED_INTEGER
 START_BYTE          = 245
 UNIT                = 'RADIANS * 20,000'
 MISSING_CONSTANT    = 65535
 DESCRIPTION         = "Angle from vertical to Sun."
END_OBJECT           = COLUMN

OBJECT               = COLUMN
 COLUMN_NUMBER       = 63
 BYTES               = 2
```

```
 NAME                  = SOLAR_PHASE
 DATA_TYPE             = LSB_UNSIGNED_INTEGER
 START_BYTE            = 247
 UNIT                  = 'RADIANS * 20,000'
 MISSING_CONSTANT      = 65535
 DESCRIPTION           = "Angle from detector 1 boresight to Sun."
END_OBJECT             = COLUMN

OBJECT                 = COLUMN
 COLUMN_NUMBER         = 64
 BYTES                 = 4
 NAME                  = EARTH_RANGE
 DATA_TYPE             = LSB_UNSIGNED_INTEGER
 START_BYTE            = 249
 DESCRIPTION           = "Time from T0 to Earth return as 32-bit fraction."
END_OBJECT             = COLUMN

OBJECT                 = COLUMN
 COLUMN_NUMBER         = 65
 BYTES                 = 2
 NAME                  = EARTH_PULSE
 DATA_TYPE             = LSB_UNSIGNED_INTEGER
 UNIT                  = 'PICOSECOND'
 MISSING_CONSTANT      = 65535
 START_BYTE            = 253
 DESCRIPTION           = "Pulse width of Earth return. Short ground pulses
  typically do not exceed 32 ns, but values should be read as unsigned."
END_OBJECT             = COLUMN

OBJECT                 = COLUMN
 COLUMN_NUMBER         = 66
 BYTES                 = 2
 NAME                  = EARTH_ENERGY
 DATA_TYPE             = LSB_UNSIGNED_INTEGER
 UNIT                  = 'ATTOJOULE'
 MISSING_CONSTANT      = 65535
 START_BYTE            = 255
 DESCRIPTION           = "Energy of Earth return. Energy saturates at ~3 fJ."
END_OBJECT             = COLUMN
```

5.2.   Contents of the LOLARADR.FMT file

```
/*****************************************************************************/
/*    LOLA_RADR.FMT v1                                                       */
/*                   3 September 2015 Kopal Jha                              */
/*****************************************************************************/
OBJECT          = COLUMN
   NAME           = LATITUDE
   COLUMN_NUMBER  = 1
   BYTES          = 10
   DATA_TYPE      = ASCII_REAL
   START_BYTE     = 1
   FORMAT         = "F10.6"
   UNIT           = "DEGREE"
   DESCRIPTION    = "The planetocentric latitude of the laser spot
     producing a trigger on a given channel."
```

```
END_OBJECT     = COLUMN

OBJECT         = COLUMN
   NAME           = LONGITUDE
   COLUMN_NUMBER  = 2
   BYTES          = 10
   DATA_TYPE      = ASCII_REAL
   START_BYTE     = 12
   FORMAT         = "F10.6"
   UNIT           = "DEGREE"
   DESCRIPTION    = "The planetocentric longitude of the laser spot
      producing a trigger on a given channel."
END_OBJECT     = COLUMN

OBJECT         = COLUMN
   NAME           = NORMAL_ALBEDO
   COLUMN_NUMBER  = 3
   BYTES          = 8
   DATA_TYPE      = ASCII_REAL
   START_BYTE     = 23
   FORMAT         = "F8.6"
   DESCRIPTION    = "The geometric albedo of the Moon at zero phase angle
   relative to Lambertian at 1064 nm wavelength, calculated using measure-
ments
   from the LOLA Reduced Data Record (RDR) version 1.0 for the 13 months of
   the nominal mission phase (LRO_NO_01 to LRO_NO_13), using the method
   described in Lemelin et al. (2015)."
END_OBJECT     = COLUMN

OBJECT         = COLUMN
   NAME           = TERRESTRIAL_DYNAMIC_TIME
   COLUMN_NUMBER  = 4
   BYTES          = 19
   DATA_TYPE      = ASCII_REAL
   START_BYTE     = 32
   FORMAT         = "F19.9"
   UNIT           = "SECOND"
   DESCRIPTION    = "Measurement time in Terrestrial Dynamical Time
   (TDT, aka TT) at the LRO spacecraft, in seconds from the J2000 epoch.
   TDT is the independent argument of apparent geocentric ephemerides.
   TDB, barycentric coordinate time, varies from TDT only by periodic
   variations. TDT is related to Coordinated Universal Time (UTC)
   through International Atomic Time (TAI) and leap seconds.
   TDT = TAI + 32.184 seconds."
END_OBJECT     = COLUMN

OBJECT         = COLUMN
   NAME           = LASER_USED
   COLUMN_NUMBER  = 5
   BYTES          = 1
   START_BYTE     = 52
   DATA_TYPE      = ASCII_INTEGER
   FORMAT         = "I1"
   DESCRIPTION    = "Laser 1 or Laser 2; the laser currently firing."
END_OBJECT     = COLUMN
```

```
OBJECT          = COLUMN
   NAME            = DETECTOR_ID
   COLUMN_NUMBER  = 6
   BYTES          = 1
   DATA_TYPE      = ASCII_INTEGER
   FORMAT         = "I1"
   START_BYTE     = 54
   DESCRIPTION    = "Receiver ID for ground or noise trigger -
                    value range from 1-5."
END_OBJECT      = COLUMN

OBJECT          = COLUMN
   NAME            = REFLECTANCE
   COLUMN_NUMBER  = 7
   BYTES          = 8
   DATA_TYPE      = ASCII_REAL
   START_BYTE     = 56
   FORMAT         = "F8.6"
   DESCRIPTION    = "Fraction of incident laser energy reflected at the
   surface."
END_OBJECT      = COLUMN

OBJECT          = COLUMN
   NAME            = RECEIVED_ENERGY
   COLUMN_NUMBER  = 8
   BYTES          = 8
   DATA_TYPE      = ASCII_REAL
   START_BYTE     = 65
   UNIT           = "zJ"
   FORMAT         = "F8.6"
   DESCRIPTION    = "Measure of reflected energy received from the ground."
END_OBJECT      = COLUMN

OBJECT          = COLUMN
   NAME            = TRANSMIT_ENERGY
   COLUMN_NUMBER  = 9
   BYTES          = 8
   DATA_TYPE      = ASCII_REAL
   UNIT           = "mJ"
   START_BYTE     = 74
   FORMAT         = "F8.6"
   DESCRIPTION    = "Energy of laser pulse fired."
END_OBJECT      = COLUMN

OBJECT          = COLUMN
   NAME            = RANGE
   COLUMN_NUMBER  = 10
   BYTES          = 7
   DATA_TYPE      = ASCII_REAL
   START_BYTE     = 83
   UNIT           = "KM"
   FORMAT         = "F7.3"
   DESCRIPTION    = "Range from spacecraft center of mass
        to bounce point, in km."
END_OBJECT      = COLUMN
```

```
OBJECT          = COLUMN
   NAME             = SOLAR_INCIDENCE_ANGLE
   COLUMN_NUMBER  = 11
   BYTES            = 6
   DATA_TYPE        = ASCII_REAL
   START_BYTE       = 91
   FORMAT           = "F6.3"
   DESCRIPTION      = "Angle between incoming solar radiation and the local
   surface horizontal vector at the bounce point."
END_OBJECT      = COLUMN

OBJECT          = COLUMN
   NAME             = OFF_NADIR_ANGLE
   COLUMN_NUMBER  = 12
   BYTES            = 6
   DATA_TYPE        = ASCII_REAL
   START_BYTE       = 98
   UNIT             = "DEGREE"
   FORMAT           = "F6.3"
   DESCRIPTION      = "The angle between the laser path and the nadir direction
   at the spacecraft."
END_OBJECT      = COLUMN

OBJECT          = COLUMN
   NAME             = DROPOFF_FIT
   COLUMN_NUMBER  = 13
   BYTES            = 8
   DATA_TYPE        = ASCII_REAL
   START_BYTE       = 105
   DESCRIPTION      = "Value for this shot/detector of the sigmoidal logistic
   function that best describes the loss of received energy during the cur-
rent
   orbit. Such a loss typically occurs in the polar regions due to a tempo-
rary
   misalignment of the LOLA laser transmitter telescope due to the changing
   thermal load from the Moon. The fit function is different for each orbit
   and was used to remove biases in the reflectance data in order to obtain a
   calibrated normal albedo (given in column #3)."
END_OBJECT      = COLUMN
```

5.3.   Sample LOLA RADR Detached Label

```
PDS_VERSION_ID                = "PDS3"
/*** FILE FORMAT ***/
FILE_RECORDS                  = 52424
RECORD_TYPE                   = FIXED_LENGTH
RECORD_BYTES                  = 114
/*** GENERAL DATA DESCRIPTION PARAMETERS ***/
PRODUCT_ID                    = "LOLARADR_092582345"
PRODUCT_VERSION_ID            = "V1"
PRODUCT_CREATION_TIME         = 2016-03-07T16:30:24
PRODUCT_TYPE                  = "RADR"
STANDARD_DATA_PRODUCT_ID      = "LOLA_DATA"
SOURCE_PRODUCT_ID             = "LOLARDR_092582345.DAT"
POSITIVE_LONGITUDE_DIRECTION  = EAST
INSTRUMENT_HOST_NAME          = "LUNAR RECONNAISSANCE ORBITER"
INSTRUMENT_NAME               = "LUNAR ORBITER LASER ALTIMETER"
```

```
INSTRUMENT_ID                  = "LOLA"
DATA_SET_ID                    = "LRO-L-LOLA-3-RADR-V1.0"
DATA_SET_NAME                  = "LRO MOON LASER ALTIMETER 3 RADR V1.0"
MISSION_PHASE_NAME             = "NOMINAL MISSION"
COORDINATE_SYSTEM_NAME         = "MEAN EARTH/POLAR AXIS OF DE421"
TARGET_NAME                    = "MOON"
PRODUCER_ID                    = LRO_LOLA_TEAM
PRODUCER_FULL_NAME             = "DAVID E. SMITH"
PRODUCER_INSTITUTION_NAME      = "GODDARD SPACE FLIGHT CENTER"
PRODUCT_RELEASE_DATE           = 2015-12-15
ORBIT_NUMBER                   = 1006
START_TIME                     = 2009-09-15T23:45:56.298
STOP_TIME                      = 2009-09-16T01:39:05.298
SPACECRAFT_CLOCK_START_COUNT   = "7721131"
SPACECRAFT_CLOCK_STOP_COUNT    = "7727920"
INSTRUMENT_MODE_ID             = {"SC_B",
        "LASER_1 ",
        "ENABLED",
        "FIRING",
          "GAINS_DIS",
        "THRESHOLDS_FSW",
        "RGATES_FSW",
        "SWINPUTS_FSW"}
^TABLE                         = "LOLARADR_092582345.TAB"
OBJECT                         = TABLE
  COLUMNS                      = 13
  INTERCHANGE_FORMAT           = ASCII
  ROW_BYTES                    = 114
  ROWS                         = 52424
  DESCRIPTION                  = "
    This product contains time-ordered, calibrated, geolocated
    active radiometric data of the Lunar Orbiter Laser Altimeter (LOLA)."
  ^STRUCTURE  = "LOLARADR.FMT"
END_OBJECT                     = TABLE
END
```

5.4.   Sample LOLA GDR Detached Label

```
PDS_VERSION_ID            = "PDS3"
/*** GENERAL DATA DESCRIPTION PARAMETERS ***/
PRODUCT_VERSION_ID        = "V2.0"
DATA_SET_ID               = "LRO-L-LOLA-4-GDR-V1.0"
PRODUCT_ID                = "LDEM_64"
INSTRUMENT_HOST_NAME      = "LUNAR RECONNAISSANCE ORBITER"
INSTRUMENT_NAME           = "LUNAR ORBITER LASER ALTIMETER"
INSTRUMENT_ID             = "LOLA"
MISSION_PHASE_NAME        = {"COMMISSIONING","NOMINAL MISSION","SCIENCE
                            MISSION","EXTENDED SCIENCE MISSION"}
TARGET_NAME               = MOON
START_TIME                = 2009-07-13T17:33:17
STOP_TIME                 = 2014-06-10T00:10:56
PRODUCT_CREATION_TIME     = 2014-09-15T00:00:00
PRODUCER_ID               = LRO_LOLA_TEAM
PRODUCER_FULL_NAME        = "DAVID E. SMITH"
```

```
PRODUCER_INSTITUTION_NAME = "GODDARD SPACE FLIGHT CENTER"
DESCRIPTION              = "This data product is a shape map (radius)
   of the Moon at a resolution of 473.802 m/pix by 473.802 m/pix,
   based on altimetry data acquired through mission phase LRO_ES_21
   by the LOLA instrument. Preliminary LOLA data used for the generation of
   previous GDR products is replaced by data geolocated using precision
   orbits based on a revised lunar gravity field GRGM 900C[LEMOINEETAL2014].

   The ground tracks were interpolated using the Generic
   Mapping Tools programs 'surface' and 'grdblend'.  The map is in
   the form of a binary table with one row for each
   0.015625 degrees of latitude, pixel registered.  Map values
   are relative to a radius of 1737.4 km.

   This label describes an IMG file in the form of a binary resampling
   to pixel registration."

OBJECT                  = UNCOMPRESSED_FILE
FILE_NAME               = "LDEM_64.IMG"
RECORD_TYPE             = FIXED_LENGTH
FILE_RECORDS            = 11520
RECORD_BYTES            = 46080
^IMAGE                  = "LDEM_64.IMG"

  OBJECT                = IMAGE
    NAME                = HEIGHT
    DESCRIPTION         = "Each sample represents height relative to a
       reference radius (OFFSET) and is generated using preliminary LOLA data
       produced by the LOLA team."
    LINES               = 11520
    LINE_SAMPLES        = 23040
    MAXIMUM             = 21545
    MINIMUM             = -18250
    SAMPLE_TYPE         = LSB_INTEGER
    SAMPLE_BITS         = 16
    UNIT                = METER
    SCALING_FACTOR      = 0.5
    OFFSET              = 1737400.

/* NOTE:                                                              */
/* Conversion from Digital Number to HEIGHT, i.e. elevation in meters, is: */
/* HEIGHT = (DN * SCALING_FACTOR).                                    */
/* The conversion from Digital Number to PLANETARY_RADIUS in meters is:    */
/* PLANETARY_RADIUS = (DN * SCALING_FACTOR) + OFFSET                  */
/* where OFFSET is the radius of a reference sphere.                  */
/* The planetopotential TOPOGRAPHY is PLANETARY_RADIUS - GEOID_RADIUS,     */
/* where GEOID_RADIUS is derived from a gravitational equipotential model. */
/* By convention, the average GEOID_RADIUS at the equator is OFFSET.       */

  END_OBJECT            = IMAGE
END_OBJECT              = UNCOMPRESSED_FILE
OBJECT                  = IMAGE_MAP_PROJECTION
 ^DATA_SET_MAP_PROJECTION    = "DSMAP.CAT"
 MAP_PROJECTION_TYPE    = "SIMPLE CYLINDRICAL"
 MAP_RESOLUTION         = 64 <pix/deg>
 A_AXIS_RADIUS          = 1737.4 <km>
```

```
 B_AXIS_RADIUS                   = 1737.4 <km>
 C_AXIS_RADIUS                   = 1737.4 <km>
 FIRST_STANDARD_PARALLEL         = 'N/A'
 SECOND_STANDARD_PARALLEL        = 'N/A'
 POSITIVE_LONGITUDE_DIRECTION    = "EAST"
 CENTER_LATITUDE                 = 0 <deg>
 CENTER_LONGITUDE                = 180 <deg>
 REFERENCE_LATITUDE              = 'N/A'
 REFERENCE_LONGITUDE             = 'N/A'
 LINE_FIRST_PIXEL                = 1
 LINE_LAST_PIXEL                 = 11520
 SAMPLE_FIRST_PIXEL              = 1
 SAMPLE_LAST_PIXEL               = 23040
 MAP_PROJECTION_ROTATION         = 0.0
 MAP_SCALE                       = 473.802 <m/pix>
 MAXIMUM_LATITUDE                = 90 <deg>
 MINIMUM_LATITUDE                = -90 <deg>
 WESTERNMOST_LONGITUDE           = 0 <deg>
 EASTERNMOST_LONGITUDE           = 360 <deg>
 LINE_PROJECTION_OFFSET          = 5759.5 <pix>
 SAMPLE_PROJECTION_OFFSET        = 11519.5 <pix>
 COORDINATE_SYSTEM_TYPE          = "BODY-FIXED ROTATING"
 COORDINATE_SYSTEM_NAME          = "MEAN EARTH/POLAR AXIS OF DE421"
END_OBJECT                       = IMAGE_MAP_PROJECTION
END
```

5.5. Sample LOLA SHADR Label

```
PDS_VERSION_ID            = PDS3
RECORD_TYPE               = FIXED_LENGTH
RECORD_BYTES              = 122
FILE_RECORDS              = 4185
^SHADR_HEADER_TABLE       = ("LGM2009A.SHA",1)
^SHADR_COEFFICIENTS_TABLE = ("LGM2009A.SHA",3)
/*** GENERAL DATA DESCRIPTION PARAMETERS ***/
PRODUCT_ID                = "LOLASHADR_2009A"
PRODUCT_VERSION_ID        = "V1"
PRODUCT_CREATION_TIME     = 2008-11-04T12:00:00
PRODUCT_TYPE              = "SHADR"
STANDARD_DATA_PRODUCT_ID  = "DATA"
SOFTWARE_NAME             = "LOLA_SHADR"
SOFTWARE_VERSION_ID       = "1.0"
COORDINATE_SYSTEM_NAME    = "MEAN EARTH/POLAR AXIS OF DE421"
INSTRUMENT_HOST_NAME      = "LUNAR RECONNAISSANCE ORBITER"
INSTRUMENT_NAME           = "LUNAR ORBITER LASER ALTIMETER"
INSTRUMENT_ID             = "LOLA"
DATA_SET_ID               = "LRO-L-LOLA-5-SHADR-V1.0"
DATA_SET_NAME             = "LRO MOON LASER ALTIMETER 5 SHADR V1.0"
MISSION_PHASE_NAME        = "COMMISSIONING"
TARGET_NAME               = "MOON"
PRODUCER_ID               = LRO_LOLA_TEAM
PRODUCER_FULL_NAME        = "DAVID E. SMITH"
PRODUCER_INSTITUTION_NAME = "GODDARD SPACE FLIGHT CENTER"
PRODUCT_RELEASE_DATE      = 2008-11-04
OBSERVATION_TYPE          = "GRAVITY FIELD"
DESCRIPTION               = "
  This file contains coefficients and related data for a spherical
```

harmonic model of the lunar gravity field."

```
OBJECT                    = SHADR_HEADER_TABLE
ROWS                      = 1
COLUMNS                   = 8
ROW_BYTES                 = 137
ROW_SUFFIX_BYTES          = 107
INTERCHANGE_FORMAT        = ASCII
DESCRIPTION               = "The SHADR header includes descriptive
 information about the spherical harmonic coefficients which follow
 in SHADR_COEFFICIENTS_TABLE.  The header consists of a single record
 of eight (delimited) data columns requiring 137 bytes, a pad of 105
 unspecified ASCII characters, an ASCII carriage-return, and an ASCII
 line-feed."

  OBJECT                  = COLUMN
    NAME                        = "REFERENCE RADIUS"
    DATA_TYPE                   = ASCII_REAL
    START_BYTE                  = 1
    BYTES                       = 23
    FORMAT                      = "E23.16"
    UNIT                        = "KILOMETER"
    DESCRIPTION                 = "The assumed reference radius of
      the spherical planet."
  END_OBJECT              = COLUMN

  OBJECT                  = COLUMN
    NAME                        = "CONSTANT"
    DATA_TYPE                   = ASCII_REAL
    START_BYTE                  = 25
    BYTES                       = 23
    FORMAT                      = "E23.16"
    UNIT                        = "N/A"
    DESCRIPTION                 = "For a gravity field model the
      assumed gravitational constant GM in km cubed per seconds
      squared for the planet.  For a topography model, set to 1."
  END_OBJECT              = COLUMN

  OBJECT                  = COLUMN
    NAME                        = "UNCERTAINTY IN CONSTANT"
    DATA_TYPE                   = ASCII_REAL
    START_BYTE                  = 49
    BYTES                       = 23
    FORMAT                      = "E23.16"
    UNIT                        = "N/A"
    DESCRIPTION                 = "For a gravity field model the
      uncertainty in the gravitational constant GM in km cubed per
      seconds squared for the planet (or, set to 0 if not known).
      For a topography model, set to 0."
  END_OBJECT              = COLUMN

  OBJECT                  = COLUMN
    NAME                        = "DEGREE OF FIELD"
    DATA_TYPE                   = ASCII_INTEGER
    START_BYTE                  = 73
    BYTES                       = 5
```

```
   FORMAT                      = "I5"
   UNIT                        = "N/A"
   DESCRIPTION                 = "Degree of the model field."
 END_OBJECT              = COLUMN

 OBJECT                  = COLUMN
   NAME                        = "ORDER OF FIELD"
   DATA_TYPE                   = ASCII_INTEGER
   START_BYTE                  = 79
   BYTES                       = 5
   FORMAT                      = "I5"
   UNIT                        = "N/A"
   DESCRIPTION                 = "Order of the model field."
 END_OBJECT              = COLUMN

 OBJECT                  = COLUMN
   NAME                        = "NORMALIZATION STATE"
   DATA_TYPE                   = ASCII_INTEGER
   START_BYTE                  = 85
   BYTES                       = 5
   FORMAT                      = "I5"
   UNIT                        = "N/A"
   DESCRIPTION                 = "The normalization indicator.
    For gravity field:
        0   coefficients are unnormalized
        1   coefficients are normalized
        2   other."
 END_OBJECT              = COLUMN

 OBJECT                  = COLUMN
   NAME                        = "REFERENCE LONGITUDE"
   POSITIVE_LONGITUDE_DIRECTION = "EAST"
   DATA_TYPE                   = ASCII_REAL
   START_BYTE                  = 91
   BYTES                       = 23
   FORMAT                      = "E23.16"
   UNIT                        = "DEGREE"
   DESCRIPTION                 = "The reference longitude for the
    spherical harmonic expansion; normally 0."
 END_OBJECT              = COLUMN

 OBJECT                  = COLUMN
   NAME                        = "REFERENCE LATITUDE"
   DATA_TYPE                   = ASCII_REAL
   START_BYTE                  = 115
   BYTES                       = 23
   FORMAT                      = "E23.16"
   UNIT                        = "DEGREE"
   DESCRIPTION                 = "The reference latitude for the
    spherical harmonic expansion; normally 0."
 END_OBJECT              = COLUMN

END_OBJECT              = SHADR_HEADER_TABLE

OBJECT                  = SHADR_COEFFICIENTS_TABLE
  ROWS                      = 4183
```

```
COLUMNS                       = 6
ROW_BYTES                     = 107
ROW_SUFFIX_BYTES              = 15
INTERCHANGE_FORMAT            = ASCII
DESCRIPTION                   = "The SHADR coefficients table contains
 the coefficients for the spherical harmonic model. Each row in the
 table contains the degree index m, the order index n, the
 coefficients Cmn and Smn, and the uncertainties in Cmn and Smn.
 The (delimited) data require 107 ASCII characters; these are
 followed by a pad of 13 unspecified ASCII characters, an ASCII
 carriage-return, and an ASCII line-feed."

OBJECT                        = COLUMN
  NAME                          = "COEFFICIENT DEGREE"
  DATA_TYPE                     = ASCII_INTEGER
  START_BYTE                    = 1
  BYTES                         = 5
  FORMAT                        = "I5"
  UNIT                          = "N/A"
  DESCRIPTION                   = "The degree index m of the
  C and S coefficients in this record."
END_OBJECT                    = COLUMN

OBJECT                        = COLUMN
  NAME                          = "COEFFICIENT ORDER"
  DATA_TYPE                     = ASCII_INTEGER
  START_BYTE                    = 7
  BYTES                         = 5
  FORMAT                        = "I5"
  UNIT                          = "N/A"
  DESCRIPTION                   = "The order index n of the C and S
   coefficients in this record."
END_OBJECT                    = COLUMN

OBJECT                        = COLUMN
  NAME                          = "C"
  DATA_TYPE                     = ASCII_REAL
  START_BYTE                    = 13
  BYTES                         = 23
  FORMAT                        = "E23.16"
  UNIT                          = "N/A"
  DESCRIPTION                   = "The coefficient Cmn for this
   spherical harmonic model."
END_OBJECT                    = COLUMN

OBJECT                        = COLUMN
  NAME                          = "S"
  DATA_TYPE                     = ASCII_REAL
  START_BYTE                    = 37
  BYTES                         = 23
  FORMAT                        = "E23.16"
  UNIT                          = "N/A"
  DESCRIPTION                   = "The coefficient Smn for this
   spherical harmonic model."
END_OBJECT                    = COLUMN
```

```
OBJECT                    = COLUMN
  NAME                      = "C UNCERTAINTY"
  DATA_TYPE                 = ASCII_REAL
  START_BYTE                = 61
  BYTES                     = 23
  FORMAT                    = "E23.16"
  UNIT                      = "N/A"
  DESCRIPTION               = "The uncertainty in the coefficient
   Cmn for this spherical harmonic model."
END_OBJECT                = COLUMN

OBJECT                    = COLUMN
  NAME                      = "S UNCERTAINTY"
  DATA_TYPE                 = ASCII_REAL
  START_BYTE                = 85
  BYTES                     = 23
  FORMAT                    = "E23.16"
  UNIT                      = "N/A"
  DESCRIPTION               = "The uncertainty in the coefficient
   Smn for this spherical harmonic model."
END_OBJECT                = COLUMN

END_OBJECT              = SHADR_COEFFICIENTS_TABLE

END
```