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Moon Mineralogy Mapper



DATA PRODUCT SOFTWARE INTERFACE SPECIFICATION

Version 9.10

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TABLE OF CONTENTS

1. Introduction 11
1.1. Purpose and Scope 11
1.2. Contents 11
1.3. Applicable Documents and Constraints 11
1.4. Relationships with Other Interfaces 13
1.5. Image Display and Analysis Software – ENVI/IDL 13

2. DATA PRODUCT CHARACTERISTICS AND ENVIRONMENT 14
2.1. Instrument Overview 14
2.2. Instrument Operations Overview 17
2.3. Data Product Overview 20
2.4. Data Processing 21
2.4.1. Data Processing Level 21
2.5. Data Product Generation 23
2.5.1. Overview 23
2.5.2. Level 0 Data Processing 23
2.5.3. Level 1B Data Processing 24
2.5.3.1. Spectral Radiance Calibration 24
2.5.3.2. Ray Tracing and Pixel Location 37
2.5.3.3. Observation Geometry 40
2.5.3.4. Observation Timing 41
2.5.4. Level 2 Processing 41
2.5.4.1. Photometrically-Corrected Spectral Reflectance Calibration 41
2.5.4.2. Limitations 60
2.5.5. Data Flow 67
2.5.6. Labeling and Identification 67
2.6. Standards Used in Generating Data Products 69
2.6.1. PDS Standards 69
2.6.2. Time Standards 69
2.6.3. Coordinate Systems 69
2.7. Data Validation 69

3. Detailed Data Product Specifications 70
3.1. M^3 Level 0 Data Products 70
3.1.1. Data Product Structure and Organization 70
3.1.1.1. L0 Image Cube File Format Overview 70
3.1.1.2. Image Frame Header 70
3.1.1.3. L0 Image Cube Format 73
3.1.1.3.1. Target Mode 73
3.1.1.3.2. Global Mode 73
3.1.1.4. L0 Detached Header File Format 74
3.1.1.4.1. Target Mode 74
3.1.1.4.2. Global Mode 75

3.1.1.5. L0 Label Description 76
3.2. M^3 Level 1B Data Products 77
3.2.1. Data Product Structure and Organization 77
3.2.1.1. L1B Spectral Radiance Image Cube File Format Overview 77
3.2.1.2. L1B Spectral Radiance Image Cube Format 78
3.2.1.2.1. Target Mode 79
3.2.1.2.2. Global Mode 79
3.2.1.3. L1B Spectral Radiance Image Cube Detached Header File Format 80
3.2.1.3.1. Target Mode 80
3.2.1.3.2. Global Mode 81
3.2.1.4. Level 1B Spectral Radiance Image Cube Label Description 81
3.2.1.5. Pixel Location File Format 81
3.2.1.6. Pixel Location Detached Header File Format 82
3.2.1.6.1. Target Mode 82
3.2.1.6.2. Global Mode 82
3.2.1.7. Observation Geometry File Format 83
3.2.1.8. Observation Geometry Detached Header File Format 83
3.2.1.8.1. Target Mode 83
3.2.1.8.2. Global Mode 84
3.2.1.9. Observation Timing File Format 84
3.3. M^3 Level 2 Data Products 85
3.3.1. Data Product Structure and Organization 85
3.3.1.1. Level 2 Spectral Reflectance Product and Label Description 85
3.3.1.2. L2 Spectral Reflectance Image Cube File Format Overview 85
3.3.1.3. L2 Spectral Reflectance Image Cube Format 87
3.3.1.3.1. Target Mode 87
3.3.1.3.2. Global Mode 87
3.3.1.4. L2 Spectral Reflectance Image Cube Detached Header File Format 88
3.3.1.4.1. Target Mode 88
3.3.1.4.2. Global Mode 89
3.3.1.5. Reflectance Supplemental File Format 89
3.3.1.6. Reflectance Supplemental Detached Header File Format 89
3.3.1.6.1. Target Mode 90
3.3.1.6.2. Global Mode 90
4. Applicable Software 90
4.1. Utility Programs 90
4.2. Applicable PDS Software Tools 91
Appendix A Detailed Description of Format and Usage of M^3 Raw Time Data 92

Appendix B Example L0 Data Product PDS Label 95
Appendix C Example L1B Data Product PDS Label 97
Appendix D Example L2 Data Product PDS Label 102
Appendix E INSTRUCTION FOR BASIC VIEWING OF AN M^3 L0/L1B/L2 Image Cube File (*.IMG) USING ENVI 4.3 105

DOCUMENT CHANGE LOG

Change	Date	Affected Portions
Swap items 6 and 7	7/30/07	Section 2.4.3.3
Add data quality	7/31/07	Section 2.4.3.5
Change Level 1A to Level 1B	8/02/07	All
Change non-resampled to resampled	8/02/07	All
Change data quality image extension from rdnq* to dq*	8/16/07	Pages 5, 12, 28
Added line item to TBD Items	1/25/08	TBD Items table
Switch position of latitude and longitude	2/12/08	Pages 24, 25
Removed data quality images	3/19/08	
Changed *_rdn.lbl to *_l1b.lbl	5/21/08	Pages 5
Added Decimal Day of Year	5/21/08	Page 12
Added DDOY to UTC Timing section	5/21/08	Page 28
Accepted all tracked changes	6/24/08	
Changed *TIM.TXT to *TIM.TAB and revised UTC timing file description	8/26/08	Page 5, 13, 27
Added Level 2 data products; Added J.Sunshine as a signatory (S. McLaughlin)	8/28/08	Most sections
Update L0 Image Frame Header details	9/9/08	Section 3
Added “incidence angle” and “emission angle” to help clarify to-sun and to-sensor zenith angles, respectively; Provided the baseline equation and inputs for converting from L1B radiance to reflectance	9/23/08	TDB Items, Sections 2.4.3.3 and 2.4.4
Added description of image time frame discrepancies between L0 and L1B data products.	9/25/08	Sections 3.1.1.2 and 3.1.2.9
Changed data storage type for L2 from 32-bit reals to 16-bit signed integers where 30000 represents 100% reflectance; Adding SCALING_FACTOR to the L2 PDS label example and L2 ENVI header; Changed the PDS dictionary namespace from M3: to CH1: in the L2 PDS labels.	11/20/08	TDB Items; Sections 2.4.4, 2.4.4.1, 3.3.1.2.1, 3.3.1.2.2, 3.3.1.3.1, 3.3.1.3.2; Figure 3-5; Appendix C
Updated L0, L1B, and L2 PDS label examples	01/07/09	Appendices A, B, C
Updated 16-bit to 32-bit for L1B radiance products and L2 reflectance products	01/26/09	Sections 3.2.1
Updated number of bands from 86 to 85 for L1B Global Mode data	07/07/09	Sections 3.2.1
Changed “Figure 2-2” to “Figure 3-1” and “Figure 2-3” to “Figure3-2” Converted *_obs.img to uppercase Changed last sentence from “Example Level 1B…” to “An Example Level 1B…”	11/04/09	Sections 3.1.1.2, 3.2.1.4

Updated all L2 sections	04/15/11	Many
Changed NOT_APPLICABLE_CONSTANT to INVALID_CONSTANT in L2 label per Imaging Node; Added removal and replacement of SOLAR_DISTANCE in Level 2 thermal correction step.	4/22/11	Appendix D, Section 2.5.4.1
Minor revisions to L2 sections and PDS label; Added section describing the thermal status of the instrument	5/5-5/6/2011	Section 2.5.4.1, 2.5.4.2 (new), Appendix D
Updated applicable documents	09/30/11	Section 1.3
Updated text and figures	09/30/11	Section 2.5.3.1
Updated Example L1B PDS Label	09/30/11	Appendix C
Added M3 team's input for Smooth Shape Correction	10/06/11	Section 2.5.3.1
Updated L2 sections	11/11/11	Sections 1.3, 2.3, 2.5.4, 3.3.1.5 Tables 2_4, 3.3
Updated L2 sections; added several references; corrected typo in Table 2.3	11/17/11	Sections 1.3, 2.3, 2.5.4, 3.3
Replaced UCLN with LOLA and fixed L2 typos (noted during L2 peer review)	11/18/11	Section 2.5.3.3, 2.3, 2.5.4, 3.3
Minor corrects from M3 team's read through; In L2 if emission angle > 85 deg force it to 85 deg for photom correction; data flow timeline; new Fig 2-1 & 2-29.	11/22/11	Sections 2.5.4.1, 2.5.4.2, 2.5.5 Figs 2-1, 2-29.

ACRONYMS

ACT	Applied Coherent Technology Corporation
ASCII	American Standard Code for Information Interchange
AU	Astronomical Unit
BDE	Bad Detector Element Image
BIL	Band Interleaved By Line Format
BIP	Band Interleaved By Pixel Format
BSQ	Band Sequential Format
CCSDS	Consultative Committee on Space Data Systems
CK	SPICE Camera-matrix Kernel
CODMAC	Committee on Data Management, Archiving, and Computing
DDOY	Decimal Day of Year
DEM	Digital Elevation Model
DN	Digital Numbers
DSS	Dark Signal Subtracted Image
ECR	Engineering Change Request
EDR	Experiment Data Record
ENVI	Environment for Visualizing Images
EXT	File Name Extension
FF	Flat Field Image
FK	SPICE Frame Definition Kernel
FWHM	Full-width-at-half-maximum
FOV	Field-of-view
HDR	Detached Header File
ICD	Interface Control Document
IDL	Interactive Data Language
IFOV	Instantaneous Field-of-View
IGDS	Instrument Ground Data System (JPL)
IMG	Image
ISO	International Standards Organization

ISIS	USGS Integrated Software for Imagers and Spectrometers
ISRO	Indian Space Research Organization
ISSDC	Indian Space Science Data Center (ISRO)
ITT	International Telephone & Telegraph
JPL	Jet Propulsion Laboratory
K	Kelvin
L0	Level 0 Data Product (raw)
L1B	Level 1B Data Product (radiance)
L2	Level 2 Data Product (reflectance)
LBL	Detached Label File
LOC	Pixel-Located Data
LOLA	Lunar Orbiter Laser Altimeter (NASA)
LGCWG	Lunar Geodesy and Cartography Working Group
LRO	Lunar Reconnaissance Orbiter (NASA)
MCT	Mercury-Cadmium-Telluride
ME	Mean Earth
MMM/M3	Moon Mineralogy Mapper (JPL/NASA)
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
NM	Nanometer
OBT	On-board Timer
OBS	Observation Geometry Data
PCU	Power Conditioning Unit
PDS	Planetary Data System
RCC	Radiometric Calibration Coefficient
RDN	Spectral Radiance Data
RFL	Spectral Reflectance Data
ROLO	Robotic Lunar Observatory
SCIF	Spacecraft Interface
SCLK	SPICE Spacecraft Clock Coefficients Kernel
SDP	Science Data Processor

SIS	Software Interface Specification
SPK	SPICE Space Vehicle/Target Body Trajectory (Ephemeris) Kernel
SUP	Supplemental Reflectance Data
T_0	Time at Zero
TAB	ASCII Data Table
TBD	To Be Determined
TDB	Barycentric Dynamic Time
TDT	Terrestrial Dynamical Time
TIM	Observation Timing Data
UMD	University of Maryland
UTC	Coordinated Universal Time
VIS	Visual Information Solutions

1. Introduction

1.1. Purpose and Scope

The purpose of this Data Product Software Interface Specification (SIS) is to provide users of the data products from the Moon Mineralogy Mapper (M^3) with a detailed description of the products and how each was generated, including data sources and destinations.

There are three M^3 data products defined in this SIS document. These include:

1) NASA Level 0 consisting of raw, science data in units of DN.
2) NASA Level 1B consisting of resampled calibrated data in units of spectral radiance, pixel center location data, observational geometry and illumination parameters, and UTC timing information for each image frame.
3) NASA Level 2 consisting of photometrically calibrated reflectance data (unitless).

Files used to reduce or calibrate the Level 1B and 2 data products are also described:

1) Spatial, spectral, and radiometric files used to generate radiance values in a Level 1B product from a Level 0 product.
2) File of photometric correction factors used to generate reflectance values in a Level 2 product from a Level 1B product.

This SIS is intended to provide enough information to enable users to read and understand the data product. The users for whom this document is intended are the scientists who will analyze the data, including those associated with the project and those in the general planetary science community.

1.2. Contents

This Data Product SIS describes how data products generated by M^3 are processed, formatted, labeled, and uniquely identified. The document details standards used in generating the products and software that may be used to access the product. Data product structure and organization is described in sufficient detail to enable a user to read the product. Finally, an example of each product label is provided.

1.3. Applicable Documents and Constraints

This Data Product SIS is responsive to the following Moon Mineralogy Mapper documents:

1. M^3 Project Data Management and Archive Plan, S. R. Lundeen and J. M. Diehl, Ver 2.8, June 24, 2010.
2. M^3 Instrument Electronic Assembly Internal ICD for Space Craft Interface Assembly, Science Data Processor (SDP), and Power Conditioning Unit (PCU), Brass Board & Flight Model (as altered by ECRs), August 2006.

3. M^3 Archive Volume Software Interface Specification, S. R. Lundeen, R. Alanis, and S. McLaughlin, Version 3.15, November 22, 2011, JPL D-38529.
4. M^3 Instrument Ground Data System, UMD/ACT, and PDS Imaging Node Interface Control Document, Version 4.2, January 25, 2008, JPL D-37304.

This SIS is also consistent with the following Planetary Data System documents:

5. Planetary Data System Archive Preparation Guide, April 1, 2010, Version 1.4, JPL D-31224.
6. Planetary Data System Standards Reference, February 27, 2009, Version 3.8. JPL D-7669.
7. Planetary Science Data Dictionary Document, Rev. E, August 28, 2002.

The reader is referred to the following documents for additional information (documents 9,10, 12, and 13 are included in EXTRAS):

8. The Unified Lunar Control Network 2005, 2006, Archinal et al., 2006, Version 1.0, http://pubs.usgs.gov/of/2006/1367
9. A Standardized Lunar Coordinate System for the Lunar Reconnaissance Orbiter and Lunar Datasets, LRO Project and LGCWG White Paper, Version 5, October 1, 2008, http://lunar.gsfc.nasa.gov/library/LunCoordWhitePaper-10-08.pdf
10. Lunar Constants and Models Document, September 23, 2005, JPL D-32296, http://ssd.jpl.nasa.gov/dat/lunar_cmd_2005_jpl_d32296.pdf
11. The Moon Mineralogy Mapper (M3) Imaging Spectrometer for Lunar Science: Instrument Description, Calibration, On-Orbit Measurements, Science Data Calibration and On-Orbit Validation, R. O. Green, C. M. Pieters, et al., 2011, *J. Geophys. Res*, doi:10.1029/2011JE003797.
12. Measuring Moonlight: an Overview of the Spatial Properties, Lunar Coverage, Selenolocation and Related Level 1B Products of the Moon Mineralogy Mapper, J. W. Boardman, C. M. Pieters, et al., 2011, *J. Geophys. Res., 116*, E00G14, doi:10.1029/2010JE003730.
13. Thermal Removal From Near-Infrared Imaging Spectroscopy Data of the Moon, R. N. Clark, C. M. Pieters, et al., 2011, *J. Geophys. Res.*, *116,* E00G16, doi:10.1029/2010JE003751.
14. Surface Reflectance Calibration of Terrestrial Imaging Spectroscopy Data: a Tutorial Using AVIRIS in Proceedings of the 10th Airborne Earth Science Workshop, R. N. Clark, G. A. Swayze, et al., 2002, JPL Publication 02-1.
15. Moon - Near-infrared spectral reflectance, a first good look, T. B McCord, et al., 1981, *J. Geophys. Res.*, *86*, 10883-10892, doi:10.1029/JB086iB11p10883.
16. The moon as a spectral calibration standard enabled by lunar samples: The Clementine example, presented at the Workshop on New Views of the Moon II: Understanding the Moon Through the Integration of Diverse Datasets, C. M. Pieters, 1999, Lunar and Planet. Inst., Flagstaff, Arizona.

17. Results of the Moon Mineralogy Mapper Investigation, 2011, *J. Geophys. Res.*, *116*, no. E6.
18. *Theory of Reflectance and Emittance Spectroscopy (Topics in Remote Sensing 3),* Hapke, 1993, Cambridge Univ. Press, Cambridge, UK.
19. Using the Modified Gaussian Model to Extract Quantitative Data from Lunar Soils, Noble, S. K., C. M. Pieters, T. Hiroi, and L. A. Taylor, 2006, *J. Geophys. Res.*, 111, E11009, doi:10.1029/2006JE002721.
20. Water and Hydroxyl on the Moon as Seen by the Moon Mineralogy Mapper (M3), Clark, R. N., C. M. Pieters, et al., 2012. *J. Geophys. Res,* in preparation.
21. MODTRAN4: Radiative Transfer Modeling for Remote Sensing, Anderson, G. P., et al., 2000, *Proc. SPIE 4049*, 176, 2000, doi:10.1117/12.410338.
22. The Solar Irradiance by Computation, R. L. Kurucz, 1995, *Proceedings of the 17th Annual Conference on Atmospheric Transmission Models*, 333-334.
23. Lunar Photometric Properties at Wavelengths 0.5-1.6 μm Acquired by SELENE Spectral Profiler and Their Dependency on Local Albedo and Latitudinal Zones, Yokota, Y., T. Matsunaga, M. Ohtake, J. Haruyama, R. Nakamura, S. Yamamoto, Y. Ogawa, T. Morota, C. Honda, K. Saiki, K. Nagasawa, K. Kitazato, S. Sasaki, A. Iwasaki, H. Demura, N. Hirata, T. Hiroi, R. Honda, Y. Iijima, H. Mizutani, 2011, *Icarus*, Vol. 215, Issue 2, pp. 639-660, doi:10.1016/j.icarus.2011.07.028.
24. A Visible and Near-Infrared Photometric Correction for the Level 2 Data of the Moon Mineralogy Mapper (M3), Besse, S., et al., 2012. *Icarus,* in preparation.

1.4. Relationships with Other Interfaces

Level 0 and 1B data products described in this SIS are produced by the M^3 Instrument Ground Data System (IGDS) located at NASA's Jet Propulsion Laboratory (JPL). Level 2 data products are produced by the University of Maryland (UMD) in partnership with Applied Coherent Technology Corporation (ACT). Changes to the IGDS processing algorithms may cause changes to the data products and thus, this SIS. The Level 1B products are dependent on the M^3 Level 0 products, and Level 2 products are dependent of Level 1B. As such, changes to the Level 0 product may affect the Level 1B and Level 2 products. Changes to the Level 1B product may affect Level 2.

Changes in M^3 data products or this SIS may affect the design of the M^3 archive volumes.

1.5. Image Display and Analysis Software – ENVI/IDL

The commercial software packages ENVI and IDL as well as ACT-REACT can be used to display and analyze Level 0, Level 1B and Level 2 data products (suffix *.IMG). ENVI and IDL are distributed by ITT Visual Information Solutions (http://www.ittvis.com/). ACT-REACT is distributed by Applied Coherent Technologies Corporation

(http://www.actgate.com). M^3 data products do not have a proprietary format. Instead they are arranged as simply and as openly as possible.

ENVI uses a general raster data format consisting of a simple flat binary file and a small associated ASCII (text) header file (suffix *.HDR). This enables ENVI's flexible use of nearly any image format, including those with embedded header information. It should be noted that ENVI/IDL and ISIS can be used in tandem for map projection and mosaicing of data.

See Appendix E for basic M^3 .IMG display instructions.

M^3 L1B and L2 data products can also be displayed with PDS's NASAView software package (L0 data products cannot be viewed with NASAView). For more information, see Section 4.1.

2. DATA PRODUCT CHARACTERISTICS AND ENVIRONMENT

2.1. Instrument Overview

The Moon Mineralogy Mapper (M^3) was selected as a NASA Discovery Mission of Opportunity in February 2005. The M^3 instrument was launched on October 22, 2008 at 00:52:02 UTC from Shriharikota in India on board the Indian Space Research Organization (ISRO) Chandrayaan-1 spacecraft for a nominal two-year mission in a 100 km polar orbit. The M^3 instrument is a high uniformity and high signal-to-noise ratio imaging spectrometer that operates in the solar dominated portion of the electromagnetic spectrum with wavelengths from 430 nm to 3000 nm (0.43 to 3.0 microns) in a high-resolution Target Mode and in a reduced-resolution Global Mode. Target Mode pixel sizes are nominally 70 meters and Global pixels (binned 2 by 2) are 140 meters, from the planned 100 km orbit.

The basis for the use of imaging spectroscopy for mapping the mineralogy of the Moon is shown in the diversity of lunar mineral spectral signatures illustrated in Figure 2-1.

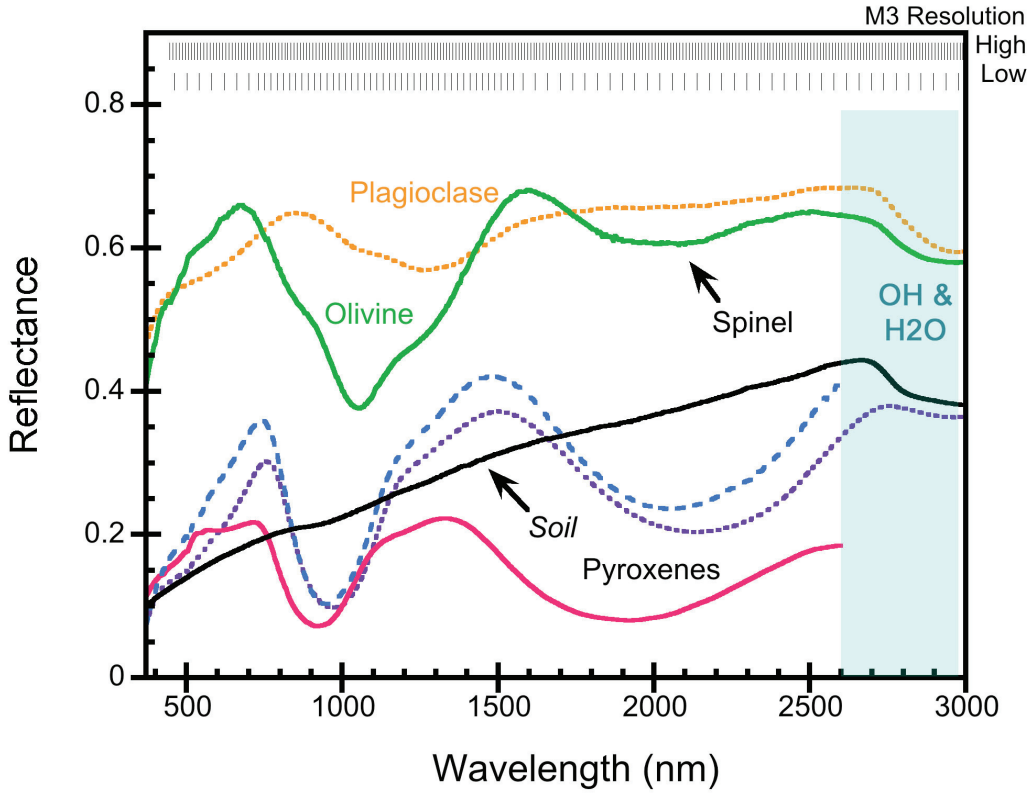


Figure 2-1. Selected reflectance spectra of lunar minerals.

For the M^3 Mission, a high throughput and uniformity optimized Offner imaging spectrometer design[1] was selected and is shown in Figure 2-2. This design uses a compact three-mirror telescope that feeds light through a uniform slit to spectrometer with one spherical mirror and a custom convex grating. The dispersed light from the spectrometer then passes through an order-sorting filter to the detector array that is sensitive from 430 to 3000 nm. This design is enabled by the structured blaze convex grating in the core of the uniform full-range spectrometer. The mass and power of the M^3 instrument are ~8 kilograms and ~15 Watts average. The volume of the optical and detector assembly is 25 X 18 X 12 centimeters.

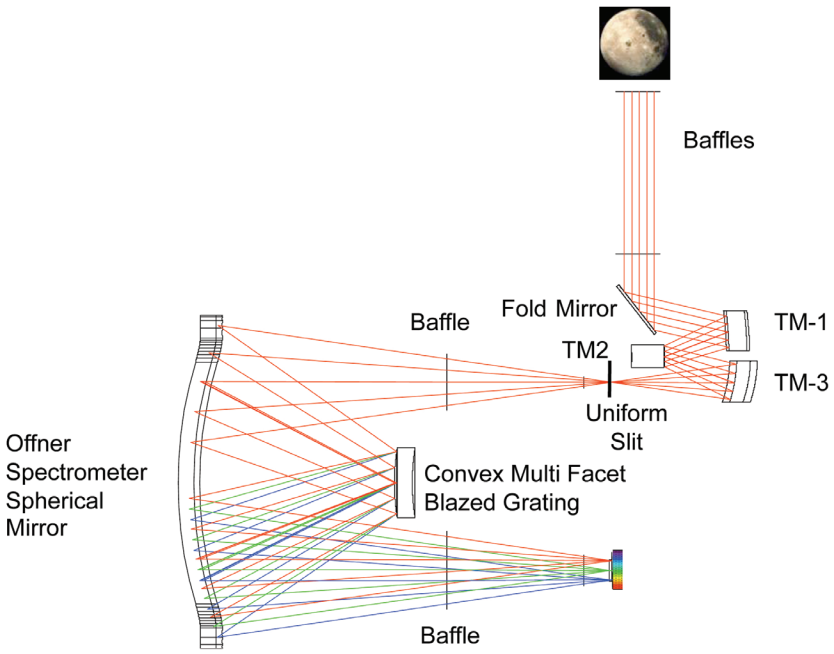


Figure 2-2. Optical layout of the M^3 imaging spectrometer instrument.

A summary of the spectral, radiometric, spatial and uniformity characteristics of the M^3 instrument are given in Table 2-1.

Table 2-1. Key M^3 Measurement Characteristics

Spectral	
Range	430 to 3000 nm
Sampling	10 nm constant
Response	FWHM <15 nm
Radiometric	
Range	0 to specified saturation
Sampling	12 bits measured,
Response	Linear to 1%
Accuracy	Within 10% absolute
Precision (SNR)	>400 @equatorial reference
	>100 @polar reference
Spatial	
Range	24 degree field-of-view
Sampling	0.7 milliradian
Response	FWHM < 1.0 milliradian

Uniformity

Spectral-cross-track	< 10% variation of spectral position across the field-of-view
Spectral-IFOV	< 10% IFOV variation over the spectral range

The M^3 instrument was completed in April of 2007. A picture of the completed instrument optical assembly and passive radiator is shown in Figure 2-3.

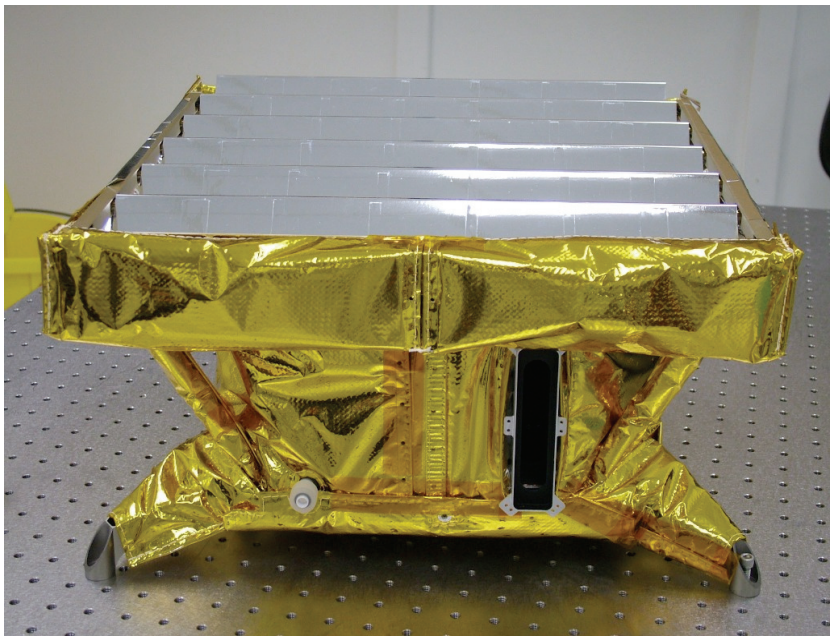


Figure 2-3. Completed M^3 instrument optical assembly and passive radiator (the entrance to the telescope is shown with the cross-track swath in a vertical orientation).

2.2. Instrument Operations Overview

The M^3 image acquisition time will be divided into peak periods or Optical Periods (OP) when lighting is optimal for observation. The Optical Periods occur twice a year and are understood to have two central months of optimal illumination (solar beta angles -30° to +30°) with two optional two-week wing periods (solar beta angles ±30° to ±45°) on either side of the optimal 2 months (thus, one Optical Period equals 13 weeks). Each 13 week optical period is followed by a 13-week hiatus. The original instrument operations plan included the acquisition of the entire surface of the Moon in low-resolution Global Mode during the first Optical Period (OP1) while OP2, OP3, OP4 were reserved for high resolution Target Mode data acquisition.

However, the mission was cut short when contact with the spacecraft was lost unexpectedly on August, 2009, after nearly ten months in lunar polar orbit. Despite the abbreviated mission and numerous technical and scientific challenges during the flight,

M^3 was able to cover more than 95% of the Moon in Global Mode. Only minimal high-resolution Target Mode images were acquired, as these were to be the focus of the second half of the mission.

The technical challenges encountered during the mission have complicated the data processing and calibration. Before imaging even commenced, the spacecraft lost one of its redundant Bus Management Units and one of its two star trackers. ISRO began re-planning the mission immediately to ensure the survival of the spacecraft and to restore balance to the operational and observational requirements. The commissioning phase was extended into January 2009 where M^3 collected periodic, abbreviated images instead of the planned 48-minute images per each of the twelve orbits per day. On January 31, 2009, M^3 was operated in its full coverage Global Mode for several discrete periods within the mission. These image acquisitions were collected during periods of higher beta angle (thus, reducing the reflected signal and increasing the effect of surface shadows in the data) due to the ongoing thermal issues. On April 15, 2009, the second optical period began in full operation. Nevertheless, in mid-May the second star tracker was lost and ISRO decided to raise the orbit to 200 kilometers as a result of limited attitude knowledge. After the new orbit was reached, M^3 continued to operate in Global Mode. The last M^3 images were acquired on August 16, 2009. Other details of these challenges are currently being documented and will be referenced and/or included in the delivery of the M^3 PDS Archive Volume. For example, Section 2.5.4.2 discusses how the thermal status affects the Level 2 reflectance calibration process. Nonetheless, the data products released in the M^3 PDS Archive Volume will contain optimal calibration and characterization.

M^3 operations were sustained for two Optical Periods. (For more detailed information regarding the spacecraft operation schedule, please see the MISSION.CAT.) Each Optical Period can be broken into sub-OPs based on instrument or spacecraft events and status. Table 2-2 provides an overview and description of each sub-OP. Figure 2-4 shows the M^3 coverage during both Optical Periods along with a cumulative coverage index of the gaps, the nearly full Global coverage and the limited Target images.

Table 2-2. Overview of M^3 Operations by Optical Period

Sub-OP Name	Description	Time Period
OP1A	Commissioning phase through “warm” data	2008 Nov 18 to 2009 Jan 24
OP1B	Start of “cold” data through end of OP1	2009 Jan 09 to 2009 Feb 14
OP2A	100 km orbit with star trackers	2009 Apr 15 to 2009 Apr 27
OP2B	100 km orbit, no star trackers	2009 May 13 to 2009 May 16
OP2C	200 km orbit, no star trackers	2009 May 20 to 2009 Aug 16

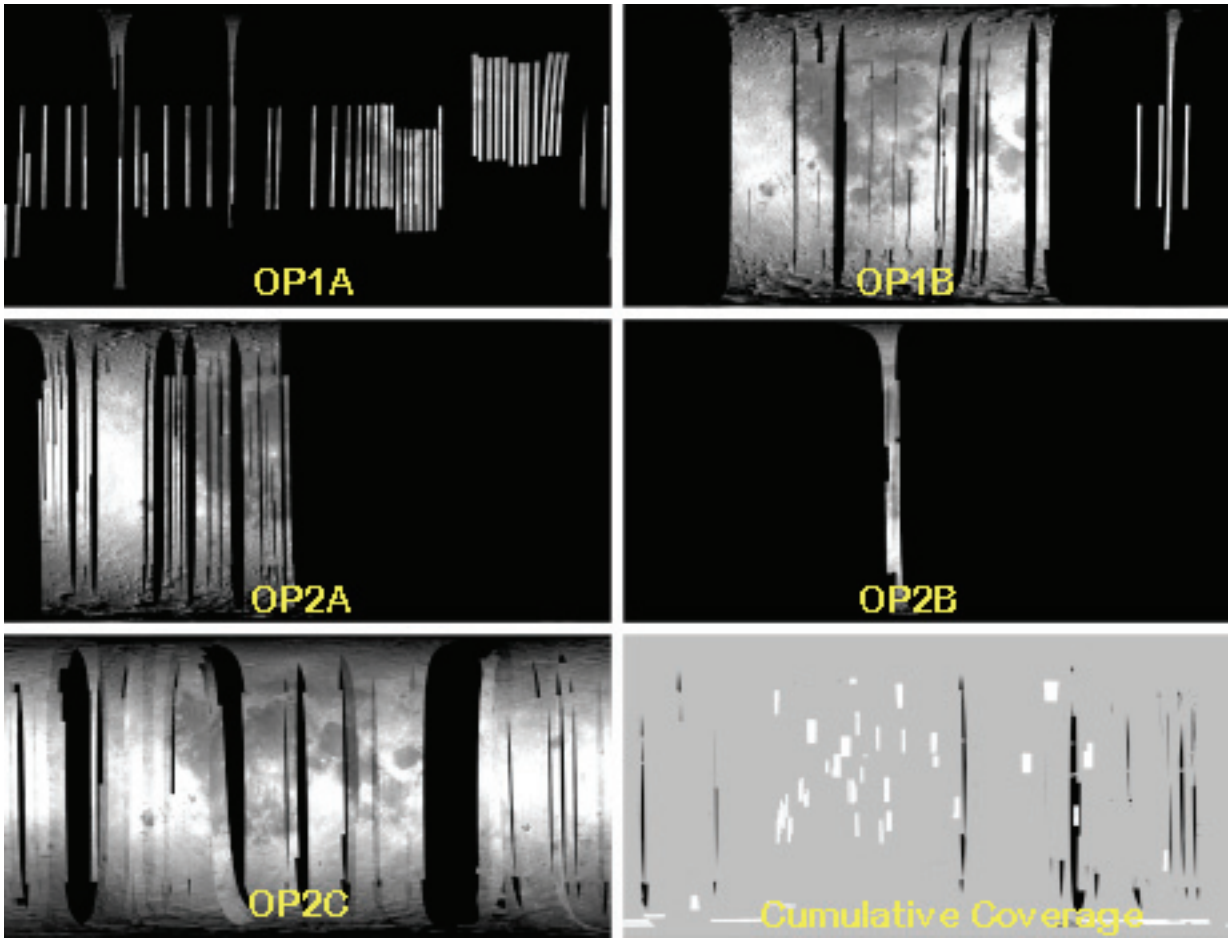


Figure 2-4. M^3 coverage by five sub-Optical Periods (from left to right, OP1A, OP1B, OP2A, OP2B, OP2C) and a cumulative coverage index (black/gray/white = gaps/Global/Target).

2.3. Data Product Overview

The two M^3 standard data products referred to collectively as M^3 Level 0 and M^3 Level 1B data products include raw images and radiometrically-calibrated, pixel-located spectral images acquired in either global or target mode. Table 2-4 provides details of the M^3 operating modes. The third M^3 standard data product referred to as M^3 Level 2 includes photometrically calibrated, pixel-located reflectance spectral images. All images are stored in binary format with a detached ASCII PDS label and a detached ASCII ENVI-compatible header file.

All M^3 data products are stored in Band-Interleaved-By-Line (BIL) image file format. BIL format stores the first line of the first band, followed by the first line of the second band, followed by the first line of the third band, interleaved up to the number of bands. Subsequent lines for each band are interleaved in similar fashion. This format provides a compromise in performance between spatial and spectral processing

A M^3 Level 0 data product consists of raw, science data in units of DN that make up one observation tagged by a unique file name. The data in one Level 0 Product represent a consistent instrument configuration (frame rate, pixel binning). A Level 0 Data Product is comprised of a single multiple-band image (suffix *_L0.IMG) stored in one file, plus a detached PDS label (ASCII; suffix *_L0.LBL) and a detached header file (ASCII; suffix *_L0.HDR).

A M^3 Level 1B Data Product consists of pixel-located, resampled, calibrated data in units of spectral radiance that make up one observation tagged by a unique file name. The data in one Level 1B Product represent a consistent instrument configuration (frame rate, pixel binning). There is a single multiple-band image (BIN; suffix *_RDN.IMG) stored in one file with a detached PDS label (ASCII; suffix *_L1B.LBL), and a detached header file (ASCII; suffix *_RDN.HDR), plus several files containing data related to pixel-located (BIN; suffix *_LOC.IMG), observation geometry (BIN; suffix *_OBS.IMG), and UTC timing for each image line (ASCII; suffix *_TIM.TAB).

A M^3 Level 2 Data Product consists of pixel-located, resampled, photometrically calibrated, reflectance data (unitless) that make up one observation tagged by a unique file name. The data in one Level 2 Product represent a consistent instrument configuration (frame rate, pixel binning), and there is one Level 2 data product for each Level 1B radiance image. A Level 2 Product includes a single multiple-band reflectance image (BIN; suffix *_RFL.IMG) stored in one file with a detached PDS label (ASCII; suffix *_L2.LBL), and a detached header file (ASCII; suffix *_RFL.HDR). A Level 2 Product also includes a supplementary three-band image (BIN; suffix *_SUP.IMG) where the first band contains one RFL.IMG channel photometrically corrected to a sphere, the second band contains a thermal map of the scene, and the third band contains the longest wavelength RAD.IMG channel (from Level 1B) that is scientifically useful; a detached header for the supplemental file (ASCII; suffix *_SUP.HDR) is also included.

2.4. Data Processing

2.4.1. Data Processing Level

This SIS uses the NASA data level numbering system to describe the processing level of M^3 data products. Table 2-3 shows the description of the Committee On Data Management And Computation (CODMAC) data processing levels and the correlation with the NASA processing levels. All M^3 data products comply with NASA processing levels standards. The CODMAC system is mentioned here because it is the standard used by the PDS.

Table 2-3. Processing Levels for Science Data Sets			
NASA Level	**Description**	**CODMAC Level**	**Description**
		1-Raw Data	Telemetry data with data embedded.
0	Instrument science packets (e.g., raw voltages, counts) at full resolution, time ordered, with duplicates and transmission errors removed. Corresponds to Space Science Board's Committee on Data Management and Computation (CODMAC) Edited Data (see National Academy press, 1986).	2-Edited Data	Corrected for telemetry errors and split or decommutated into a data set for a given instrument. Sometimes called Experimental Data Record. Data are also tagged with time and location of acquisition. Corresponds to NASA Level 0 data.
1A	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). Corresponds to CODMAC Calibrated Data.	3-Calibrated Data	Edited data that are still in units produced by instrument, but that have been corrected so that values are expressed in or are proportional to some physical unit such as radiance. No resampling, so edited data can be reconstructed. NASA Level 1A.
1B	Irreversibly transformed (e.g., resampled, remapped, calibrated) values of the instrument measurements (e.g., radiances, magnetic field strength). Corresponds to CODMAC Resampled Data.	4-Resampled Data	Data that have been resampled in the ti me or space domains in such a way that the original edited data cannot be reconstructed. Could be calibrated in addition to being resampled. NASA Level IB.
1C	Level 1A or 1B data, which 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). Corresponds to CODMAC Derived Data.	5-Derived Data	Derived results, as maps, reports, graphics, etc. NASA Levels 2 through 5.
2	Geophysical parameters, generally derived from Level 1 data, and located in space and time commensurate with instrument location, pointing, and sampling. Corresponds to CODMAC Derived Data.	5-Derived Data	Derived results, as maps, reports, graphics, etc. NASA Levels 2 through 5.
3	Geophysical parameters mapped onto uniform space-time grids. Corresponds to CODMAC Derived Data.	5-Derived Data	Derived results, as maps, reports, graphics, etc. NASA Levels 2 through 5.
		6-Ancillary Data	Nonscience data needed to generate calibrated or resampled data sets. Consists of instrument gains, offsets, pointing information for scan platforms, etc.
		7-Correlative Data	Other science data needed to interpret space-based data sets. May include groundbased data observations such as soil type or ocean buoy measurements of wind drift.
		8-User Description	Description of why the data were required, any peculiarities associated with the data sets, and enough documentation to allow secondary user to extract information from the data.
		N	Not Applicable

Table 2-4. Description of M^3 Operating Modes

M^3 Mode	Description	Data Product	Num of Channels	Num of Samples	Data Product Format
Target	Target Mode produces the maximum spectral resolution science data.	Level 0	260	640	16-bit Integer
		Level 1B	256	608	32-bit Floating Point
		Level 2	256	608	32-bit Floating Point
Global	Global Mode reduces spectral resolution by 3 times. • 4 block of 2x and 4x summing • 44 lines of summed by 4x and 42 lines of summed by 2x The spatial data is summed in a 2 by 2 format.	Level 0	86	320	16-bit Integer
		Level 1B	85	304	32-bit Floating Point
		Level 2	85	304	32-bit Floating Point

2.5. Data Product Generation

2.5.1. Overview

Level 0 and Level 1B standard products are generated in the M^3 Instrument Ground Data System (IGDS) at JPL. Level 2 standard products for delivery to the PDS is managed by the University of Maryland (UMD) in partnership with Applied Coherent Technology Corporation (ACT). Each Level 0 and Level 1B, and Level 2 data file contains data acquired while the spacecraft is on the illuminated side of a single orbit.

2.5.2. Level 0 Data Processing

The data received on the ground are in the form of compressed, 8-bit “digital numbers” (DN). Level 0 processing involves identification of the raw science telemetry packets, processing secondary header time stamps, decompressing the data into 16-bit, signed integers and reassembling the packets into time-sequenced image cubes for further data processing. Packet check sum errors, out of sequence packets, compression errors, and missing packet errors are flagged in the Level 0 Product.

2.5.3. Level 1B Data Processing

Level 1B data is irreversibly transformed; Level 1B processing involves the following operations:

- converts the decompressed, uncalibrated image cube data into resampled, scaled, calibrated spectral radiance image cubes
- calculates the lunar surface location of all pixel centers
- calculates the observation geometry and illumination on a pixel-by-pixel basis
- calculates the UTC time for the middle of the integration period for each frame of the image data

2.5.3.1. Spectral Radiance Calibration

The calibration of M^3 took place during the month of April 2007. A complete set of spectral, radiometric, spatial and uniformity calibration measurements were acquired. Figure 2-5 shows an M^3 image of a laser-illuminated integrating sphere with wavelengths of 532, 1064, 2065 nm across the field-of-view (FOV). The calibrated spectral range is from 403.9 to 2982.8 nm. Spectral sampling was measured as 9.995 nm (constant through the entire band). A scanning monochromator was used to establish the spectral response functions over the entire spectral range. Figure 2-6 shows a set of M^3 measured spectral response functions in the range from 2000 to 2200 nm.

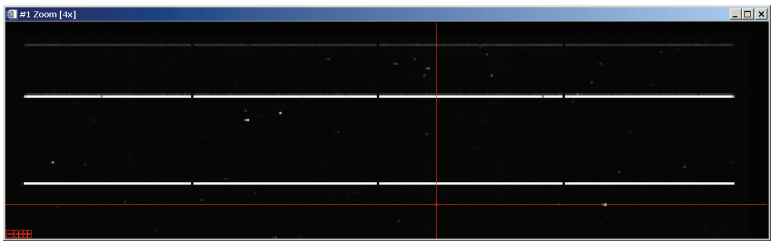


Figure 2-5. M^3 FOV measurement of three laser lines for determination of spectral range and sampling (600 cross-track samples by 260 spectral channels).

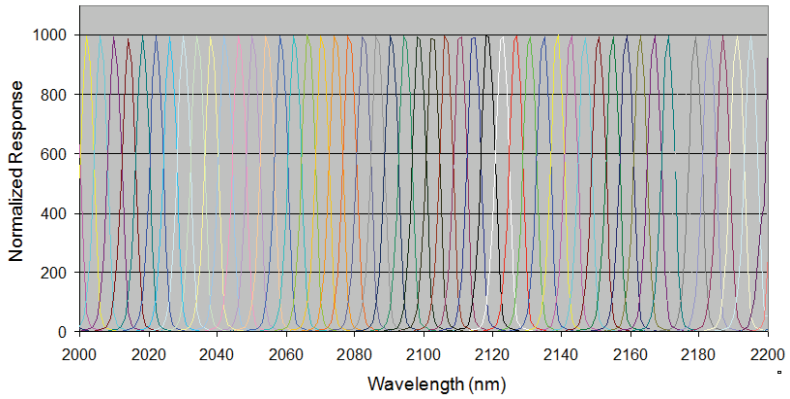


Figure 2-6. M^3 normalized spectral response function subset from 2000 to 2200 nm.

Radiometric calibration was traced to a National Institute of Standards and Technology (NIST) irradiance lamp and a reflectance panel standard. Figure 2-7 shows an M^3 calibrated measurement of the radiometric calibration source. With radiometric calibration and instrument noise measurement, the signal-to-noise ratio of M^3 was calculated for the polar and equatorial reference radiances and is shown in Figure 2-8.

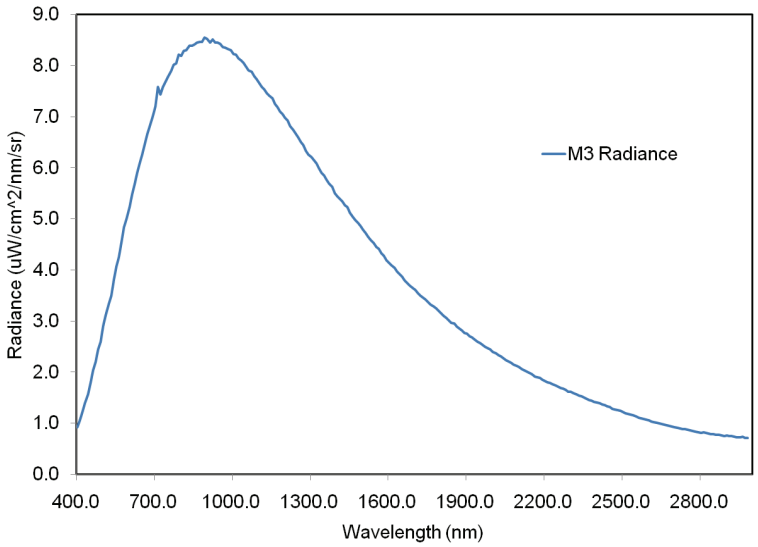


Figure 2-7. Radiometrically calibrated M^3 measurements from laboratory radiance standard.

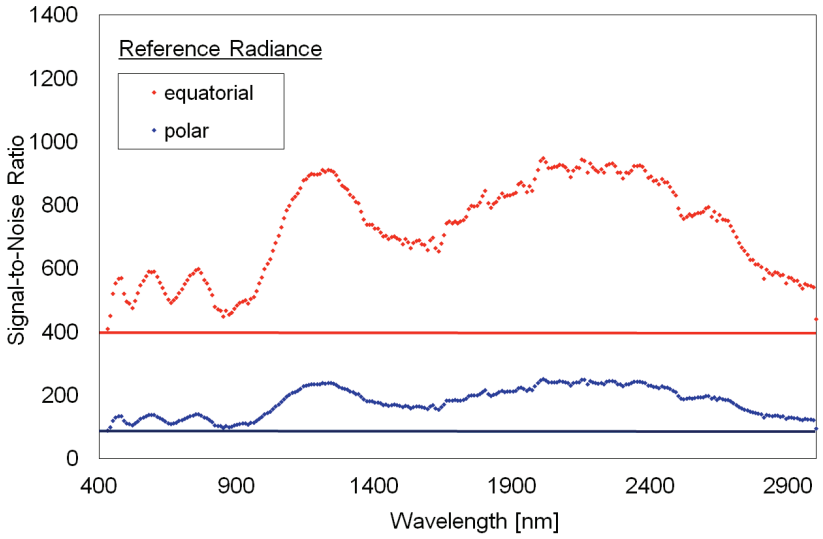


Figure 2-8. M^3 calculated signal-to-noise ratio based on laboratory measured instrument throughput and noise and signal from Apollo 16 soil at 0 and 80 degrees zenith.

The spatial field-of-view (FOV), sampling, and response function were measured as well. The image FOV of M^3 is 24 degrees with a cross-track sampling of 0.7 milliradians. The full-width-at-half-maximum (FWHM) for the spatial response function was measured as ~1 milliradian.

The imaging spectrometer uniformity of M^3 was specified at > 90% for both the spectral cross-track uniformity and spectral-IFOV (instantaneous field-of-view) uniformity. Figure 2-9 shows the spectral cross-track uniformity measured from a Neodymium spectral target. Figure 2-10 shows the spectral-instantaneous-FOV uniformity measured from a cross-track scanning white-light slit through a collimator.

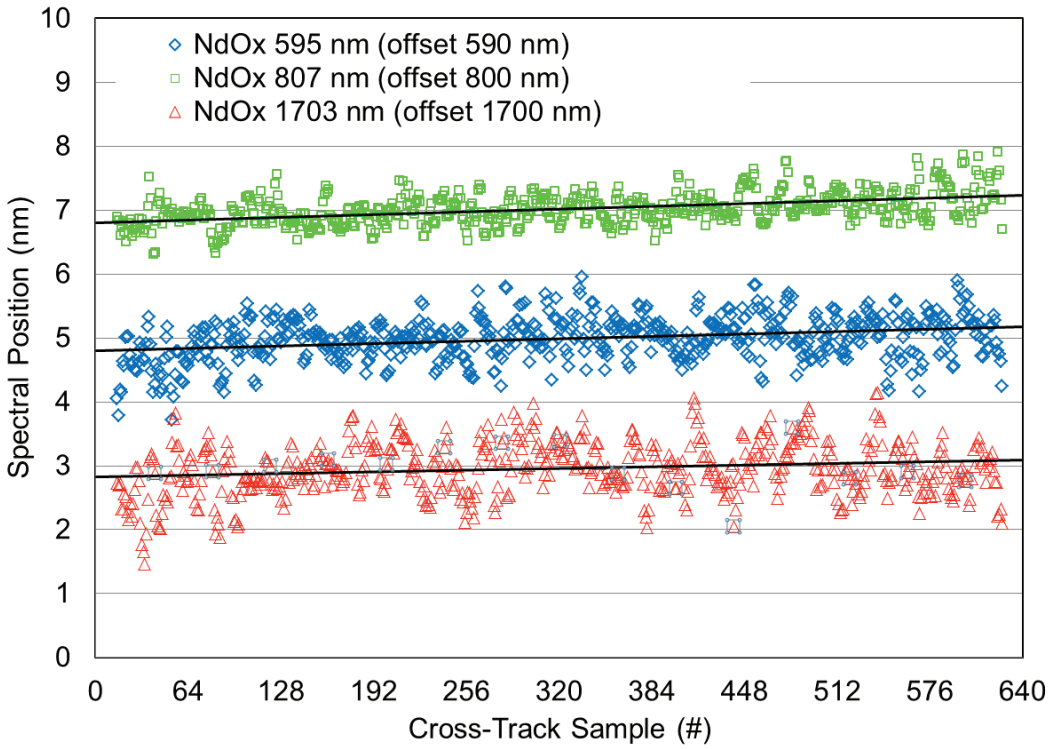


Figure 2-9. M^3 spectral cross-track uniformity. There is less than 0.5 nm cross-track spectral variation with respect to 10 nm spectral sampling.

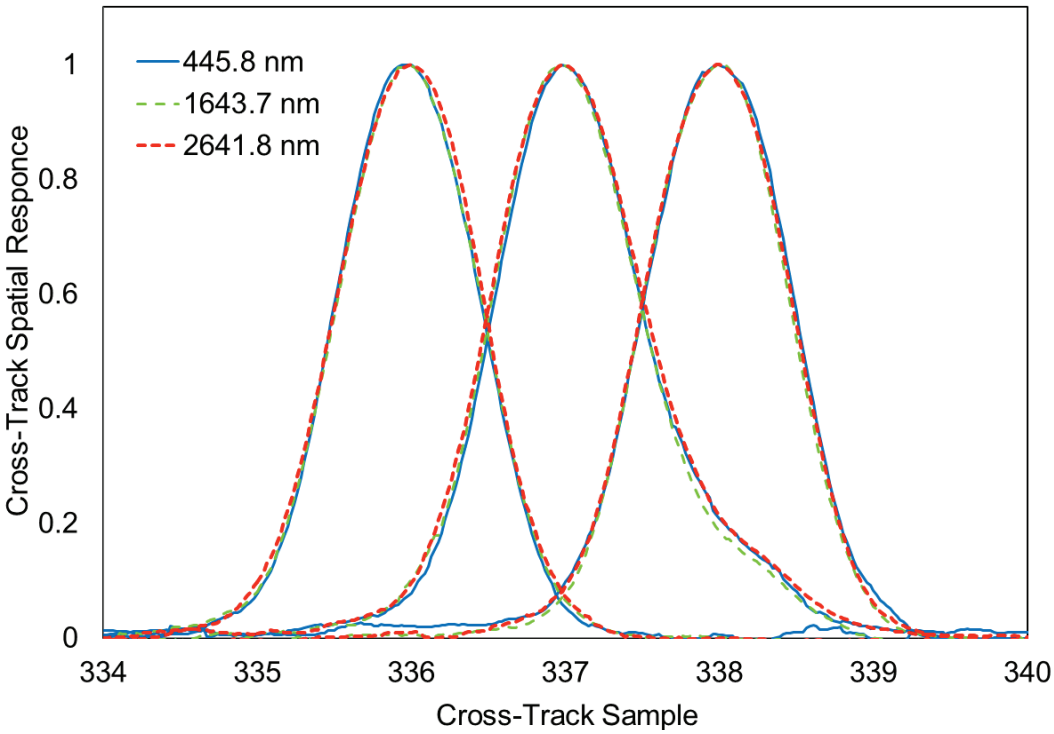


Figure 2-10. Derived M^3 spectral-IFOV uniformity over the spectral range. The blue spatial response curve is from the 445, green from 1643 and the red is from 2641 nm.

Based upon these laboratory measurements as well as on-orbit assessment of the measured lunar data, a series of calibration processing steps are applied to convert the reported Digitized Number (DN) to units of spectral radiance. A description of these calibration processing steps is given below. An article titled "The NASA Moon Mineralogy Mapper (M^3) Imaging Spectrometer for Lunar Science: Instrument Description, Calibration, and On-orbit Performance," is in preparation and will provide further description of the calibration processing algorithms and sequence for M^3. See Green, et al., 2011.

Dark Signal Subtraction (DSS)

For nominally acquired M^3 data sets a dark signal data set is acquired on the unilluminated side of the Moon prior to acquisition of the illuminated data set. This provides a one-to-one relationship with dark signal measurement and illuminated orbit measurements. Each dark signal data set is averaged for all lines to generate a dark signal average with one value for each spatial and spectral sample. For Target mode data, this is an array of 640 by 260 real, dark signal values for each data set. For Global mode data, this is an array of 320 by 86 real, dark signal values for each data set. The dark signal subtracted (DSS) image is generated by subtracting the specific dark signal average values from the corresponding illuminated signal M^3 image. In cases where a dark signal image was not specifically acquired with an illuminated image, the nearest dark signal image is used.

Bad Detector Element Correction (BDE)

M^3 uses 166400 detector elements of the 6604a mercury-cadmium-telluride (MCT) detector array. A number of these detector elements exhibit non-standard behavior ranging from non-responsive high and low to excessively noisy. These non-standard detector elements are referred to as bad detector elements (BDE). The number of BDEs vary somewhat with time and is also a function of the temperature of the detector array. For each illuminated M^3 image, the number and location of BDEs is determined by calculating the mean and standard deviation of the signal in the corresponding dark signal image. Detector elements that are non-responsive or excessively noisy are flagged in a BDE image (640 spatial by 260 spectral for Target Mode and 320 spatial by 86 spectral for Global Mode). Figure 2-11 shows map of bad detector elements, the detector tap boundaries, and the filter seams. The tap boundaries and filter seams are discussed below. The identified bad detector elements are replaced in the DSS image using simple linear interpolation in the spectral direction.

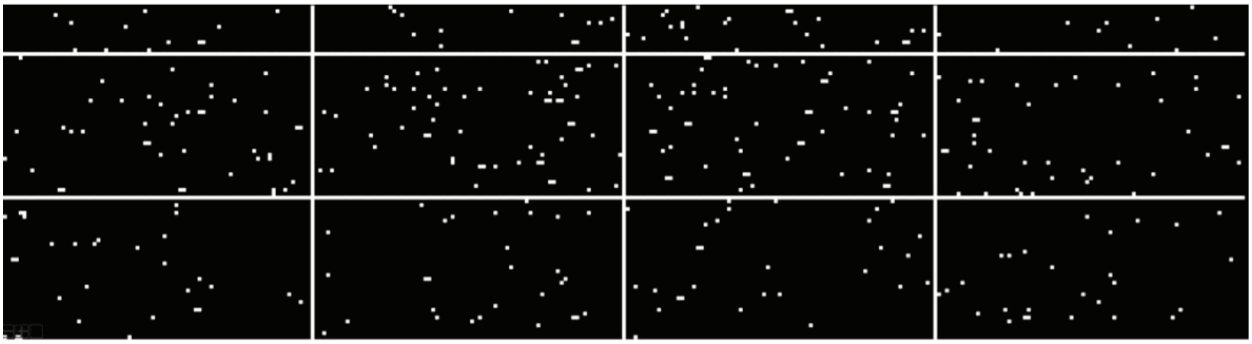


Figure 2-11. An example map of bad detector elements, the detector tap boundaries, and the filter seams for a M^3 Global Mode data set. The horizontal dimension is the spatial domain and the vertical dimension is the spectral domain of the M^3 imaging spectrometer.

Detector Array Tap Interpolation

The 6604a detector array is read out in four zones that are tied to columns 1, 161, 321, and 481 in the cross-track, 640 dimension. In the M^3 signal chain electronics these columns are severely impacted by the readout and the values are replaced with simple linear interpolation using the samples on each side of the impacted column. For target mode, these interpolated columns are 161, 321 and 481. For Global mode data, these interpolated columns are 81, 161, and 241.

Filter Seam Interpolation

The order sorting filter directly in front of the detector array has seams between the filter zones that impact the quality of the data recorded. To suppress the impact from the filter seams, the detectors below the seams are replaced with simple linear interpolations in the spectral direction. The spectral channels that are replaced for Target Mode are 41, 42 and 116. Channels 13 and 50 are replaced in Global Mode data.

Electronic Panel Ghost Correction

As the M^3 6604a detector array signal chain is read out through the four outputs, a small electronic ghost is generated. For example, if a bright signal is present at cross-track sample 50, a small negative signal will be imparted in the other three detector zones at sample 50+160, 50+320 and 50+480. This has been assessed based on laboratory and on-orbit measurements as a 0.0048 fraction of the signal effect. A corresponding cross-track offset fractional correction processing step is applied to the DSS image to suppress this electronic panel ghost artifact.

Dark Pedestal Shift Correction

Another characteristic of the M^3 6604a signal chain is expressed as a small drop in the dark signal level when the array is illuminated. This effect is captured by a set of dark

masked detector array elements in cross-track columns 1-8 and 637-640. With these dark masked detector elements, a function has been developed to estimate the dark pedestal shift based upon the signal in the illuminated portion of the array. This correction is applied to the image on a line-by-line basis to compensate for the dark pedestal shift in the DSS image.

Scattered Light Correction

Late during laboratory characterization/calibration, anomalous scattered light was identified, dominantly impacting the short wavelength portion of the spectrum. M^3 was designed with columns of detector elements that are nominally vignetted by the spectrometer slit. Signal arriving at these detectors provides an estimate of the scattered light. These vignetted column detector elements correspond to samples 9-15 and 628-636. Using laboratory and on-orbit measurements from these vignetted detector array columns, a scattered light correction function has been developed to estimate the scattered light based upon the signal distribution in the illuminated portion of the array. Figure 2-12 shows an example of the estimate of scattered light. This correction is applied to the image on a line-by-line basis to compensate for the scattered light in the DSS image.

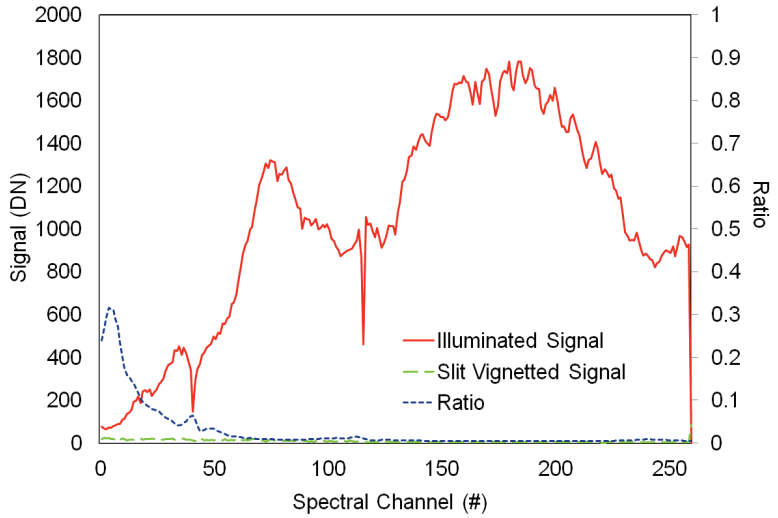


Figure 2-12. Estimate of scattered light effect in M^3.

Laboratory Flat Field Correction

When illuminated by a uniform light source, there is some variability in the cross-track radiometric response. To correct for this, laboratory measurements were acquired across the field of view from a uniform source. Figure 2-13 shows the laboratory flat field image. The flat field is 640 spatial by 260 spectral values for Target Mode and 320 spatial by 86 spectral values for Global Mode. The flat field is multiplied by the DSS image to compensate for this radiometric variability in the full system.

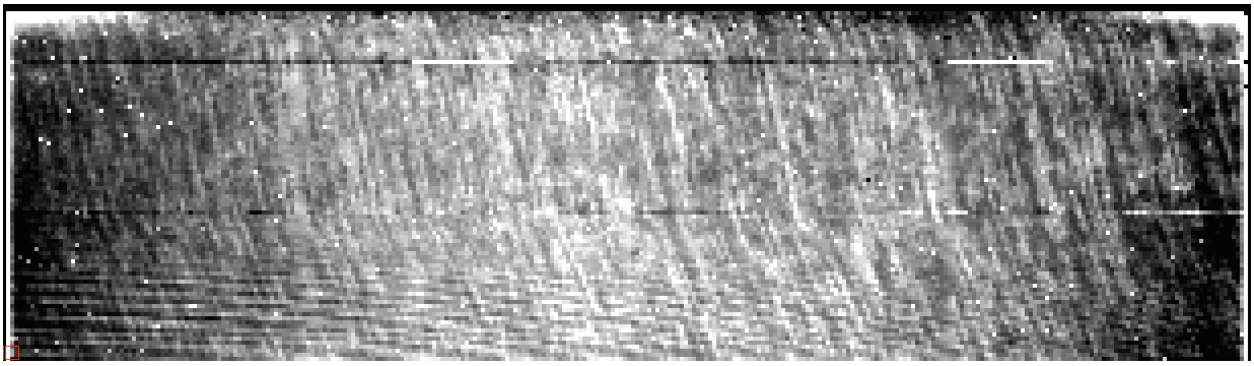


Figure 2-13. Laboratory calculated flat field image for M^3 Global Mode (M3G20081031_LABFF.IMG located in EXTRAS).

Imaging Based Flat Field Correction

Once in orbit around the Moon, an assessment of the flat field correction was made through averaging long orbital data sets. Analysis of these image based flat field images showed that an additional flat field correction was required for the on-orbit measurements of M^3. Image based flat field correction values were derived by averaging the longest on-orbit data sets and then dividing by the cross-track average value. This simple approach also removed the cross-track photometric signal. To retain the cross-track photometry, a two-dimensional plane is fit to the image based flat field and retained in the image based flat field correction factor. To suppress the impact of features on the lunar surface in the image based flat field, a smoothed spectral average of the function is divided out in a final step. Figure 2-14 shows one of the image based flat field correction data sets. The DSS image is multiplied by the image based flat field to suppress this radiometric response variability that is not compensated for by the laboratory flat field.

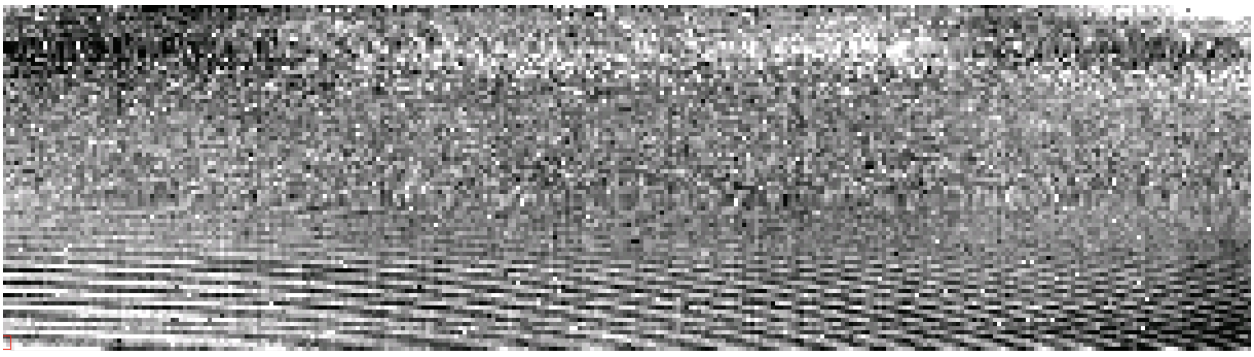


Figure 2-14. Example of Image based flat field.

Radiometric Calibration

Following the full suite of pre-processing steps described above, the DSS image is multiplied by the laboratory traced radiometric calibration coefficients that convert DN of

the DSS image to units of radiance (W/m^2/μm/sr). The laboratory spectral calibration values are also associated with the calibrated image in this final step. Figure 2-15 shows an example of the input DSS image and the DN per channel spectrum. Figure 2-16 shows the output image and radiance per wavelength spectrum of the calibrated image.

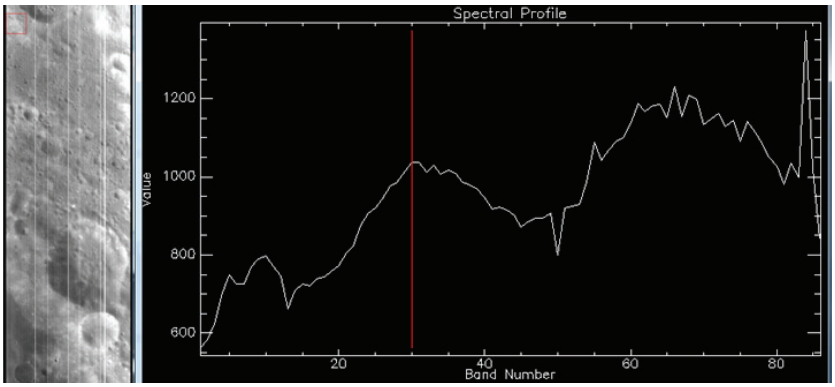


Figure 2-15. Input raw image and data from the M^3 instrument.

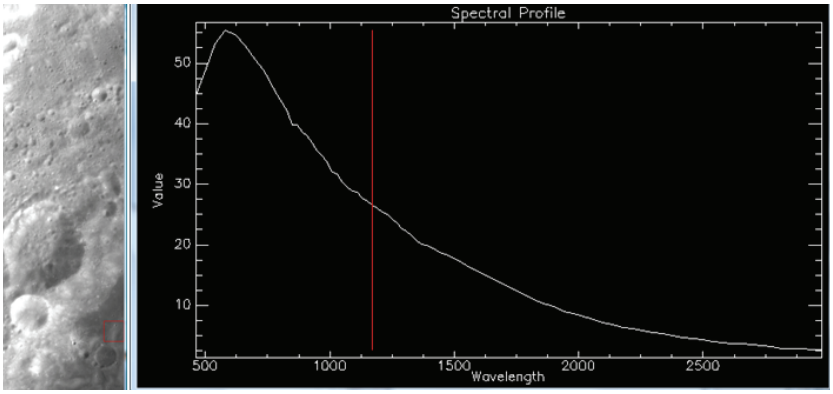


Figure 2-16. Output image and spectrum from the M^3 calibration processing pipeline.

The result of radiometric and spectral calibration is an image cube in units of spectral radiance ($W/m^2/\mu m/sr$). Associated calibration files can be found in the CALIB directory of the Level 1B volume. Bad detector element maps (BDE.IMG) and image-based flat field files (FF.IMG) can be found in the EXTRAS directory of the Level 1B volume.

All validation results and updates of the radiometric and spectral calibration will be reported and published in the journal literature as well as associated documentation of the M^3 PDS archive. See also Green, et al., 2011.

Smooth Shape Correction

A detector-temperature-driven empirical gain adjustment to the M^3 Level 1B spectral radiance data has been developed with the delivery of CH1M3_0003 (Version 3.0). This correction is referred to as the SSC_ADJ correction. It is a wavelength-dependent factor and is applied to each Level 1B spectral radiance cube after nominal spectral radiometric calibration. An appropriate SSC_ADJ correction is identified for each data cube based on the detector temperature during data acquisition of that cube, and each spectrum in the radiance cube is multiplied by this correction factor. The SSC_ADJ factor used for each data set if reported in the archive and can be removed with a simple ratio if required for specific analyses. This section describes the genesis of the family of correction factors used over the 10 months of Chandrayaan-1 operation and how they were developed.

After the first full-mission set of Level 1B radiance data were created, it became apparent that there were instabilities in the data that were not adequately compensated. These issues were identified when it became possible to compare spectra of the same lunar region taken under two different measurement conditions. Under nominal conditions, such comparisons should show only known spectral effects of changing illumination, surface temperature, and photometry (viewing geometry). Instead, extensive empirical investigation demonstrated that ratios of spectra for the same lunar areas exhibited weak but consistent artifacts that are similar to the shape of the raw M^3 signal (DN, or Level 0). The spectral artifact appears to be dominantly correlated with detector temperature. Ratios of data collected at similar temperatures, even with widely different observation epochs, show very little or none of this effect. Spectral ratios across regions of a single M^3 data strip that include very high and very low signal levels do not exhibit significant artifacts, suggesting the origin is not dominated by an offset component. This suggests that the artifact is driven largely by factors correlated with detector temperature and it was repeatable over the several heating/cooling cycles experienced by the instrument as reported by the detector temperature housekeeping data.

Chandrayaan-1 mission operations resulted in M^3 being operated at a temperature well beyond its designed range, both above (warm) and below (cold) [see Figure 2-23]. Possible explanations for resulting artifacts include a temperature-dependent signal chain non-linearity or a temperature-dependent total instrument throughput.

In order to quantify and model the observed effect, M^3 radiance data for the same surface area was identified in six, separate image cubes, spanning the full mission time period and nearly the full range of detector temperatures experienced by M^3. The data were seleno-corrected to make six sets of overlapping images of the same area on the Moon. The six image cubes used were M3G20090118T022705, M3G20090214T074247, M3G20090423T152245, M3G20090617T045633, M3G20090714T122932 and M3G20090811T013030. The associated detector temperatures for these six files are 158.78K, 146.79K, 150.82K, 167.90K, 157.35K and 147.47K. The matching area for the six temps had 266,671 pixels in the region covered

by all six. Since the file M3G20090714T122932 was closest to the M^3 reference calibration temperature (156K), the other five image cubes were ratioed (spatial element by spatial element) to the data from the reference scene, M3G20090714T122932, with the reference scene as the denominator. The ratio spectra were then normalized and averaged, giving five spectral measurements of the observed artifacts of the radiance data that are dependent on the temperature. Figure 2-17 shows these ratio spectra. Each of the ratio spectra is essentially a normalized average of 266,671 ratio spectra. The central flat line shows the self-ratio of the reference scene to itself. The systematic nature of this set of ratio curves revealed that the instrument artifacts exhibited systematic temperature dependence.

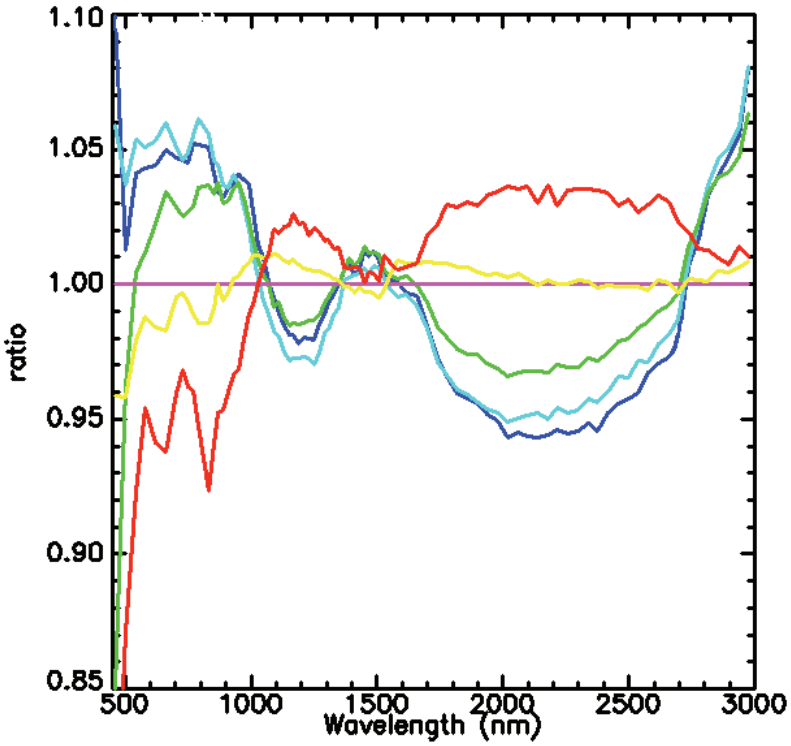


Figure 2-17. Normalized and averaged ratios of same-area spectra data for six different detector temperatures, all referenced to the M3G20090714T122932 radiance data. [Red is highest temperature and blue is lowest.]

It was not possible to develop a simple model of a single temperature-dependent signal chain non-linearity to explain these artifacts. Thus, the effect was modeled based on the matching data. A channel-independent gain was derived that is a linear function of detector temperature. Using the five ratios (six temperatures), a band-by-band regression of the ratio values was performed to find a best-fit linear function of temperature. These temperature functions at each band were then used to calculate the derived adjustment curves for all detector temperatures and extrapolated to 140K to 180K at an interval of 0.1K. The result of this modeling is a suite of 401 spectral gain curves, each with 85 bands matching the M^3 Global Mode data. Next, the ratio curves

were smoothed with a five-channel moving average. Figure 2-18 shows the smoothed modeled gain adjustment curves.

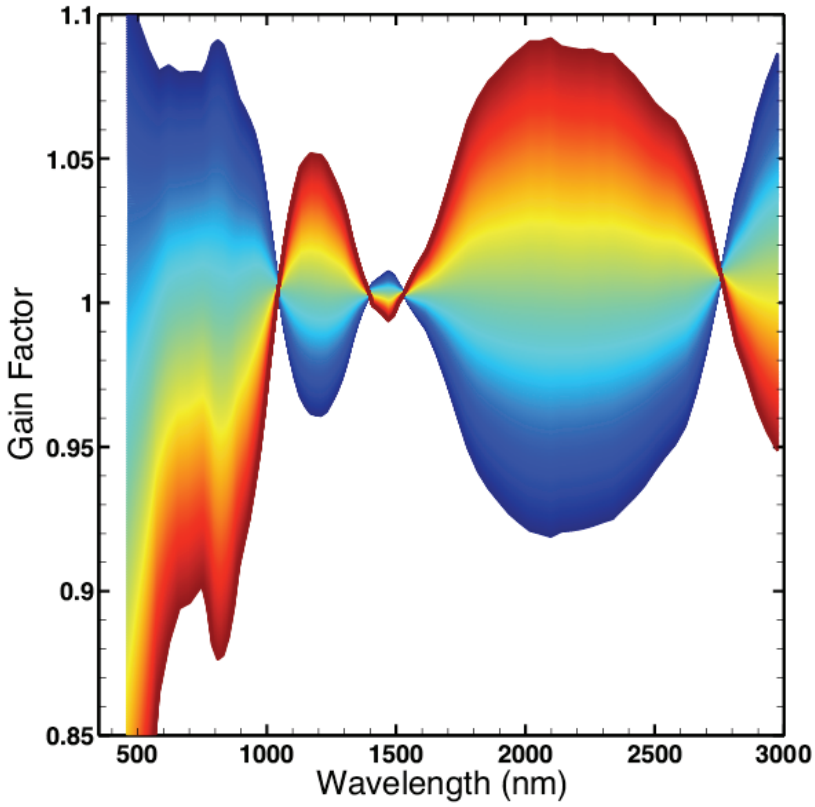


Figure 2-18. Smoothed family of global correction gain curves as derived from data ratios, spanning a 140K (blue) to 180K (red) temperature range of the detector in continuous 0.1 degree intervals.

Since at the longer wavelengths (beyond 2100 nm) M^3 data may also contain thermally emitted photons, one additional adjustment was required to produce appropriate data-derived correction factors for spectral artifacts linked to detector temperature. The gain factors of Figure 2-18 are derived from some data that contain excessive signal at longer wavelengths due to thermal emission photons. Thus, those spectra do not accurately represent the reflected radiation from the surface. The spacecraft operational temperatures are closely related to the solar illumination geometry of the surface being measured while warm detector temperatures are generally correlated with high thermal emission for equatorial surface regions. The thermal emission biases the ratios of Figure 2-17 for longer wavelengths as well as the derived correction coefficients of Figure 2-18, which are intended to be used to bring the reflectance measured under different conditions to the same value. To accommodate this bias, the magnitude of the correction factors from 2100 nm to longer wavelengths was smoothly reduced to values more commensurate with the overall shape of the detector sensitivity/throughput.

Examples of the final gain curves used are shown in Figure 2-19. These curves were used as the final step in the Level 1B spectral radiance calibration. For each image

cube, the detector temperature measured during data acquisition is used to identify the appropriate correction gain factor and every spectrum in the image cube is multiplied by the gain curve applicable to that temperature. For the Target data, the smooth curves of Figure 2-19 were interpolated to the Target wavelengths. For each image cube, the multiplied gain curve used is reported in the EXTRAS directory with a file name that matches the image file base name, suffixed with a "_SSCADJ.TAB" extension (i.e. M3G20081118T222604_SSCADJ.TAB). While this empirical correction does not address the root cause of this artifact, the data-derived correction provides an acceptable approach to minimizing this adverse effect in the M^3 spectral radiance data as well as improving the consistency and accuracy of the M^3 Level 1B archive across the full mission. Specifically, this correction means that spectral ratios at two different instrument temperatures are not dominated by this spectral artifact and can be compared and used more reliably for scientific analyses. This effect will continue to be investigated in an attempt to trace it more directly to a specific source in the signal chain or in the instrument.

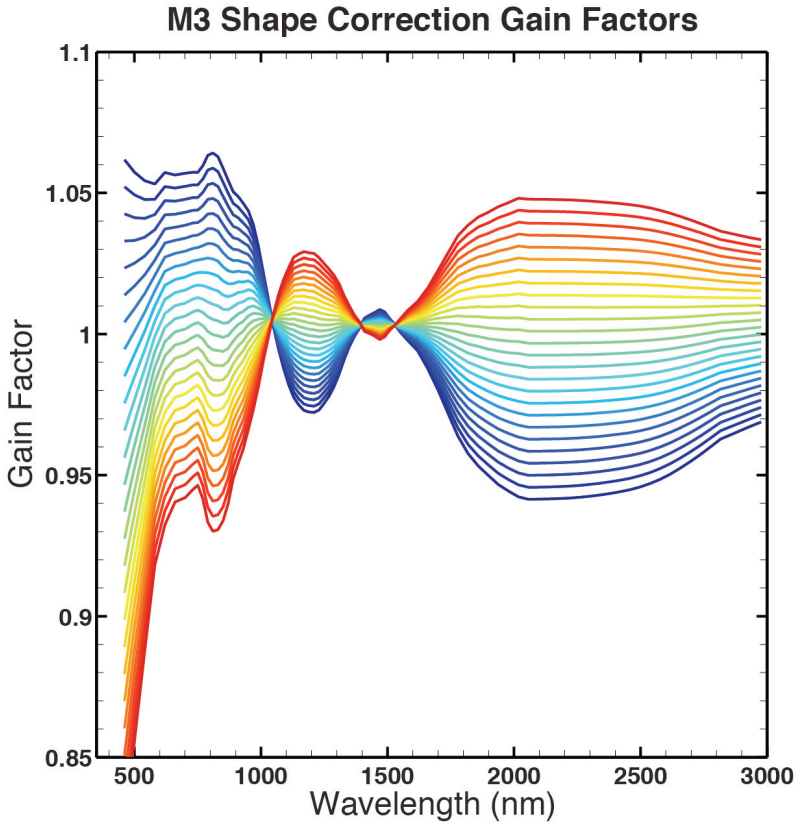


Figure 2-19. Final set of Global gain correction curves after modification to account for thermal emission effects. Shown here are a series of example gain factors from the measurement range of 145 K (blue) to 170 K (red). The actual series used has a resolution of 0.1 K.

2.5.3.2. Ray Tracing and Pixel Location

The pixel location data for each radiance and reflectance image cube contain 3 parameters. The three parameters are as follows:

1) planetocentric latitude (reported in decimal degrees)
2) longitude (reported in decimal degrees)
3) radius (reported in meters from the Moon center)

The location file is, in essence, a three-band set of "detached backplanes" that match the sample and line spatial extent of the radiance image cube data. No map correction or resampling is applied to the radiance image cube; the file only reports the surface locations of the unadjusted pixel centers.

The pixel location data for each radiance image cube are created by a full four-dimensional ray-tracing subroutine of the Level 1B processing. The spacecraft ephemeris and timing are derived from the respective SPICE SPK and SCLK kernels. Due to problems in the spacecraft attitude data, the attitude for each orbit and the in-flight camera model were derived via a non-linear optimization leveraging image overlaps and ground control derived from LOLA topography. The derived camera model is reported in an IK kernel. Three increasingly complex attitude models were used to derive the spacecraft attitude history over the course of the mission as the attitude knowledge and control deteriorated. The first model solves for a per-orbit roll, pitch and yaw relative to an ideal nadir attitude. The second model similarly solves for roll, pitch and yaw biases and also allows for linear roll, pitch and yaw rates. The third model, required for much of Optical Period 2 after both star trackers were lost and the orbit altitude raised, is the most generic. It solves for a roll, pitch and yaw initial state and an arbitrary axis of rotation in the J2000 frame along with a rotation rate around that axis. The parameters associated with the derived per-orbit attitude models are reported for each image, relative to an instantaneous orbit-based frame, in the PDS label. The details of the three attitude models and their associated parameters are listed below. See Boardman, et al., 2011 for further information.

<u>Attitude Model I</u> - Fixed roll, pitch and yaw

The SPACECRAFT_ORIENTATION keyword reflects data-derived M^3 instrument attitude angles (roll, pitch, and yaw respectively) as referenced to the CH1 orbit frame. The ideal nadir attitude (zero roll, pitch and yaw) is determined by the to-Moon-center-of-mass unit vector (+z), orbit plane normal unit vector (+y) and the unit vector that completes the 3-D frame that is nearly coincident with CH1 velocity (+x). These attitude angles were derived through image optimization using LOLA topography data and M^3-to-M^3 image overlap matching; the provided CH1 attitude data were not capable of

producing a stable and accurate result. The roll, pitch and yaw angles are in degrees and positive for a right-handed rotation about the specified axes: roll around +x, pitch around +y and yaw around +z. The minimum and maximum values for the roll, pitch, and yaw as captured by the SPACECRAFT_ORIENTATION keyword are -180 to 180.

Attitude Model II - Initial roll, pitch and yaw and roll at T_0, T_0 and roll, pitch and yaw rates

This attitude model is an extension of Model I, allowing for linearly changing roll, pitch and yaw biases based on a T_0 epoch. The CH1:INIT_SC_ORIENTATION keyword defines the initial S/C orientation in the same roll, pitch and yaw frame described for Model 1, at the time of the dark side equator crossing preceding the image collection. The T_0 time is supplied in Barycentric Dynamic Time (TDB) seconds in keyword CH1:SC_ORIENTATION_EPOCH_TDB_TIME. The linear roll, pitch and yaw rates in degrees per second are supplied in keyword CH1:SC_ORIENTATION_RATES.

Attitude Model III - Initial roll, pitch and yaw at T_0, T_0, xyz of rotation axis in J2000

Attitude Model III is the most generic model. As in Attitude Model II, the initial roll, pitch and yaw state at T_0 and the TDB epoch of T_0 are supplied in the CH1:INIT_SC_ORIENTATION and CH1:SC_ORIENTATION_EPOCH_TDB_TIME keywords. The S/C rotation is then described in terms of a J2000 XYZ unit vector and a rotation rate in degrees per second about this axis. The rotation axis is supplied in keyword CH1:SC_ROTATION_AXIS_VECTOR. The scalar rate of rotation about this axis is found in keyword CH1:SC_ROTATION_RATE.

Each pixel is individually ray traced to its center point intersection with the Moon's surface. The topography of the Moon is represented by NASA's Lunar Orbiter Laser Altimeter (LOLA) data. The ray tracing models the full complexity of the three dimensions of the spacecraft-camera-Moon model along with the subtle effects of light-time and velocity aberration. As detached backplanes these data can be updated as improved inputs are derived or supplied, without requiring an update for the voluminous radiance image data.

The coordinate system used in the ray tracing and data reporting is the new "Standardized Lunar Coordinate System for the Lunar Reconnaissance Orbiter" (LRO Working Group, 2007). This new lunar coordinate system is being adopted as an international standard and will greatly facilitate the direct integration of data from multiple missions and among international partners. The coordinate system is based on lunar planetocentric coordinates in the Mean Earth/Polar Axis (ME) reference frame. The z-axis is the mean axis of rotation with the positive direction pointing to the north. The x-axis is the intersection of the Equator and Prime Meridian, as defined by the

mean Earth direction. The y-axis completes the frame in a right-handed sense and points in the direction of +90 degrees longitude. Latitude ranges from +90 to -90 from the North Pole to the South Pole. Longitude will be reported as 0 to 360 degrees increasing to the East.

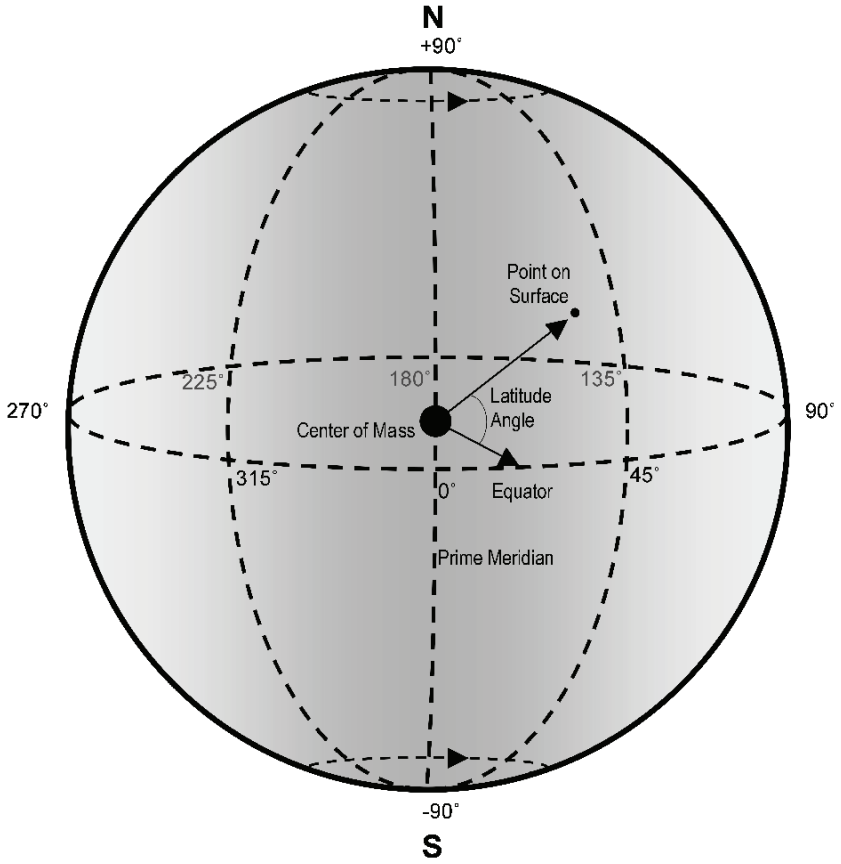


Figure 2-20. Planetocentric coordinates are expressed as right-handed coordinates with the origin at the center of mass of the body (from LRO Working Group, 2007).

The M^3 IGDS shall deliver data to the PDS with planetocentric coordinates in the ME system only in the form of latitude, longitude and radius. These coordinates are fully compliant and in accordance with the PDS Standards Reference (PDS, 2006).

Conversions between the ME system and other systems can be accomplished by using SPICE tools, as developed by the JPL NAIF (NAIF/SPICE, 1996). The ME system is adopted standard system for all lunar missions including Chanrdrayaan-1 and the Lunar Reconnaissance Orbiter. Internal to the Science Team the radius values will be converted to elevations above and below the newly accepted IAU standard lunar radius of 1737.400 kilometers. For mapping purposes that employ these location data, M^3 will use this standard radius and a spherical figure for the selenoid. Conversion from 0-to-360 longitudes to -180-to-180 longitudes is straightforward.

2.5.3.3. Observation Geometry

As a by-product of the pixel-location process, the Level 1B processing also provides a suite of ten important parameters that characterize the details of the observation geometry and illumination on a pixel-by-pixel basis. The ten parameters are as follows:

1) to-sun azimuth angle (decimal degrees, clockwise from local north)
2) to-sun zenith angle (incidence angle in decimal degrees, zero at zenith)
3) to-sensor azimuth angle (decimal degrees, clockwise from local north)
4) to-sensor zenith angle (emission angle in decimal degrees, zero at zenith)
5) observation phase angle (decimal degrees, in plane of to-sun and to-sensor rays)
6) to-sun path length (decimal au with scene mean subtracted and noted in PDS label)
7) to-sensor path length (decimal meters)
8) surface slope from DEM (decimal degrees, zero at horizontal)
9) surface aspect from DEM (decimal degrees, clockwise from local north)
10) local cosine i (unitless, cosine of angle between to-sun and local DEM facet normal vectors)

Similar to the pixel-location data, this file is, in essence, a ten-band set of “detached backplanes” that match the sample and line spatial extent of the radiance image cube data. No map correction or resampling is applied to the radiance image cube; the file only reports the observation parameters of the unadjusted pixel centers.

The first seven values at each pixel derive solely from the position of the Sun, Moon and camera at the moment of observation. The final three values at each pixel incorporate parameters from the local lunar topography as described by the interim LOLA data products available to us at the time of processing.

The to-sun and to-sensor angles are measured in a local topocentric frame (east, north, up axes). The azimuth angles are measured according to convention, but contrary to the local frame axes, in a positive manner clockwise from North (0 to 360 degrees). The zenith angles (incidence and emission) are measured relative to the local vertical z-axis of the topocentric frame. The phase angle is measured in the plane of the to-sun and to-sensor vectors. Path lengths are determined using light time correction and reported on a per-pixel basis. The to-sun path length is reported as the deviations from the scene mean to preserve precision. This scene mean value is noted in the PDS label by the keyword SOLAR_DISTANCE.

The surface slope and aspect are determined relative to the LOLA data used during processing. The final value, local cosine of the incidence angle, is measured by calculating the angle between the local topographic normal vector and the to-sun vector.

The values, reported on a per pixel basis, can be used in subsequent product generation for photometric and radiometric corrections and analyses of the radiance image data.

2.5.3.4. Observation Timing

The timing data consists of the mid-time for each image frame and are derived by decoding the spacecraft timing data, as supplied in the SPICE SCLK kernels, and then converting them from Ephemeris Time to UTC and Decimal Day of Year.

2.5.4. Level 2 Processing

M^3 Level 2 processing involves converting the at-sensor radiance data from Level 1 to "reflectance" at an incidence angle of 30° and an emission angle of 0°. Here we define "reflectance" as radiance factor (RADF; Hapke, [1993], p. 262, Eq. 10.5) consistent with Level 2 data from SELENE Spectral Profiler (Yokota et al, [2011]). As described below the L2 processing employs a limb-darkening based photometric function to correct all M^3 data to the reference i=30°, e=0° geometry using normalization factors derived from OP2C1 highland units. M^3 reflectances are thus "normalized" as if they were all measured at i=30°, e=0°.

(It should be noted that under the RADF definition of reflectance there is no correction of the incident light to normal incidence, 1/cos(30), as there would be for data normalized to reflectance factor {REFF; Hapke, [1993], Eq. 10.3}.)

L2 processing includes a photometric correction using actual topography (derived from LOLA) for all channels. In addition, to preserve topography, a separate, single-channel photometric correction relative to a sphere is also produced.

2.5.4.1. Photometrically-Corrected Spectral Reflectance Calibration

The L2 Photometrically-Corrected Reflectance (λ) process is described below in six reversible application steps:

1) Iπ/F Correction,
2) Statistical Polishing,
3) Thermal Removal,
4) Photometric Correction,
5) Ground Truth Correction (an optional step**), and
6) Flag degraded channels.

The Level 2 applies the above steps in serial manner:

$L1b(\lambda) \rightarrow L2_{s1}(\lambda) \rightarrow L2_{s2}(\lambda) \rightarrow L2_{s3}(\lambda) \rightarrow L2_{s4}(\lambda) \rightarrow L2_{s5}(\lambda)^{**} \rightarrow L2_{s6}(\lambda)$

Note that specific wavelengths called out in the following Level 2 steps are for the global mode where channels (bands) are binned. For target mode the equivalent unbinned wavelengths are used.

The resulting Level 2 data product consists of a three-dimensional reflectance image file (*RFL.IMG) and its respective ENVI header file (*RFL.HDR) and a supplementary data file, with an ENVI header (*SUP.IMG and *SUP.HDR, respectively. The supplementary file contains three images to assist analyses:

1) The 1489-nm reflectance image photometrically corrected to a sphere (retaining topographic illumination),
2) A map of the derived temperatures used for thermal correction, and
3) The longest wavelength band (number 84 for global or 253 for target) of the Level 1B radiance image (*RDN.IMG, W/(m^2 μm sr) per pixel) that is scientifically useful; this band contains both reflected solar and thermal emitted components and is highly sensitive to local topography.

The Level 2 product and its data and header files are described in detail in section 3.3.

***** Step 5, Ground Truth Correction, was not applied to the Level 2 data archived at PDS. However the necessary calibration files are provided in the Level 2 archive for individual users to apply the correction factors on an as-needed basis. See Step 5 below for more information.***

Level 2, Step 1: Iπ/F Conversion

$$\mathbf{L2_{s1}(\lambda)} = \mathbf{L1b(\lambda)} * \pi \ / (\text{SolarIrrad}(\lambda) / d^2)$$

Where:

- λ is the wavelength (global or target)
- At-Sensor Radiance from ***Level 1B (version 3.0 in the PDS archive)***
  - W/(m^2 μm sr) per pixel from *RDN.IMG (*L1B.LBL)
  - W/(m^2 μm sr) per pixel from *RDN.IMG (*RDN.HDR)
- SolarIrrad(λ) is a Global or Target file providing the exo-atmospheric solar spectrum at 1 Astronomical Unit as determined with MODTRAN. See Anderson et al., [2000] and Kurucz, [1995].
  - Units are irradiance W/(m^2 μm)
  - Supplied by the science team
  - In the PDS label, the keyword CH1:SOLAR_SPECTRUM_FILE_NAME identifies the solar spectrum file that was used: M3{G,T}20110224_RFL_SOLAR_SPEC.TAB. The files are located in the CALIB directory of the L2 dataset.

- Normalized Sun-Moon Distance, d, from Level 1B
  - Value for the scene mean in units of AU supplied by the SOLAR_DISTANCE keyword in *L1B.LBL
  - Although the per-pixel (SOLAR_DISTANCE) + (To-Sun Path Length in *OBS.IMG) as a double-precision value provides more than 6 decimal places, it approaches the topographic uncertainties and thus is not used by the data pipeline. Only the scene's mean distance (above) is used.

Level 2, Step 2: Statistical Polishing

$$\mathbf{L2_{s2}(\lambda)} = \mathbf{L2_{s1}(\lambda)} * g_{SP}(\lambda) + o_{SP}(\lambda))$$

where

- λ is the wavelength (global or target)
- $g_{SP}(\lambda)$ is a Global or Target File of derived gains (radiance correction factors) for statistical polishing
  - Gains are unitless
  - These values are supplied by the M^3 science team. A summary of how $g_{SP}(\lambda)$ was derived is provided here:
    1) Select a suite of featureless spectra, about several million pixels for instrument warm and instrument cold states (colored lines in Figure 2-21) found by searching for spectra with weak to no spectral features (described in Clark et al., [2012]).
    2) Hand fit a spline through the spectrum (black line in Figure 2-21). The cubic spline is not physically hand drawn, but rather a cubic spline is fit through the data at channels where the polisher correction factor equals 1.0.
    3) Divide the average spectrum by a fitted line continuum = S. The results are shown in Figure 2-22.
    4) Radiance Correction factor (RC) = average spectrum/S for the L2 delivery, this is called U2RC1 (earlier statistical polishing work combined cold and warm data and was designation R4RC1). The U2RC1 multiplier spectra are shown in Figure 2-22.
    5) Four correction spectra were derived for instrument warm and instrument cold states, each for global and target modes.
- $o_{SP}(\lambda)$ is a Global or Target File of derived offsets for statistical polishing
  - Offsets are unitless
  - Supplied by the science team
  - For this PDS delivery, $o_{SP}(\lambda)$ is set to zero (no offset).

- Statistical polishing [U2RC1] depends on effects of the spacecraft environment. We have derived values as a function of observing date ranges, when the overall temperature of the detector was generally cold or warm. The wavelength-dependent gains and offsets for the cold periods are provided together in a Global or Target table file: M3G20110830_RFL_STAT_POL_1.TAB or M3T20111020_RFL_STAT_POL_1.TAB, respectively. Gains and offsets for the warm periods are provided in a separate Global or Target table file: M3G20110830_RFL_STAT_POL_2.TAB or M3T20111020_RFL_STAT_POL_2.TAB, respectively. In the L2 PDS label, the keyword CH1:STATISTICAL_POLISHER_FILE_NAME identifies the statistical polishing file that was used. The files are located in the CALIB directory of the L2 dataset.

The statistical polishing table to be applied is selected by START_TIME from the L2 PDS label:

Table 2-5. Selecting a Statistical Polishing Table

If START_TIME in L2 PDS Label is:	Then apply this table of gains and offsets for Statistical Polishing
(>= 2009-01-19T00:00:00 and < 2009-02-15T00:00:00) or (>= 2009-04-15T00:00:00 and < 2009-04-28T00:00:00) or (>= 2009-07-12T00:00:00 and < 2009-08-17T00:00:00)	M3G20110830_RFL_STAT_POL_1.TAB or M3T20111020_RFL_STAT_POL_1.TAB (cold)
(>= 2008-11-18T00:00:00 and < 2009-01-19T00:00:00) or (>= 2009-05-13T00:00:00 and < 2009-05-17T00:00:00) or (>= 2009-05-20T00:00:00 and < 2009-07-10T00:00:00)	M3G20110830_RFL_STAT_POL_2.TAB or M3T20111020_RFL_STAT_POL_2.TAB (warm)

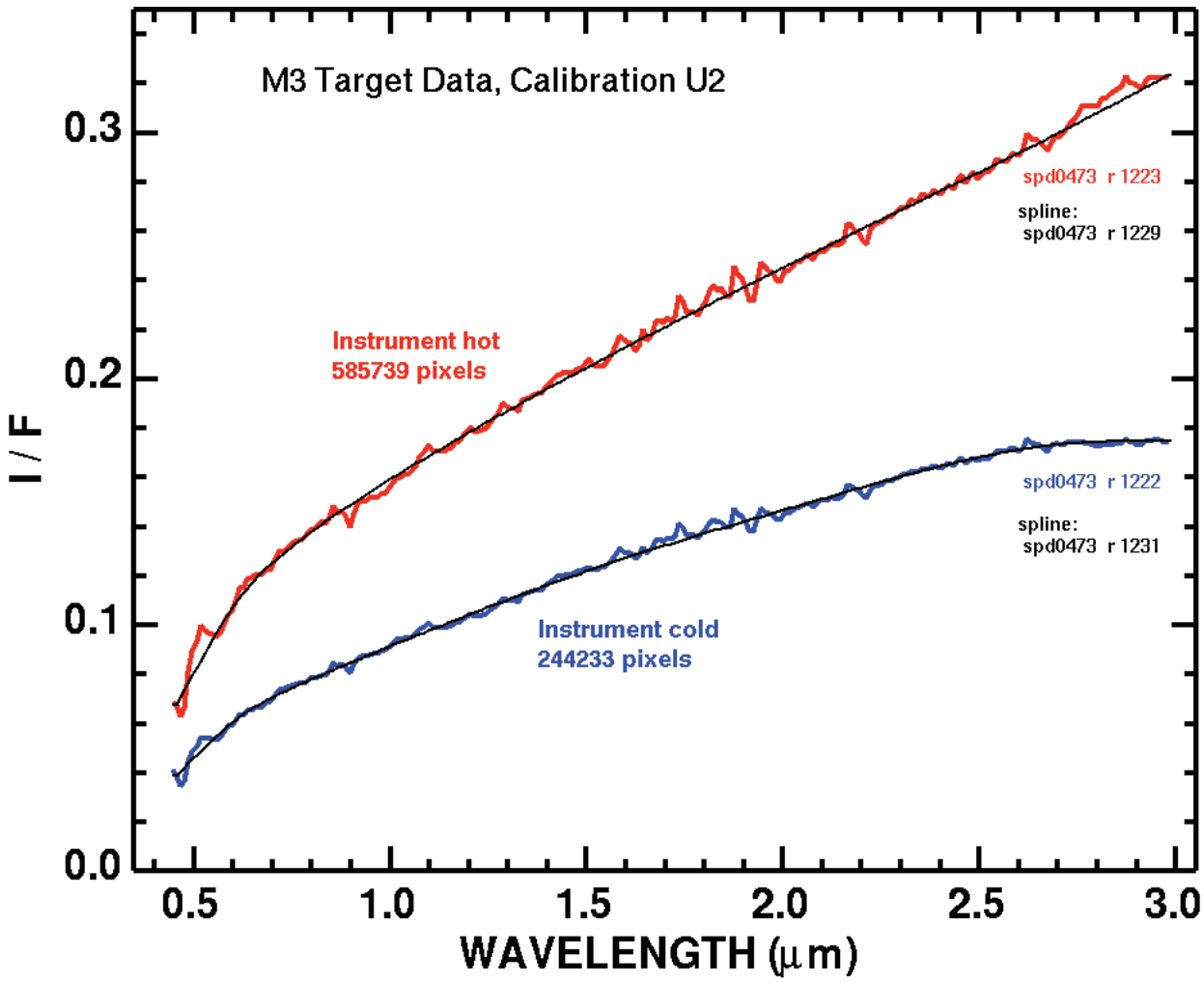


Figure 2-21. The entire M^3 data set was averaged 10x10 pixels, then searched for minimum absorption features under two separate conditions: instrument warm and instrument cold. The blue and red lines show the results of those averages. Each of the 585,739 instrument warm and 244,233 instrument cold pixels corresponds to 100 original M^3 pixels, thus the average represents 58,573,900 and 24,423,300 original M^3 pixels. The black lines are the cubic spline fits by hand through the average spectra to follow the low frequency curvature of the spectrum without introducing unusual absorption features in the judgment of the science team. (The cubic spline fits are not physically hand drawn, but rather cubic splines are fit through the data at channels where the polisher correction factor equals 1.0.) A similar set of instrument warm and instrument cold averages were created for target mode. The levels in the plot above are not due to the temperature of the instrument. The levels are due to the solar elevation: when the sun is higher, the heat from the hotter lunar surface heated the instrument.

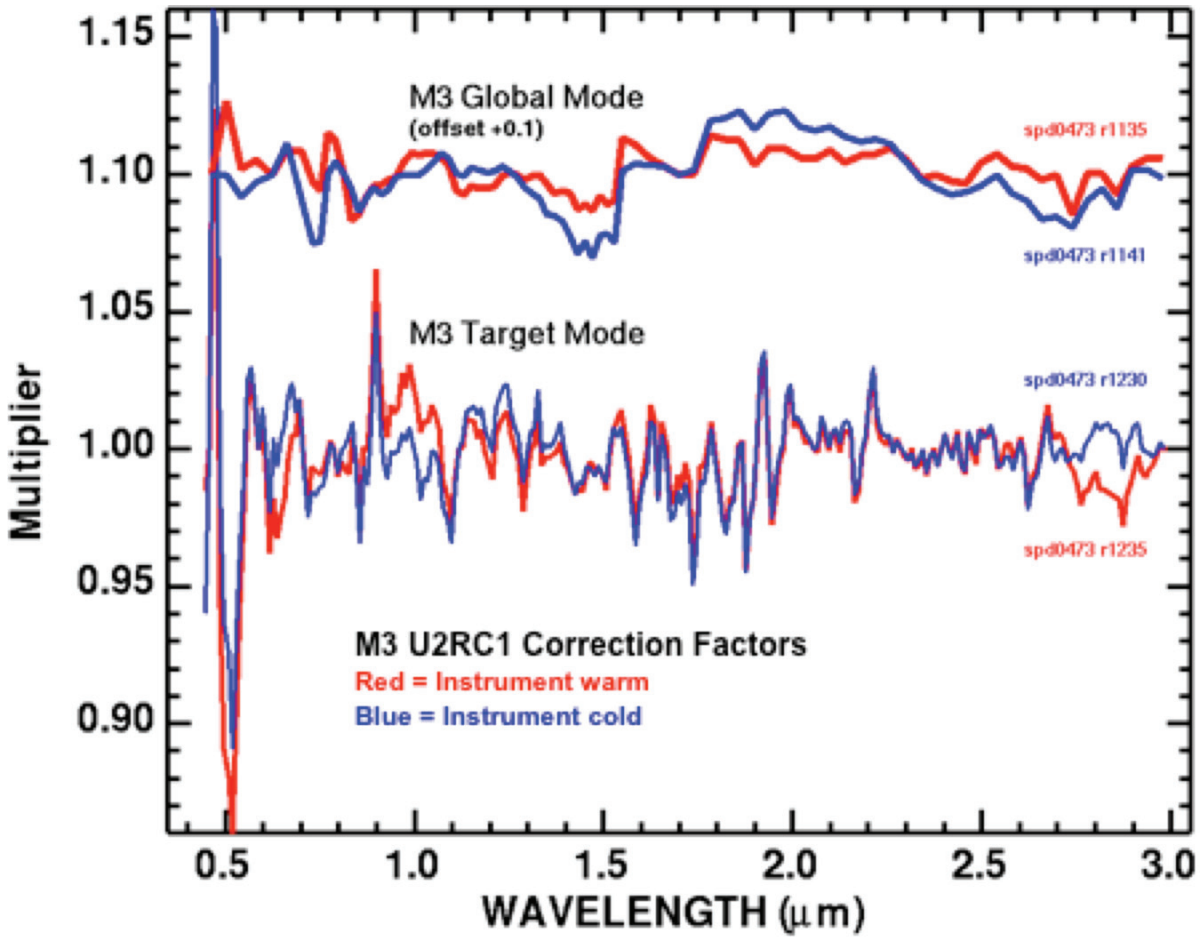


Figure 2-22. The averages illustrated in Figure 2-21 are divided by the fitted cubic spline to make the derived polishing multiplier for global mode instrument warm and instrument cold (top red and blue thick lines). A ratio of similar averages by fitted cubic splines for target mode data are shown for the lower red and blue (thin) lines. The global mode lines are offset 0.1 (the average level is 1.0).

Level 2, Step 3: Thermal Removal (iterative function)

$$\mathbf{L2_{s3}(\lambda)} = F(\mathbf{L2_{s2}(\lambda)})$$

or

$$\mathbf{L2_{s3}(\lambda)} = \mathbf{L2_{s2}(\lambda)} - T(\lambda \mid \mathbf{L2_{s2}(\lambda)})$$

where

- λ is the wavelength (global or target)
- $F(\mathbf{L2_{s3}(\lambda)})$ denotes an interactive process, supplied by the science team, where each spectrum in an image cube $\mathbf{L2_{s3}(\lambda)}$ is independently analyzed to remove the thermal component from the lunar data (which can also be described as a net subtraction vs. wavelength):

1) Remove only the SOLAR_DISTANCE correction, applied in L2 Step 1, to the input data $\mathbf{L2_{s2}(\lambda)}$.

2) For each spectrum, the I/F is linearly projected from wavelengths A and B in Table 1 (below) to wavelength C.

3) The projected I/F at wavelength C is subtracted from the observed I/F at wavelength C to give the thermal component T1.

4) If the difference is negative, the temperature is not derived. (Private correspondence from R. Clark: This can happen frequently because there is a lot of water on the Moon; see Clark et al., [2012].) If the difference is positive, the difference is assumed to be thermal emission and the temperature whose black body emission that best matches that of T1, is derived. The emissivity is assumed to be constant with wavelength equal to 1- I/F at wavelength A.

5) The derived thermal emission is subtracted from the observed I/F, giving a new I/F estimate IOF1 as a function of wavelength.

6) R1 is then corrected for incidence angle and phase angle effects = IOF 1c (as of the writing of this paper, phase angle corrections for the 2 to 3-μm wavelength region for the lunar surface are not yet available).

7) The wavelength dependent emissivity is then computed from e = 1 – IOF1c.

8) Next a new projection using IOF 1 is made from wavelengths D and E (Table 2.6) to a new I/F at wavelength C, and the difference, T2, computed.

9) A new temperature (T) is derived from the thermal difference (T2) by computing a new black body that includes the wavelength dependent emissivity estimate, e, and cosine correction (and once available, a phase correction).

10) The thermal emission, $r_o^2 e B_o(T)/F_{sun}$, is computed from this 2nd iteration estimate and subtracted from the original I/F spectrum, producing a new estimate, IOF2c.

11) If the derived temperature difference from the first and second iteration is less 2 K, the solution is complete. Otherwise, a third iteration is computed by going back to step 6 and substituting IOF2c for IOF1c.

12) Put back SOLAR_DISTANCE correction removed in 1) above.

- Table 2.6. Wavelengths Used to Project Lunar Spectra

Wavelength in μm				
A	B	C	D	E
1.55	2.35	2.7	2.28	2.59

- Tests were made with additional iterations (up to 12) and it was determined that after 3 iterations, thermal emission was added back into some spectra that displayed 2-μm pyroxene bands. It was determined that 2 to 3 iterations provided the optimum solution for a single temperature.
- When the method cannot detect excess thermal emission in the presence of sufficiently strong absorption in the 3-μm region in M^3 data (defined by the initial projection of the spectrum discussed above falling above the observed data), no derivation of a temperature is performed and no removal of thermal emission in M^3 data is performed. This means that water and hydroxyl bearing areas have no thermal emission removed and that any mapping of these absorptions and derivations of abundance is conservative and provides lower limits. By the nature of the algorithm design, that of linear extrapolation, the algorithm will not produce a downturn in M^3 data, and thus can not introduce an artificial water absorption when multiple iterations are done in the retrieval of the reflectance spectrum. It is an almost certainty that thermal emission hides areas containing water in the lunar surface and reduces the water band strengths in almost all areas measured by M^3, except in low sun angle areas (for example, near the poles and slopes facing away from the sun at mid-to-high latitudes, where the surface temperatures are below about 250 K). More on this method can be found in Clark et al., [2011].
- We limit the I/F cosine correction and the computed reflectance to avoid errors due to lower spatial resolution to topography and registration topography to prevent very high computed reflectances. If cosine(incidence) is less than 0.05 then 0.05 is used as the value for cosine(incidence). If the computed reflectance is greater than 0.6 then 0.6 is used as the value for computed reflectance.
- In the PDS label, the keyword CH1:THERMAL_CORRECTION_FLAG is set to "Y" if the thermal correction was performed. Otherwise the keyword is set to "N".
- The temperature that is estimated by this step for each pixel is stored in units of kelvin in the second band of the Level 2 supplemental data file, M3{G,T}YYYYMMDD_VNN_SUP.IMG along with an ENVI header M3{G,T}YYYYMMDD_VNN_SUP.HDR. These files are defined by the SUPPLEMENTAL_FILE and SUPPLEMENTAL_HDR_FILE objects in the PDS label.

For further information, see Clark et al., [2011].

Level 2, Step 4: Photometric Correction

This step consists of a photometric correction performed on the entire image cube using local topography (derived from available LOLA data) and a separate photometric correction of the 1489-nm band relative to a sphere to preserve topography. The photometric correction using local topography is the primary product of Step 4 and is thus described first.

$$\mathbf{L2_{s4}(\lambda)} = \mathbf{L2_{s3}(\lambda)} * \{ X_{L_norm}(i_{_topo}, e_{_topo}, \alpha) * F_{alpha_norm}(\alpha, \lambda) \}$$

where

- λ is the wavelength (global or target); all bands.
- Geometry Information from Level 1B based on local topography
  - $i_{_topo}$= incidence angle in degrees as supplied by the equation: i=acos(cos(obs[1])*cos(obs[7])+sin(obs[1])*sin(obs[7])*cos((obs[0]-obs[8]))). *If the resulting incidence angle is greater than or equal to 85.0 degrees then set $i_{_topo}$ to 85.0 before proceeding with the photometry correction.*
  - $e_{_topo}$= emission angle in degrees as supplied by the equation: e=acos(cos(obs[3])*cos(obs[7])+sin(obs[3])*sin(obs[7])*cos((obs[2]-obs[8]))). *If the resulting emission angle is greater than or equal to 85.0 degrees then set $e_{_topo}$ to 85.0 before proceeding with the photometry correction.*
  - OBS[0]= “per pixel to-sun azimuth” band in *OBS.IMG
  - OBS[1]= “per pixel to-sun zenith” band in *OBS.IMG
  - OBS[2]= “per pixel to-M^3 azimuth” band in *OBS.IMG
  - OBS[3]= “per pixel to-M^3 zenith” band in *OBS.IMG
  - OBS[7]= “per pixel facet slope” band in *OBS.IMG
  - OBS[8]= “per pixel facet aspect” band in *OBS.IMG
  - α = phase angle in degrees as supplied by the “per pixel phase” band in *OBS.IMG
- Photometric Limb Darkening Factor, $X_L(\alpha)$, for Global or Target Modes
  - $X_{L_norm}(i_{_topo}, e_{_topo}, \alpha)$ is normalized to 30º phase; equal to $X_L(30,0,30)$ / $X_L(i_{_topo}, e_{_topo}, \alpha)$ where:
    - $X_L(i_{_topo}, e_{_topo}, \alpha) = (\cos(i_{_topo}) / (\cos(e_{_topo}) + \cos(i_{_topo})))$, a simple Lommel-Seeliger model
- $F_{alpha_norm}(\alpha, \lambda)$ correction, for Global or Target Modes
  - The actual $F_{alpha_norm}(\alpha, \lambda)$ factor to be applied, is linearly interpreted in α from a look-up table $F_{alpha}(\alpha, \lambda)$ (global or target, supplied by the science team) of correction factors dependent on α and λ.
  - $F_{alpha_norm}(\alpha, \lambda)$ is normalized to 30º phase, $F_{alpha}(30, \lambda) / F_{alpha}(\alpha, \lambda)$

- In the PDS label, the keyword CH1:PHOTOMETRY_CORR_FILE_NAME identifies the $F_{alpha}(\alpha, \lambda)$ file that was used: M3{G,T}20111109_RFL_F_ALPHA_HIL.TAB. The files are located in the CALIB directory of the L2 dataset.

- **$L2_{s4}(\lambda)$** is the resulting 3-dimensional, photometrically-corrected, reflectance image file and ENVI header stored as M3{G,T}YYYYMMDD_VNN_RFL.IMG and M3{G,T}YYYYMMDD_VNN_RFL.HDR, respectively. These files are defined by the RFL_FILE and RFL_HEADER_FILE objects in the PDS label.

A separate task in Step 4 is to perform a photometric correction of only the 1489-nm band relative to a sphere. The results are provided as a supplemental image for each data file. This product corrects broad latitudinal variations, but retains the effects of topography (including shadows and gradients) and features are readily recognized at the scale of the measurement. The resulting file is part of the Level 2 product for PDS.

$$\mathbf{L2_{S4_TOPO_PRESERVED}(\lambda)} = \mathbf{L2_{s4}(\lambda)} * \{ X_{L_norm}(i_{_sphere}, e_{_sphere}, \alpha) * F_{alpha_norm}(\alpha, \lambda) \}$$

where

- λ is one specific wavelength (global or target): 1489 nm.

- Geometry Information from Level 1B based on a sphere
  - $i_{_sphere}$ = incidence angle in degrees as supplied by the "per pixel to-sun zenith" band in *OBS.IMG. *If the incidence angle is greater than or equal to 85.0 degrees then set $i_{_sphere}$ to 85.0 before proceeding with the photometry correction*.
  - $e_{_sphere}$ = emission angle in degrees as supplied by the "per pixel to-M3sensor zenith" band in *OBS.IMG. *If the emission angle is greater than or equal to 85.0 degrees then set $e_{_sphere}$ to 85.0 before proceeding with the photometry correction.*
  - α = phase angle in degrees as supplied by the "per pixel phase" band in *OBS.IMG

- Photometric Limb Darkening Factor, $X_L(\alpha)$, for Global or Target Modes
  - $X_{L_norm}(i_{_sphere}, e_{_sphere}, \alpha)$ is normalized to 30º phase; equal to $X_L(30,0,30)$ / $X_L(i_{_sphere}, e_{_sphere}, \alpha)$ where:
    - $X_L(i_{_sphere}, e_{_sphere}, \alpha) = (\cos(i_{_sphere}) / (\cos(e_{_sphere}) + \cos(i_{_sphere})))$, a simple Lommel-Seeliger model

- $F_{alpha_norm}(\alpha, \lambda)$ correction, for Global or Target Modes
  - The actual $F_{alpha_norm}(\alpha, \lambda)$ factor to be applied, is linearly interpreted in α from a look-up table $F_{alpha}(\alpha, \lambda)$ (global or target, supplied by the science team) of correction factors dependent on α and λ.

- $F_{alpha_norm}(\alpha, \lambda)$ is normalized to 30º phase, $F_{alpha}(30, \lambda) / F_{alpha}(\alpha, \lambda)$
- In the PDS label, the keyword CH1:PHOTOMETRY_CORR_FILE_NAME identifies the $F_{alpha}(\alpha, \lambda)$ file that was used: M3{G,T}20111109_RFL_F_ALPHA_HIL.TAB. The files are located in the CALIB directory of the L2 dataset.

- **$L2_{S4_TOPO_PRESERVED}(\lambda)$** is the resulting 2-dimensional image containing the1489-nm reflectance band with photometry relative to a sphere to preserve topography. It is stored in the first band of the Level 2 supplemental data file M3{G,T}YYYYMMDD_VNN_SUP.IMG along with an ENVI header M3{G,T}YYYYMMDD_VNN_SUP.HDR, respectively. These files are defined by the SUPPLEMENTAL_FILE and SUPPLEMENTAL_HDR_FILE objects in the PDS label.

For further information, see Besse et al., [2012].

Level 2, Step 5: Ground Truth Correction (Optional**)

***** Step 5, Ground Truth Correction, was not applied to the Level 2 data archived at PDS. However the necessary calibration files are provided in the Level 2 archive for individual users to apply the correction factors on an as-needed basis. See Table 2-7 below.***

$$\mathbf{L2_{s5}(\lambda)} = \mathbf{L2_{s4}(\lambda)} * g_{GT}(\lambda) + o_{GT}(\lambda)$$

where

- λ is the wavelength (global or target)
- **$L2_{s4}(\lambda)$** is the 3-dimensional, photometrically corrected, reflectance image file produced by Step 4.
- $g_{GT}(\lambda)$ is a Global or Target File of derived gains for a ground truth correction…
  - Gains are unitless
  - Supplied by the science team
- $o_{GT}(\lambda)$ is a Global or Target File of derived offsets for a ground truth correction…
  - Offsets are unitless
  - Supplied by the science team
  - For this PDS delivery, $o_{GT}(\lambda)$ is set to zero (no offset).
- The ground truth correction is sensitive to effects of the spacecraft environment on M^3 data. Therefore we have derived values as a function of observing date ranges, when the overall temperature of the detector was either cold or warm. The wavelength-dependent gains and offsets for the cold periods are provided

together in a Global or Target File, M3{G,T}20111117_RFL_GRND_TRUTH_1.TAB. Gains and offsets for the warm periods are provided in a separate Global or Target table file, M3{G,T}20111117_RFL_GRND_TRUTH_2.TAB. In the L2 PDS label, the keyword CH1:GROUND_TRUTH_CORR_FILE_NAME identifies the file that was used. The files are located in the CALIB directory of the L2 dataset.

The ground truth correction is presently an optional step that can be turned on or off in the pipeline. If this step was not applied by the pipeline, then the keyword CH1:GROUND_TRUTH_CORR_FILE_NAME in the L2 PDS label is set to "N/A".

The ground truth correction table to be applied is selected by START_TIME in the L2 PDS label:

Table 2-7. Selecting a Ground Truth Correction Table

If START_TIME in L2 PDS Label is:	Then apply this table of gains and offsets for the Ground Truth Correction
(>= 2009-01-19T00:00:00 and < 2009-02-15T00:00:00) or (>= 2009-04-15T00:00:00 and < 2009-04-28T00:00:00) or (>= 2009-07-12T00:00:00 and < 2009-08-17T00:00:00)	M3{G,T}20111117_RFL_GRND_TRU_1.TAB (cold)
(>= 2008-11-18T00:00:00 and < 2009-01-19T00:00:00) or (>= 2009-05-13T00:00:00 and < 2009-05-17T00:00:00) or (>= 2009-05-20T00:00:00 and < 2009-07-10T00:00:00)	M3{G,T}20111117_RFL_GRND_TRU_2.TAB (warm)

This reversible calibration step corrects M^3 reflectance spectra to be consistent with the visible to near-infrared spectral properties of the lunar soils known from extensive laboratory study of lunar samples. This correction leverages the unique advantage of lunar remote sensing represented by reliable ground truth information. This advantage is afforded by the return of samples from known locations on the lunar surface. Mature highland soil 62231 from the Apollo 16 landing site has been the standard reference standard for ground truth corrections to visible to near-infrared lunar remote sensing, beginning with earth-based telescopic observations and continuing through Galileo and Clementine lunar observations (e.g., McCord et al., [1981], Pieters, [1999]). This mature soil sample is representative of sampled mature highland soils and has been exceptionally well characterized with laboratory

visible to near-infrared reflectance spectroscopy. It is applied as ground truth by comparison of remote sensing observations to the laboratory reference spectrum. The general procedures are summarized here. Remote observations are collected from a region of smooth, mature feldspathic highland soils, for which the 62231 soil sample is assumed to be representative. The remotely-sensed data for this region are regressed against the reference spectrum, and a set of gains (and in some cases offsets) are derived to bring the remote data into consistency with the absolute laboratory providing ground truth. As the remote data have normally been calibrated based on absolute calibration sources (e.g. Level 1B calibration for M^3), this correction is typically mild and the ground truth correction only makes minor adjustments.. For further discussion of calibration of remote sensing datasets with ground truth information, see Pieters, [1999] and Clark et al., [2002].

The reference standard used in the ground truth correction for the M^3 Level 2 dataset is based on the average 62231 soil spectrum discussed by Pieters, [1999], illustrated in Figure 2-23. Because the overall albedo and continuum slope are affected by observing conditions and surface texture, the M^3 team used an approach that would not affect absolute albedo and continuum slope. The M^3 team elected to use a standard continuum removal approach on the reference standard and on the comparison M^3 data used in deriving the correction. Removal of the continuum slope from spectra prior to deriving the correction mitigates any effects of differing albedo and continuum slope between the laboratory and remote measurements. The continuum removal approach employed by the M^3 team used a convex hull continuum slope, in which linear segments are fit between high points in the spectra. The continuum removed 62231 soil spectrum contains a small amount of residual band-to-band "noise". The M^3 team elected to use a spectral smoothing approach based on application of a convolution filter to remove these band-to-band artifacts. There are several issues applying a ground truth approach from 1500 to 3000 nm. Laboratory measurements, even under water-free purged conditions, contain residual features near 3 μm caused by OH and H_2O. To avoid introducing or removing features associated with hydration or with the specific laboratory reference standard used, the M^3 team produced a special composite reference standard spectrum for the long wavelength portion of the spectrum. This reference standard is based on continuum-removed data as described above. The Modified Gaussian Model (MGM) was used to fit the reference standard from 1500 to 2500 nm. The fit used 2 absorptions to fit the 2000 nm mafic absorption. At longer wavelengths, the values of the reference standard are set to 1.0. For more information regarding MGM fits to lunar soil reflectance spectra, please refer to the discussion by Noble et al. [2006]. The reference standard used is thus a combination of the 62231 average spectrum (short wavelengths) and the extrapolated MGM fit (long wavelengths, > ~1500 nm), filtered with the convolution filter discussed above and resampled to M^3 global mode wavelengths. The resulting reference standard used to derive the ground truth correction for M^3 is illustrated in Figure 2-23. Note that the reference standard has a regular well-known shape that is linked to feldspathic highland soil mineralogy, but that the features are relatively weak (<3%).

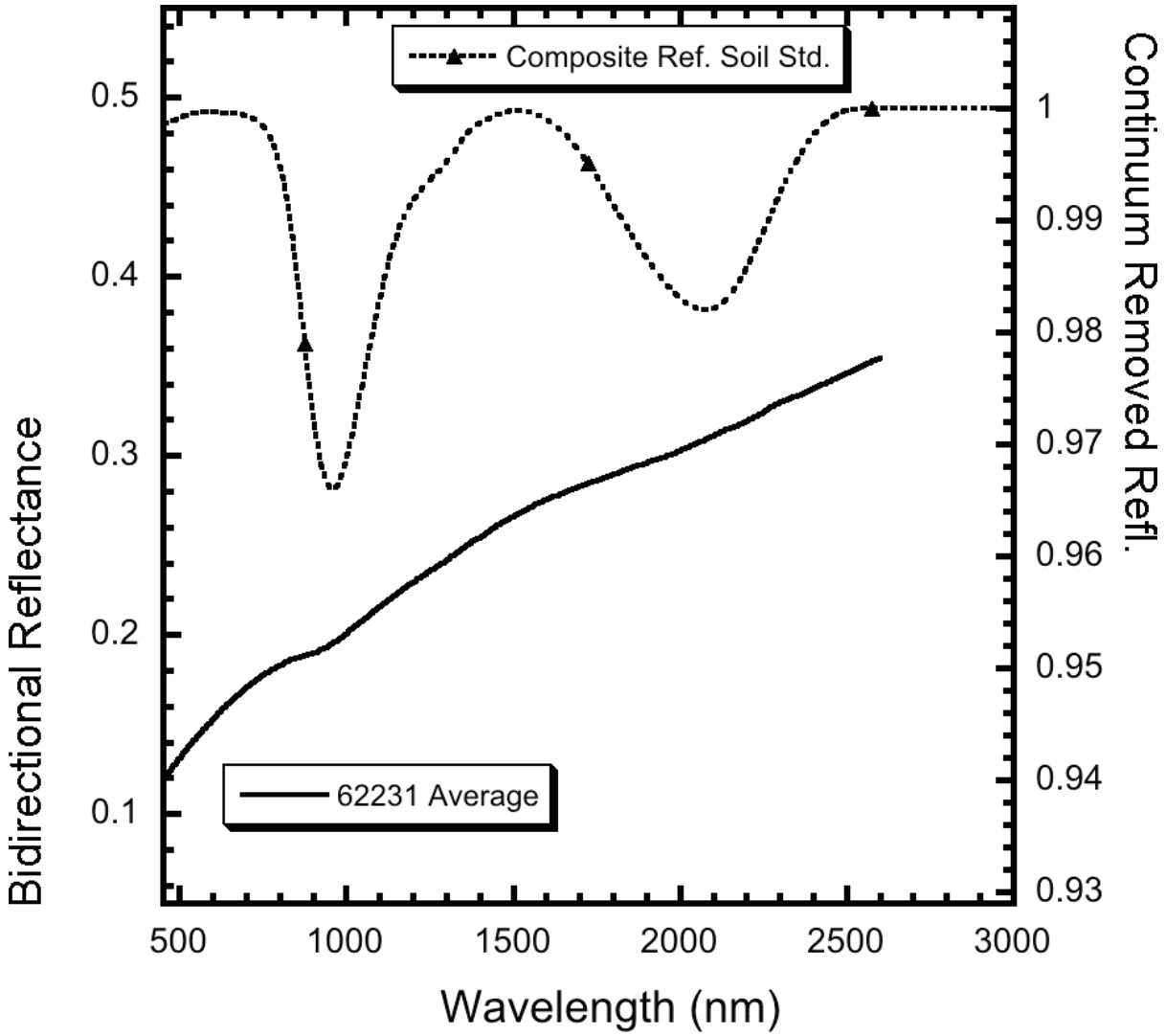


Figure 2-23: 62231 Average spectrum and composite reference soil standard used by the M^3 team to derive the ground truth correction. As discussed in the text, the reference standard is based on the 62231 average spectrum, and its derivation involves continuum removal, Modified Gaussian Model (MGM) fitting, and convolution filtering.

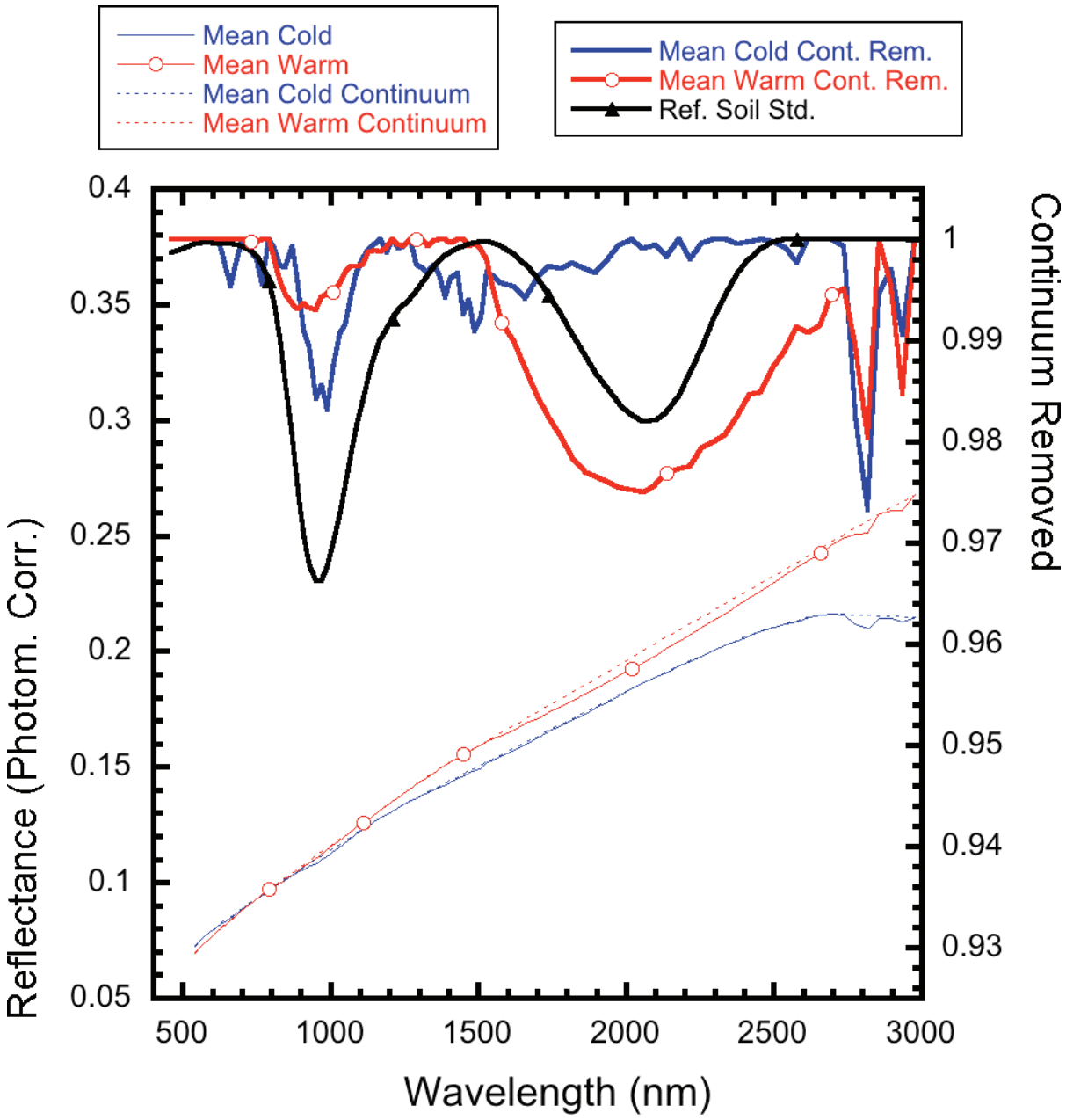


Figure 2-24: M^3 ROI average spectra for mature highland soils used to derive the ground truth correction along with reference standard spectrum (black) resampled to M^3 global mode resolution. The average photometrically-corrected reflectance spectra and continuum slopes are shown in thin solid and dotted lines, respectively, and the continuum removed spectra in heavy solid lines. The reference standard spectrum is shown only as continuum removed.

The M^3 team identified a number of small regions within a number of specific M^3 files that are dominated by mature, feldspathic highland soils. These regions were identified such that they cover a diverse range of operational times, instrument conditions, and geographic coverage. From each region, the average reflectance spectrum was extracted (in this context, “reflectance” refers to the output of the Level 2 pipeline up

through the photometric correction, or in other words, after the division by solar flux and solar distance correction, application of statistical polisher, thermal removal, and photometric correction). The resulting averages were separated into cold and warm groups according to the conditions encountered (defined over time ranges specified above). A composite average of each subset was then calculated, producing two average spectra, one each for the cold and warm subsets. These average spectra are illustrated in Figure 2-24. In evaluating these average Level 2 spectra, the M^3 team noted possible calibration artifacts affecting wavelengths above ~1500 nm, likely due to residual effects of the diverse instrument/spacecraft operational conditions. These artifacts include the presence of an apparent, anomalous broad feature near 2 μm in the 'warm' data and strong sharp features near ~2800 nm. These issues are seen in Figure 2-24.

Due to these unresolved issues, the M^3 team has delivered ground truth correction factors only for wavelengths below ~1500 nm. These ground truth corrections to Level 2 data are intended to restore the well-known character of weak features near 1000 nm for highland soils. The average cold and warm spectra shown in Figure 2-24 were truncated at this wavelength (global band 47, ~1509 nm). A convex hull continuum was fit to the truncated average spectra (using the same procedure used for the reference standard spectrum discussed above) to remove the continuum slope. Continuum removed data to 1500 nm for the average Level 2 highland soil spectra are illustrated in Figure 2-25. Ground truth correction factors were derived through a straight ratio of the continuum removed M^3 averages with the continuum removed reference standard discussed above.

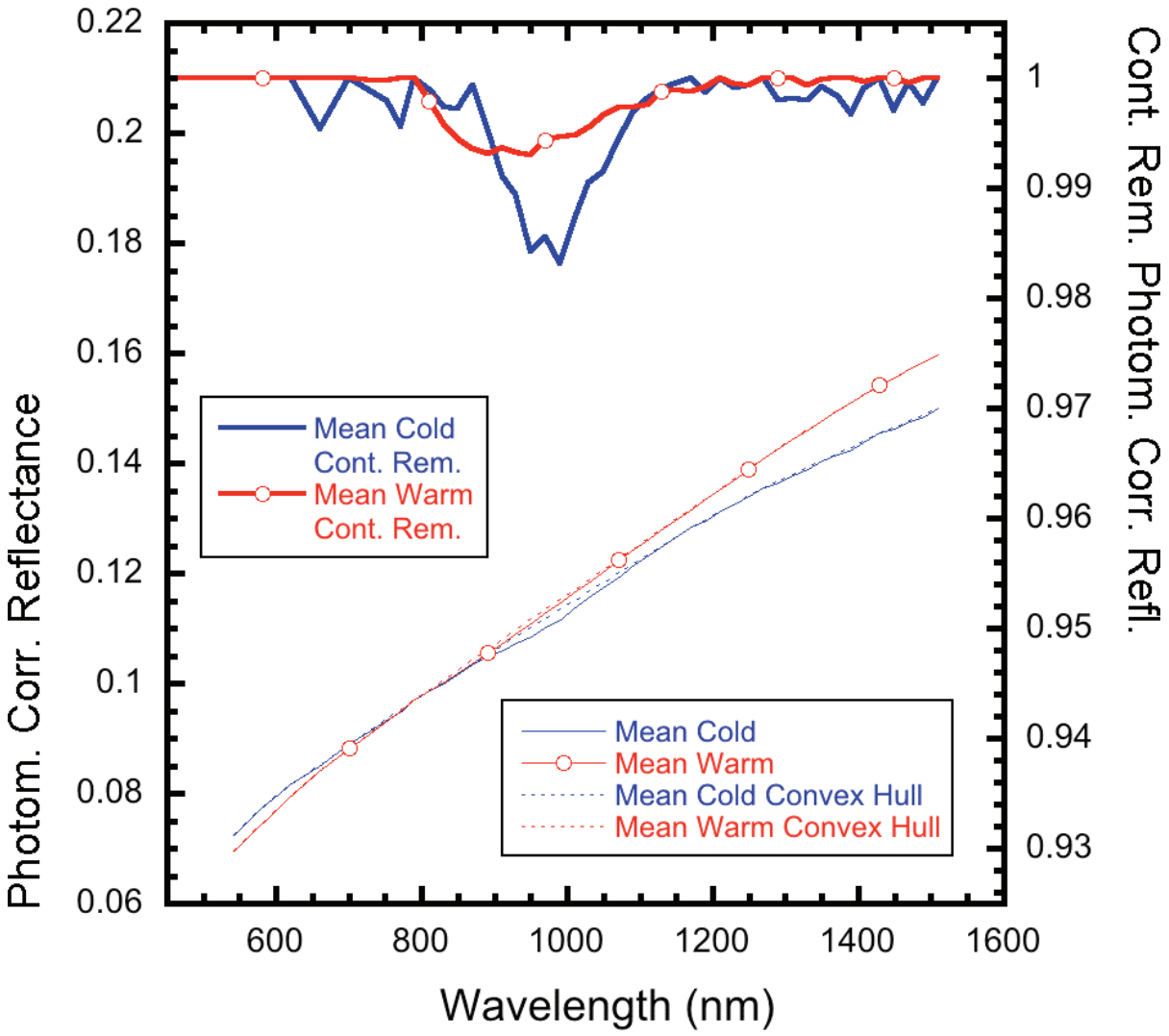


Figure 2-25: Continuum removal process for M^3 ROI average spectra to 1500 nm. The spectra are the same as those shown in Figure 2-24, but have been truncated at ~1509 nm (M^3 global mode band 47).

The global mode ground truth correction factors are illustrated in Figure 2-26. These correction factors are delivered for all 85 bands of global mode data, but are set to 1.0 above 1500 nm. The limited spatial coverage of M^3 target mode data does not allow reasonable average soil spectra to be derived. Target mode correction factors are thus only estimated by interpolating the global mode correction to target mode wavelengths. Global and target mode ground truth factors are illustrated in Figure 2-27. The correction is a simple multiplier (the offset values are set to 0.0). This allows for the correction to be applied with a simple multiplicative step. In the judgment of the M^3 team, the most reliable reflectance dataset is produced for global mode data by applying the ground truth correction, especially for wavelengths below ~1500 nm. However, the ground truth correction will affect absorption band strengths in the 1000 nm region but not the 2000 nm region, so care should be exercised in analyzing weak

2000 nm absorptions relative to 1000 nm absorptions. The magnitude of the adjustment is relatively small, such that it will have minimal impact on strong absorption features present in immature materials, and is a significant adjustment only for the very weak absorption features found in lunar soils. Individual users must make a determination of whether the ground truth correction is appropriate to apply for their particular investigation. As such, the ground truth factors are provided as calibration files but have NOT been applied to the delivered Level 2 datasets, and should be applied by individual users on an as-needed basis.

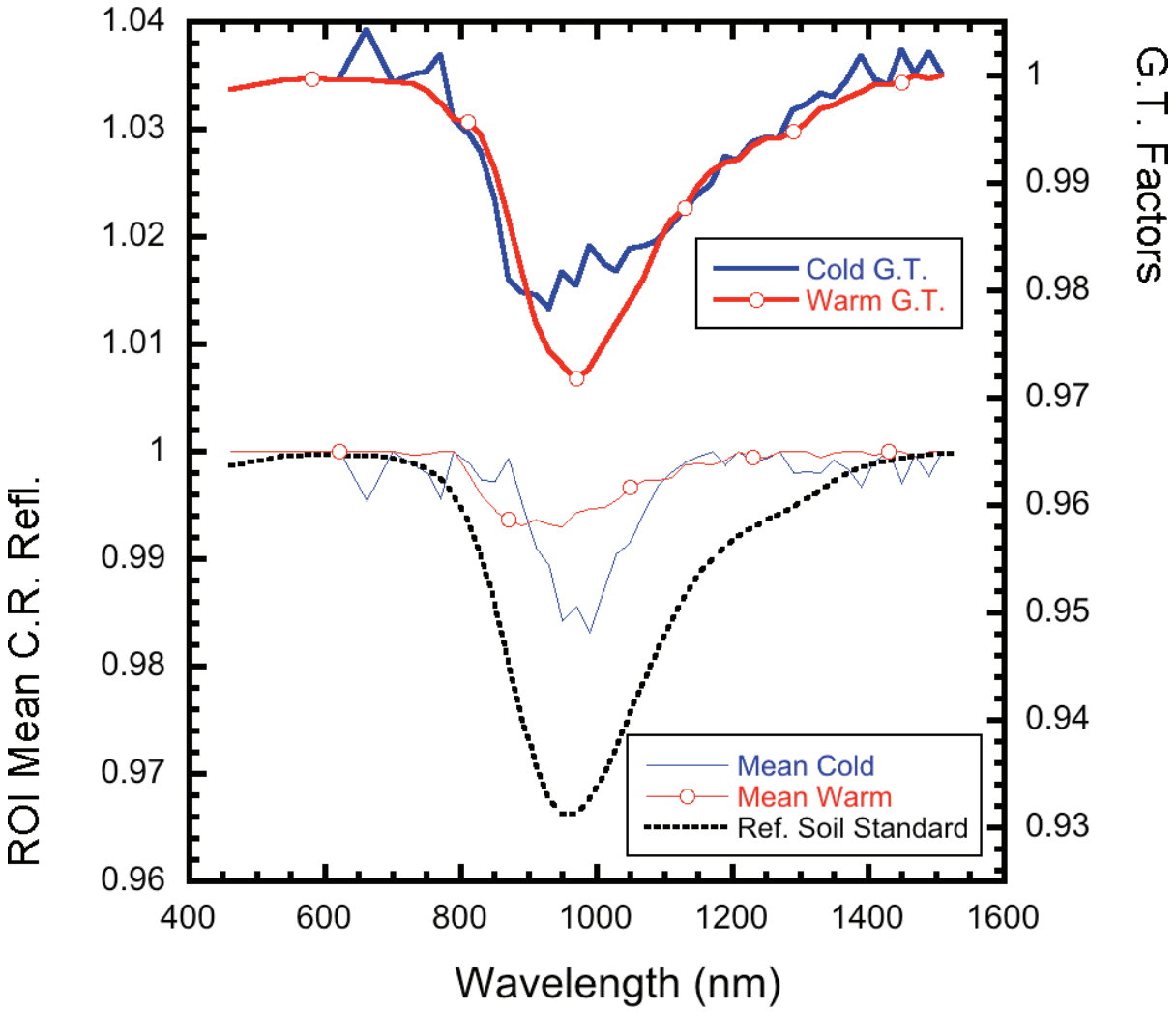


Figure 2-26: Ground truth correction factors for cold and warm M^3 data. The continuum removed ROI average spectra illustrated in Figure 2-25 are reproduced for reference, along with the reference standard spectrum across these wavelengths.

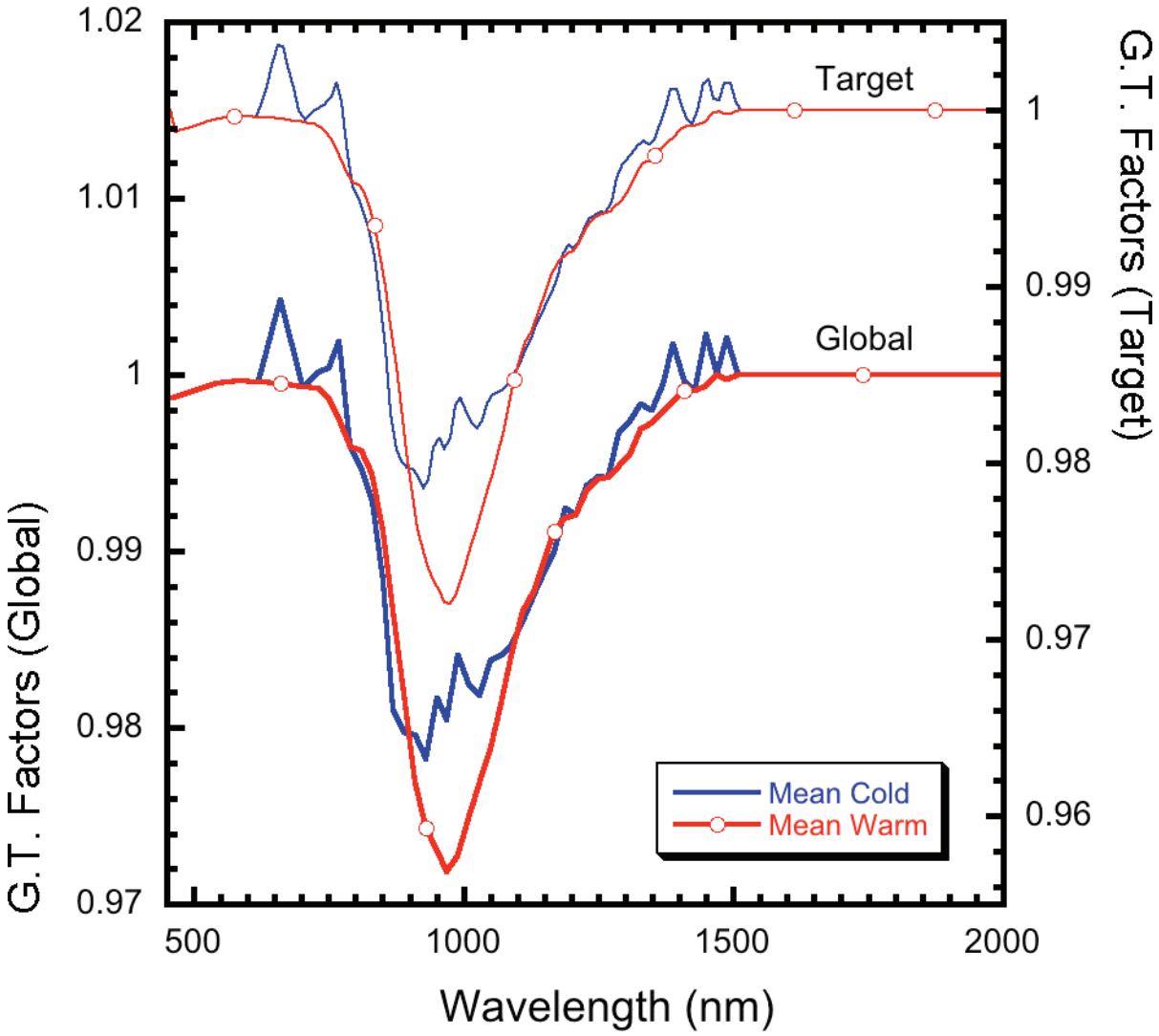


Figure 2-27: M^3 ground truth correction factors for global mode and target mode (interpolated from global mode, as discussed in the text). Global mode factors are shown in heavy lines (left axis) and target mode factors in thin lines (right axis). The correction factors are shown only to 2000 nm, but are delivered for all wavelengths in both modes, set to 1.0 beyond 1500 nm.

Level 2, Step 6: Flag Degraded Channels

$$L2_{s6}(\lambda) = L2_{s5}(\lambda_{Global} < 540.0 \text{ nm or } \lambda_{Target} < 525.0 \text{ nm or } \lambda_{Target} > 2990.0 \text{ nm}) \rightarrow -999.0$$

where

- Specified degraded channels are flagged as not reliable. These include all global-mode channels less than 540.0 nm (i.e., the first two channel) and target-mode channels less than 525.0 nm (i.e., the first 8 channels) or greater than 2990.0 nm (i.e., the last channel, 256)In the L2 PDS label, the keyword

INVALID_CONSTANT =-999.0 in the RFL_IMAGE object identifies degraded data; in the RFL.HDR file, a degraded channel is identified by setting its entry in the bad band list to 0 (bad). .

- **$L2_{s5}(\lambda)$** is the 3-dimensional, ground truth and photometrically corrected, reflectance image file produced by Step 5.
- **$L2_{s6}(\lambda)$** is the resulting 3-dimensional, photometrically-corrected, Level 2 reflectance image file and ENVI header archived as M3{G,T}YYYYMMDD_VNN_RFL.IMG and M3{G,T}YYYYMMDD_VNN_RFL.HDR, respectively. These files are defined by the RFL_FILE and RFL_HEADER_FILE objects in the PDS label.

Due to the non-nominal spacecraft thermal environment as well as the low lighting conditions necessitated during much of M^3 data acquisition, data for a few M^3 channels experienced more spurious effects than could be accommodated by standard calibration procedures. These channels were deemed unreliable by the M^3 team during validation and are set to -999.0 in Level 2 reflectance cube to indicate they should not be used in standard analyses. Radiance values for these degraded channels remain in Level 1B data and may be used to recover the data if corrections are later found.

When displaying a Level 2 image, please note that bands flagged as degraded (-999.0) may appear black. This can be avoided by only displaying good bands: band numbers 3 and greater for global mode and band numbers 9 through 255 for target mode.

2.5.4.2. Limitations

This section discusses the known limitations of the Level 2 reflectance calibration process.

Instrument Thermal Status – Cold versus Warm

The Chandrayaan-1 spacecraft experienced a diverse range of non-nominal thermal and field-of-view (largely pointing) conditions while M^3 data were acquired (see discussions in Boardman et al., [2011] and Green et al., [2011]). During two optical periods (OP), five general conditions or states of the instrument are defined as summarized in Table 2.8 (from Boardman et al., [2011]). The operating conditions during these periods of M^3 data acquisition are illustrated in Figure 2-23 (after Green et al., [2011]). Solar illumination of the lunar surface (captured by Beta Angle) not only affected the measured signal level, but it clearly also strongly affected the spacecraft environment and operations and consequently the temperature of the M^3 detector.

As described in Green et al., [2011]) the nominal temperature for M^3 detector operation is 157 K. Unfortunately, this was rarely achieved during Chandrayaan-1 operations, and calibration procedures were necessarily adjusted to accommodate non-nominal operation by using in-flight data to derive corrections. As discussed above, it was recognized that the wide range of operating conditions encountered (Figure 2-28) produced artifacts in which comparisons of cool data to warm data exhibited spurious

spectral features that mimic raw signal (see Figs 7 and 39 of Green et al., [2011]). A correction procedure ("Smooth Shape Correction") was implemented during L1B calibration (see L1B discussion and Figure 2-19) to minimize artifacts that mimic raw signal (see Figs 2-12 and 2-15) but ultimately result from the wide range of operating conditions encountered. The L1B corrections minimize the dominant artifacts. Nevertheless, residual smaller effects are often apparent in L2 data, and several L2 calibration steps include separate correction factors for Warm and Cold periods (e.g. statistical polishing and ground truth) to accommodate these different states of the instrument and spacecraft.

Table 2-8. Optical Periods and Operating Conditions (Boardman et al., [2011])

Sub-OP Name	Time Period	Cold or Warm?	Orbit	Star Trackers	Description
OP1A	2008 Nov 18 - 2009 Jan 18	Warm	100 km	1 of 2	Commissioning phase through "warm" data
OP1B	2009 Jan 19 - 2009 Feb 14	Cold	100 km	1 of 2	Start of "cold" data through end of OP1
OP2A	2009 Apr 15 - 2009 Apr 27	Cold	100 km	1 of 2	100 km orbit with star trackers
OP2B	2009 May 13 - 2009 May 16	Warm	100 km	0 of 2	100 km orbit, no star trackers
OP2C	2009 May 20 - 2009 Jul 9	Warm	200 km	0 of 2	200 km orbit, no star trackers
	2009 Jul 12 - 2009 Aug 16	Cold	200 km	0 of 2	200 km orbit, no star trackers

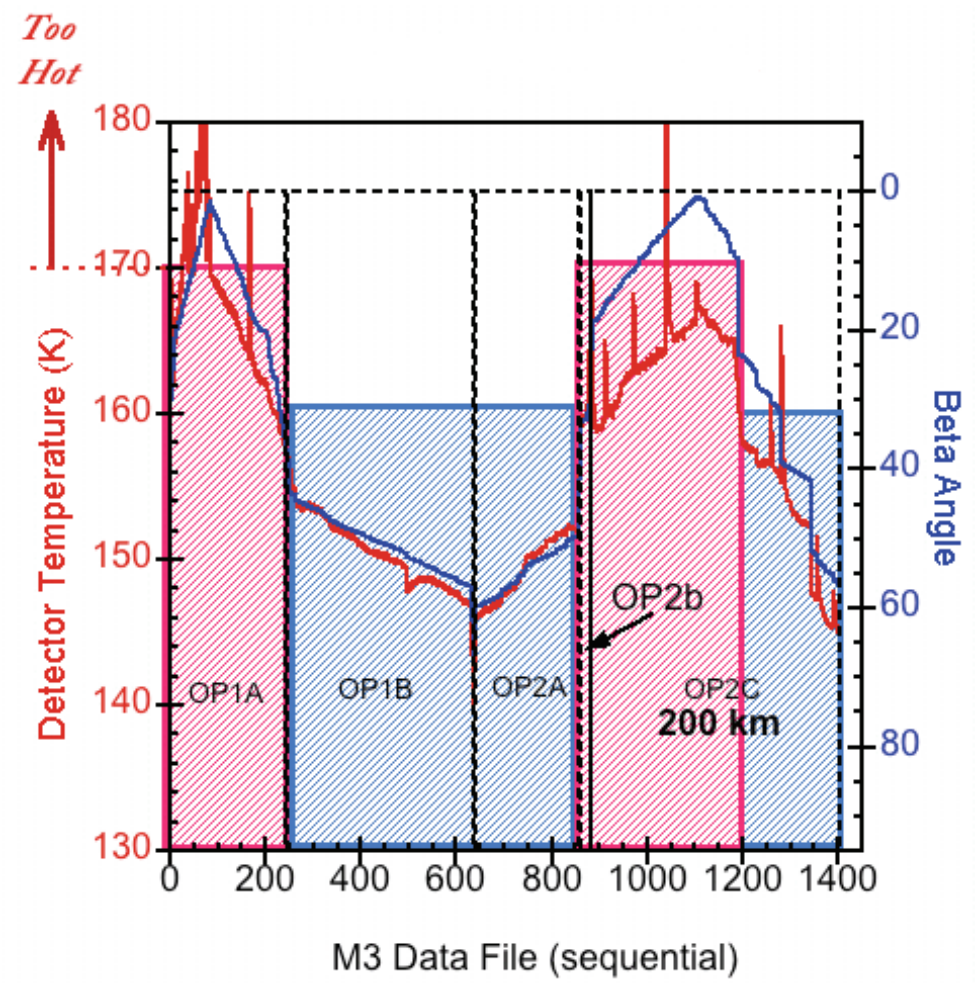


Figure 2-28. Plot of solar beta angle and M^3 detector temperature when data were acquired over the life of the mission (after Green et al., [2011]). Data files processed with Level 2 warm corrections are indicated in pink; data files processed with Level 2 cold corrections are indicated in blue. The inclusive dates for each are indicated in Table 2-8.

Consistency Among Optical Periods

Validation analyses of M3 data for each of the five OPs summarized in Table 2-8 and Figure 2-28 demonstrate high consistency among data within each period. However, there may be relative differences among data acquired under different measurement conditions that complicate inter comparison of data from different OPs. Largest relative differences are observed between data acquired in cold compared to warm states (Figure 2-29).

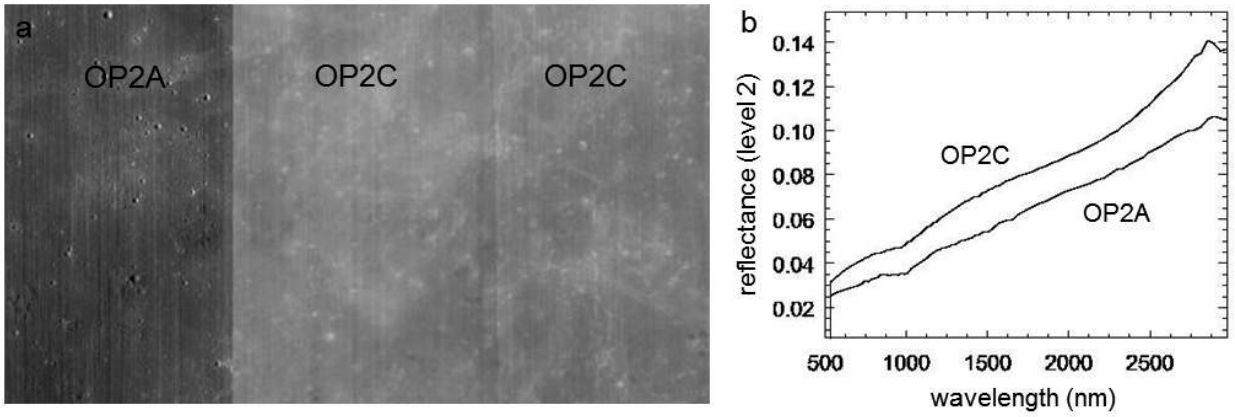


Figure 2-29. a) Mosaic of level 2 images M3G20090419T013221(OP2A), M3G20090612-T142522 (OP2C), and M3G20090612T101600 (OP2C) at 1010nm. The images from OP2C are often brighter than images of the same unit from OP2A. b) Spectra (10x10 average) extracted from the same location in M3G20090419T013221(OP2A) and M3G20090612-T142522 (OP2C). Weak spectral features may exhibit differences when measured under different operational conditions.

In addition to the difference in average reflectance level, data from different OPs may exhibit subtle spectral differences (Figure 2-29) when spectra from cold and warm periods are compared. Any difference in overall spectral shape is often evident when parameter maps designed to measure specific spectral features are compared between optical periods. Although relative differences among spectra extracted from a single image strip provide valuable information and are meaningful, small differences between spectra extracted across different OPs may not be real and should be interpreted with caution.

Statistical Polishing

The statistical polisher removes all the artifacts in the M3 data, including the weak absorptions at 1000 nm and 2000 nm. Therefore the ground truth correction was developed to put back those absorptions. This effect is important with working with weak absorptions.

Thermal Correction

When the 2000-nm absorption is strong, the thermal correction algorithm suppresses too much thermal signal and can remove part of the absorption.

Photometric Correction

As previously stated in the photometric correction step, we force emission and incidence angles greater than or equal to 85.0 degrees to 85.0 to prevent the limb darkening term to get to very high or negative values.

The Phase function

The photometric correction is based on the phase function F(alpha) that is provided by the science team. The phase function has been exclusively derived from highland terrains and is consequently more accurate for highland terrains.

The objective of the photometric correction is to provide one global correction for most of the Moon terrains; therefore we have selected only the highlands.

The phase function is extrapolated between 85 and 120 degrees (phase angle). This extrapolation is done with the same polynomial function as described previously; it is needed because of the lack of data at these phase angles.

The phase function is extrapolated between 2058 and 3000 nm (wavelengths) to avoid any residual from the thermal removal step. This interpolation is also needed to remove some artifacts at long wavelengths that are probably related to the water/OH deposit at high latitude and consequently high phase angles for M^3 observations.

The Correction based on topography

The photometric correction uses incidence and emission angles based on the best available surface topography at the time of M^3 data production. We used the last LOLA (Laser altimeter of Lunar Reconnaissance Orbiter mission) topography release to the public as of May 30, 2011. Given the spatial resolution of M3, this basemap may produce artifacts due to interpolation of the topography, especially at the equator.

Some artifacts and the interpolation limit the accuracy of reflectance based on the photometric correction using calculations of incidence (i) and emission (e) from surface topography. In Figure 2-30, the reflectance image presents a positive feature (dome-like) that is not present in the radiance image. A closer look at the topography shows an

artifact (perhaps a data drop out), in that case a “non real” depression that transformed into a dome-like in the final Level 2 product.

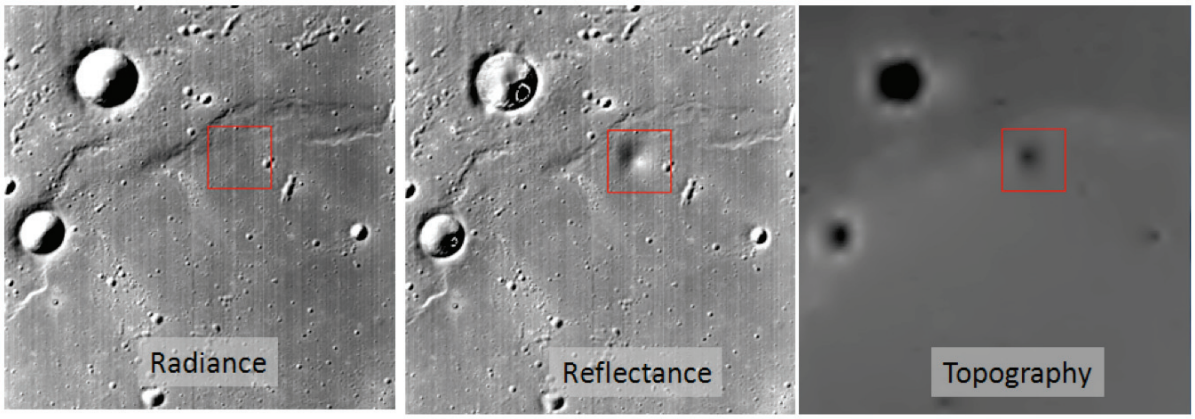


Figure 2-30: The left image is the Level 1B radiance image, the center image is the final photometrically corrected reflectance image of Level 2, and the right image is the topography derived from LOLA. The red box is centered on an artifact that is in the final M^3 Level 2 product (center image).

In Figure 2-31, an artifact is seen at the edge of a crater. Because of the M^3 observational geometry, this part of the crater is in shadow. Thus the final Level 2 products present an artifact where the limit between shadow and light is straight and not realistic. This is directly an effect of the accuracy of the topography.

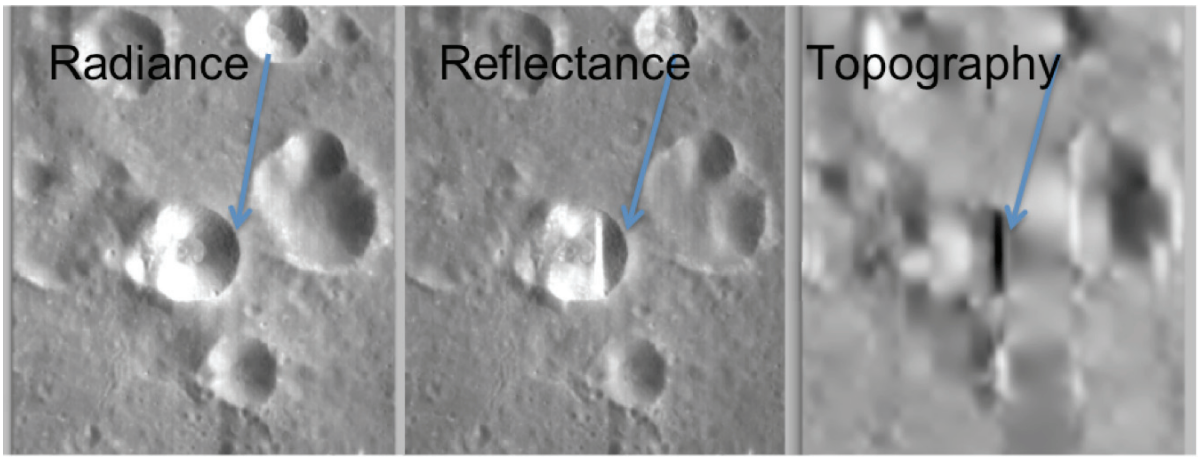


Figure 2-31: The left image is the Level 1B radiance image, the center image is the final photometrically corrected reflectance image of Level 2,, and the right figure is the topography derived from LOLA. Arrows point to the artifact in the topography that creates an artifact in the final M^3 Level 2 product (center image).

Recommendations: During analysis of Level 2 photometrically corrected data, we strongly recommend use of the first supplemental file image of reflectance (relative to a sphere) to evaluate the actual lighting conditions of the data as well as the associated topography. The topography used for the photometric correction is available as the band 10 (Cos(i) image) of the Level 1B *OBS.IMG file. Close to the poles, there is some

important offset between the radiance and reflectance images and the topography because of incomplete recovery of the spacecraft attitude. In these areas, the photometric correction is not reliable because it uses incorrect local topography.

Given the accuracy of the topography that was used and the problems with the pointing of the Chandrayaan-1 spacecraft, we recommend checking the topography for all images. We are very grateful to the LOLA team for sharing an early version of their data, which had some artifacts, with us. It is important to that those artifacts are suppressed in the final version of the LOLA data archived in the PDS.

Ground Truth

The ground truth correction, as with any strict ground truth correction, relies on a fundamental assumption that the reference standard being used is directly representative of the materials observed in the remotely-sensed dataset. For the ground truth correction derived for the M^3 dataset, the specific assumption made is that the reference standard spectrum (derived from laboratory reflectance measurements of mature feldspathic highlands soil 62231) is directly representative of the average mature feldspathic highlands materials covered in the geographic regions used to define the average M^3 spectrum used in deriving the correction. This assumption implies that the single laboratory reference standard spectrum is representative of relatively large geographic areas (typically hundreds of pixels, with each pixel representing over 100 m^2. Issues such as spatial resolution are discussed by Clark et al. [2002].

The ground truth correction also addresses the variable instrument performance correlated with operating temperatures, as discussed above under calibration of the Level 1B dataset ("Smooth Shape Correction"). However, as discussed above, the variable instrument performance was observed to vary "continuously" with operational temperature (i.e., the variation was gradual rather than a binary "either-or" case), necessitating the use of a range of correction factors with a temperature sampling of 0.1 K. However, such an approach is not feasible for the ground truth correction, and only two factors were derived – one each for cold and warm operational conditions as described above. Thus, the ground truth correction can only correct such condition-dependent effects on average, and cannot address effects at precise operational conditions.

As discussed above, the ground truth correction was derived only for wavelengths below ~1500 nm; it is set to 1.0 above this wavelength. This was done due to residual differences between M^3 data collected under various instrument and spacecraft operational conditions. The ground truth correction, as demonstrated by the plots in the ground truth section above, does introduce changes in band strength and shape, based on knowledge of the properties of lunar materials from laboratory analyses. The adjustments are mild and should not affect strong absorption features present in immature materials. The adjustments will be most apparent for weak features found in lunar soils. The M^3 team has concluded that the Level 2 product with the ground truth correction included represents the best-available true reflectance product from the M^3 observations, especially for wavelengths below ~1500 nm. However, as the correction

only treats wavelengths below ~1500 nm, individual users must decide if the ground truth correction is appropriate for their specific investigation, particularly if analyzing regional band strengths in mature areas or if evaluating relative band strengths between the 1000 and 2000 nm regions. As such, the correction factors have NOT been applied to the delivered Level 2 data, but are provided as calibration files for individual users to apply to the dataset on an as-needed basis.

2.5.5. Data Flow

Downlinked M^3 science data and spacecraft navigation data were retrieved by the IGDS at JPL from the International Space Science Data Center (ISSDC) in Bangalore, India. Upon ingestion into the system, the raw science data and navigation data were processed to Level 1B through the Operations Pipeline on a weekly basis (non-real time). Level 1B data products were then forwarded to UMD/ACT for generation of Level 2 data products. After validation, M^3 data products were transferred to the PDS Imaging Node for archiving and distributing. Appendix F contains an overview of M^3 science data flow.

Ground data including calibration files were delivered ("safed") to the PDS on 19 August 2009. For flight data, Level 0 and Level 1B data products were delivered to the PDS at 6-month intervals. The first delivery occurred in June 2010 and consisted of Level 0 and Level 1B data acquired during Optical Period 1 (version 1.0, volume CH1M3_0001). The second delivery occurred in December 2010 and consisted of Level 0 and Level 1B data acquired during Optical Period 2 (version 1.0, volume CH1M3_0001). In September 2011, the Level 1B calibration was improved, and all Level 1B data were redelivered to PDS as version 2.0 in one final volume (CH1M3_0003). A separate, final M^3 archive volume (CH1M3_0004) for all Level 2 data products (derived from Level 1B, version 2.0) was delivered to the PDS in November 2011. Delivery media consisted of external hard drives.

2.5.6. Labeling and Identification

Level 0, Level 1B, and Level 2 data products represent M^3 standard products. Each M^3 data product is stored in a single file and has the following naming convention:

M3GYYYYMMDDTHHMMSS_VNN_PT.EXT

Or

M3TYYYYMMDDTHHMMSS_VNN_PT.EXT

M3:	The instrument.
G or T:	The imaging mode; G for global mode and T for target mode.
YYYY:	The year of the time stamp from the first image frame of the image cube.
MM:	The month of the time stamp from the first image frame of the image cube.

DD: The day of the time stamp from the first frame of the image cube.

T: A single character string that precedes the UTC time of the time stamp from the first frame of the image cube.

HH: The hour in UTC of the time stamp from the first frame of the image cube.

MM: The minute within the hour in UTC of the time stamp from the first frame of the image cube.

SS: The second within the minute in UTC of the time stamp from the first frame of the image cube.

VNN: The version number of the product.

PT: The type of data product:

L0 = Level 0

L1B = Level 1B

L2 = Level 2

RDN = Spectral Radiance data (Level 1B)

LOC = Pixel-located data (Level 1B)

OBS = Observation geometry data (Level 1B)

TIM = Observation timing data (Level 1B)

RFL = Spectral Reflectance data (Level 2)

SUP = Supplementary data for Reflectance product (Level 2)

EXT: The file name extension:

IMG = Image object

HDR = Detached header file

LBL = Detached label file

TXT = ASCII text file

TAB = ASCII data table

All fields must occupy the allotted number of characters. Thus, if fewer digits are required to express a number than are allotted, the convention fills the unneeded spaces with leading zeroes.

2.6. Standards Used in Generating Data Products

2.6.1. PDS Standards

The M^3 data product complies with the PDS standards for file formats and labels, specifically the PDS image and table data objects. File names follow the ISO 9660 Level 2 convention and are no longer than 27.3 characters.

2.6.2. Time Standards

Two time standards are used in M^3 data products:

- Spacecraft time in seconds (PDS keywords SPACECRAFT_CLOCK_START_-COUNT and SPACECRAFT_CLOCK_STOP_COUNT)
- UTC (PDS label keywords START_TIME, STOP_TIME, and PRODUCT_CREATION_TIME)

2.6.3. Coordinate Systems

The coordinate system used is the new "Standardized Lunar Coordinate System for the Lunar Reconnaissance Orbiter" (LRO Working Group, 2008). This new lunar coordinate system has been adopted as an international standard and greatly facilitates the direct integration of data from multiple missions and among international partners. The coordinate system is based on lunar planetocentric coordinates in the Mean Earth/Polar Axis (ME) reference frame. The z-axis is the mean axis of rotation with the positive direction pointing north. The x-axis is the intersection of the Equator and Prime Meridian, as defined by the mean Earth direction. The y-axis completes the frame in a right-handed sense and points in the direction of +90 degrees longitude. Latitude ranges from +90 to -90 form the North Pole to the South Pole. Longitude will be reported as 0 to 360 degrees increasing to the East.

2.7. Data Validation

Basic data validation is performed at the IGDS for M^3 Level 0 – Level 1B data products and at ACT/UMD for M^3 Level 2 data products and consists of the following:

- IGDS and ACT/UMD team members check the data products for conformance to this document and the Archive Volume SIS, and for valid science content.
- Generation of data products and volumes, together with validation are completed within the required validation period of six months from the availability of processing input data.
- Prior to delivery of the products, PDS representatives and other interested parties review a sample product set generated by the IGDS and ACT/UMD and may request changes to the data product set as necessary.

3. Detailed Data Product Specifications

3.1. M^3 Level 0 Data Products

3.1.1. Data Product Structure and Organization

3.1.1.1. L0 Image Cube File Format Overview

M^3 captures data in image frames. Each image frame consists of a 1280 byte image frame header, followed by image data. The format of the image data depends on the instrument mode (global/target - see Table 2-4 for details) at the time the data was collected.

3.1.1.2. Image Frame Header

The image frame header is 1280 bytes long. The first 640 bytes of data in the frame header are zero values. The second 640 bytes of data contain 22 bytes of raw binary data. These 22 bytes contain the raw time information from the CCSDS header for the particular image frame. The raw time data in M^3 L0 data are stored in three fields comprised of 6, 8 and 8 bytes respectively. These three fields carry the 22 bytes of raw data that record the CH-1 clock tick at the once-per-minute synch mark, the M^3 clock tick at the once-per-minute synch mark and the M3 clock tick at the image frame time. The first two values are used to develop the CH-1 clock to M^3 clock regression in the Level 1B processing. The third value is used to time tag each image frame in M^3 ticks, then CH-1 ticks via the regression and finally in real time via the clock kernel that is built from raw on-board-time versus Earth-received time data provided by ISRO. The clock kernel (*.TSC) is located in the GEOMETRY directory.

An overview of the M^3 image frame header format is included in Table 3-1. See Appendix A for a detailed description of the formatting and conversion of the 22 bytes of timing data into the three clock tick values.

Table 3-1 Image Frame Header

Field Number	Title	Start Char	Stop Char	Description	Format
1	Unused	0	639	Unused	Blank, zero values
2	S/C-at-mark	640	645	Provides the tick count of the Chandrayaan-1 clock at the most recent once-per-minute synchronization pulse between spacecraft clock and M^3 instrument clock.	6-byte long float in MIL-STD-1750a format

Field Number	Title	Start Char	Stop Char	Description	Format
3	M3-RTC-at-mark	646	653	Provides the tick count of the M^3 clock at the most recent once-per-minute synchronization pulse between spacecraft clock and M^3 instrument clock.	8-byte float in a native M^3 time format
4	M3-RTC-at-frame-sync	654	661	Provides the tick count of the M^3 clock at the image frame (line) time.	8-byte float in a native M^3 time format
5	Unused	662	1279	Unused	Blank, zero values

The per-image optimized calculation used in the Level 1B processing yields the most accurate frame times and are captured in the Observation Timing File products (*TIM.TAB and *TIM.LBL).

The L0 multiple-band image cube has dimensions of sample, line, and channel, where the first channel of each image frame contains the image frame header. This is illustrated in Figure 3-1 and Figure 3-2. The M^3 image cube's size and format depends on the observation mode (global/target).

Figure 3-1. Contents of an M³ L0 Image Cube File

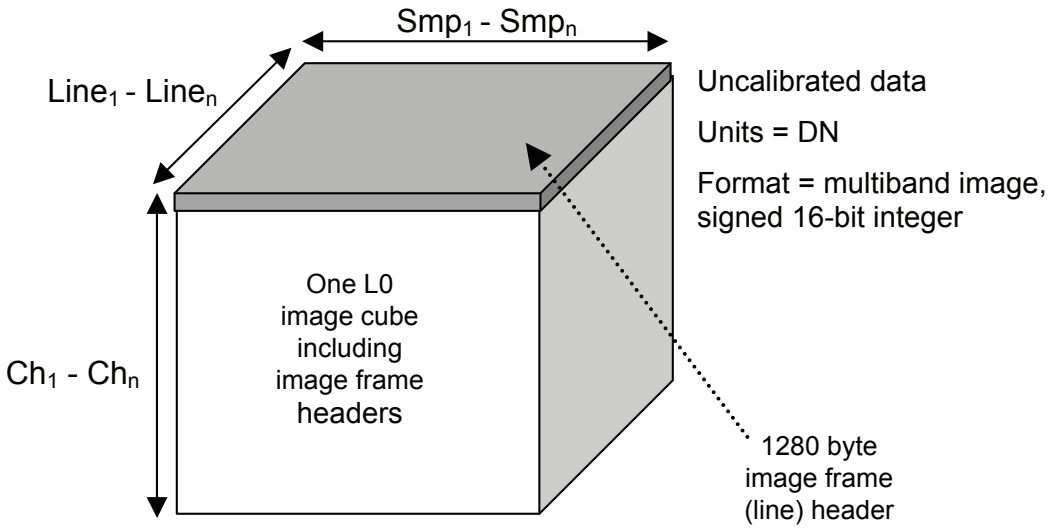


Figure 3-2. Illustration of a Single M³ L0 Image Frame (Line)

Spatial Samples

Spectral Channels	1	2	…	Ch_1, Smp_n
1				
2	Ch_2, Smp_1	Ch_2, Smp_2	…	Ch_2, Smp_n
.			.	
.			.	
.			.	
n	Ch_n, Smp_1	Ch_n, Smp_2	…	Ch_n, Smp_n

1280 bytes of Image Frame Header

3.1.1.3. L0 Image Cube Format

The format of the M^3 L0 image cube depends on the instrument mode at the time the data was taken. During the transmission and encoding/decoding of the data, some data elements may be lost. Data lost to poor compression or complete packet loss are noted in the *.LOG files located in the EXTRAS directory.

3.1.1.3.1. Target Mode

In target mode, the image cube has the following characteristics:

16-bit signed integer

Little endian

260 spectral channels [Ch]

640 spatial samples [Smp]

N image lines

Band interleaved by line

640 16-bit word image line header [H]

In the line by line file summary below, Ch_xSmp_y identifies a 16-bit signed integer in little endian format.

Ch_1 contains the shortest wavelength and C_{260} contains the longest wavelength.

Smp_1 is located at the left-hand side of the image and Smp_{640} is located at the right-hand side of the image.

$LINE_1$ [H_1…H_{1280}-Ch_1Smp_1…Ch_1Smp_{640}-Ch_2Smp_1…Ch_2Smp_{640}-
$Ch_{260}Smp_1$…$Ch_{260}Smp_{640}$]

.

.

.

$LINE_N$ [H_1…H_{1280}-Ch_1Smp_1…Ch_1Smp_{640}-Ch_2Smp_1…Ch_2Smp_{640}-
$Ch_{260}Smp_1$…$Ch_{260}Smp_{640}$]

3.1.1.3.2. Global Mode

In global mode, the image cube has the following characteristics:

16-bit signed integer

Little endian

86 spectral channels

320 spatial samples

N image lines

Band interleaved by line

640 16-bit word image line header

In the line by line file summary below, Ch_xSmp_y identifies a 16-bit signed integer in little endian format.

Ch_1 contains the shortest wavelength and Ch_{86} contains the longest wavelength.

Smp_1 is located at the left-hand side of the image and Smp_{320} is located at the right-hand side of the image.

$LINE_1$ [H_1…H_{1280}-Ch_1Smp_1…Ch_1Smp_{320}-Ch_2Smp_1…Ch_2Smp_{320}-
$Ch_{86}Smp_1$…$Ch_{86}Smp_{320}$]

.

.

.

$LINE_N$ [H_1…H_{1280}-Ch_1Smp_1…Ch_1Smp_{320}-Ch_2Smp_1…Ch_2Smp_{320}-
$Ch_{86}Smp_1$…$Ch_{86}Smp_{320}$]

3.1.1.4. L0 Detached Header File Format

Each L0 image cube file will be accompanied by a detached header file. A detached header provides compatibility with ENVI (version 4.4) software. The header file is a separate ASCII text file that contains information ENVI uses to read an image data file. The header file provides the following information:

- The dimensions of the image
- The embedded header, if present
- The data format
- Other pertinent information

The detached header file will include the following text (see Table 3-3 for a description of the fields):

3.1.1.4.1. Target Mode

```
ENVI
description = {}
samples = 640
```

```
lines = N*
bands = 260
header offset = 0
major frame offsets = {1280, 0}
file type = ENVI
data type = 2
interleave = bil
byte order = 0
```

**N equals the number of image lines of the output file.*

3.1.1.4.2. Global Mode

```
ENVI
description = {}
samples = 320
lines = N*
bands = 86
header offset = 0
major frame offsets = {1280, 0}
file type = ENVI
data type = 2
interleave = bil
byte order = 0
```

**N equals the number of image lines of the output file*

Table 3-3 Detached ASCII Header Details

Field	Description
`description`	A character string describing the image or the processing performed.
`samples`	The number of samples (pixels) per image line for each band.
`lines`	The number of lines per image for each band.
`bands`	The number of bands per image file.
`header offset`	The number of bytes of embedded header information present in the file. ENVI skips these bytes when reading the file.
`major frame offsets`	The number of extra bytes to skip at the beginning and ending of the major frame.

Field	Description
file type	The ENVI-defined file type, such as a certain data format and processing result.
data type	The type of data representation, where 1=8-bit byte; 2=16-bit signed integer; 3=32-bit signed long integer; 4=32-bit floating point; 5=64-bit double-precision floating point; 6=2x32-bit complex, real-imaginary pair of double precision; 9=2x64-bit double-precision complex, real-imaginary pair of double precision; 12=16-bit unsigned integer; 13=32-bit unsigned long integer; 14=64-bit signed long integer; and 15=64-bit unsigned long integer.
interleave	Refers to whether the data are formatted as Band Sequential (BSQ), Band Interleaved by Pixel (BIP), or Band Interleaved By Line (BIL).
byte order	The order of the bytes in integer, long integer, 64-bit integer, unsigned 64-bit integer, floating point, double precision, and complex data types. Use one of the following: • Byte order=0 (Host (Intel**)** in the Header Info dialog) is least significant byte first (LSF) data (DEC and MS-DOS systems). • Byte order=1 (Network (IEEE**)** in the Header Info dialog) is most significant byte first (MSF) data (all other platforms).
wavelength units	Text string indicating the wavelength units.
wavelength	Lists the center wavelength values of each band in an image. Units should be the same as those used for the fwhm field (described next) and set in the wavelength unit's parameter.
fwhm	Lists full-width-half-maximum (FWHM) values of each band in an image. Units should be the same as those used for wavelength and set in the wavelength unit's parameter.
band names	Allows entry of specific names for each band of an image.
bbl	Lists the ENVI display flag for each band in the image; a value of 1 instructs ENVI to display that band and 0 causes ENVI to ignore it.

3.1.1.5. L0 Label Description

Each M^3 L0 data product is described by a PDS label stored in a separate text file with an extension ".LBL." A PDS label is object-oriented and describes objects in the data file. The PDS label contains keywords for product identification, along with descriptive information needed to interpret or process the data objects in the file.

PDS labels are written in Object Description Language (ODL). PDS label statements have the form of "keyword = value." Each label statement is terminated with a carriage return character (ASCII 123) and a line feed character (ASCII 10) sequence to allow the label to be read by many operating systems. Pointer statements with the following format are used to indicate the location of data objects:

^object = location

where the carat character (^, also called a pointer) is followed by the name of the specific data object. The location is the name of the file that contains the data object.

The M^3 L0 label is a combined-detached label that describes both the image and detached header file that make up a M^3 L0 data product. An example L0 label is in Appendix B.

3.2. M^3 Level 1B Data Products

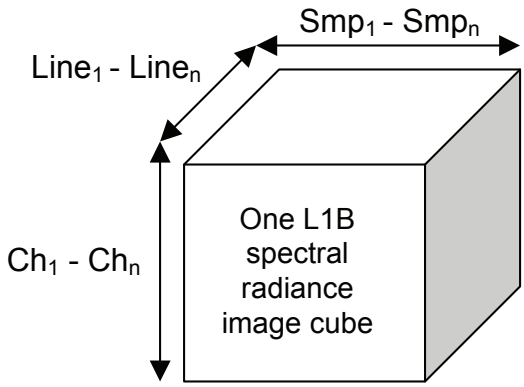
3.2.1. Data Product Structure and Organization

3.2.1.1. L1B Spectral Radiance Image Cube File Format Overview

The L1B multiple-band spectral radiance image cube has dimensions of sample, line, and channel (see section 2.4.3.1 for details regarding conversion to spectral radiance). This is illustrated in Figure 3-3 and Figure 3-4. The M^3 spectral radiance image cube's size and format depends on the observation mode (global/target - see Table 2-4 for details).

All M^3 Level 1B products are standardized to remove the different effects of the four possible orbit limb and flight yaw mode combinations: descending/forward; descending/reverse; ascending/forward and ascending/reverse. In ascending limb data the lines/times are reversed, so all Level 1B images have the northernmost image line first. In descending/reverse and ascending/forward modes the samples are reversed, so the first sample is on the west side of the image and do not appear left-right mirrored. In descending/forward no changes in lines or samples are performed; this is the only case that matches the Level 0 data. Refer to the ORBIT_LIMB_DIRECTION and SPACECRAFT_YAW_DIRECTION keywords in the PDS label (*_L1B.LBL – See Appendix B for more details) to reconcile a specific Level 1B image product with the associated Level 0 data.

Figure 3-3. Contents of an M^3 L1B Spectral Radiance Image Cube File



Calibrated at-sensor radiance data

Units = W/(m^2 um sr)

Format = multiband image, 4-byte, floating point

Figure 3-4. Illustration of a Single M^3 L1B Spectral Radiance Image Frame (Line)

Spatial Samples

	1	2	…	Smp_n
1	Ch_1, Smp_1	Ch_1, Smp_1	…	Ch_1, Smp_n
.			.	
.			.	
.			.	
n	Ch_n, Smp_1	Ch_n, Smp_1	…	Ch_n, Smp_n

Spectral Channels

3.2.1.2. L1B Spectral Radiance Image Cube Format

The format of the M^3 Level 1B spectral radiance image cube depends on the instrument mode at the time the data was taken. During the transmission and encoding/decoding

of the data, some data elements may be lost. Data lost to poor compression or complete packet loss are noted in the *.LOG files located in the EXTRAS directory.

3.2.1.2.1. Target Mode

In target mode, the spectral radiance image cube has the following characteristics:

32-bit floating point

Little endian

256 spectral channels [Ch]

608 spatial samples [Smp]

N image lines

Band interleaved by line

In the line by line file summary below, Ch_xSmp_y identifies a 32-bit signed floating point in little endian format.

Ch_1 contains the shortest wavelength and C_{256} contains the longest wavelength.

Smp_1 is located at the left-hand side of the image and Smp_{608} is located at the right-hand side of the image.

$LINE_1$ [Ch_1Smp_1…Ch_1Smp_{608}-Ch_2Smp_1…Ch_2Smp_{608}-$Ch_{256}Smp_1$…$Ch_{256}Smp_{608}$]

.

.

.

$LINE_N$ [Ch_1Smp_1…Ch_1Smp_{608}-Ch_2Smp_1…Ch_2Smp_{608}-$Ch_{256}Smp_1$…$Ch_{256}Smp_{608}$]

3.2.1.2.2. Global Mode

In global mode, the spectral radiance image cube has the following characteristics:

32-bit floating point

Little endian

85 spectral channels

304 spatial samples

N image lines

Band interleaved by line

In the line by line file summary below, Ch_xSmp_y identifies a 32-bit floating point in little endian format.

Ch_1 contains the shortest wavelength and Ch_{85} contains the longest wavelength.

Smp_1 is located at the left-hand side of the image and Smp_{304} is located at the right-hand side of the image.

$LINE_1$ [Ch_1Smp_1…Ch_1Smp_{304}-Ch_2Smp_1…Ch_2Smp_{304}-$Ch_{85}Smp_1$…$Ch_{85}Smp_{304}$]

.

.

.

$LINE_N$ [Ch_1Smp_1…Ch_1Smp_{304}-Ch_2Smp_1…Ch_2Smp_{304}-$Ch_{85}Smp_1$…$Ch_{85}Smp_{304}$]

3.2.1.3. L1B Spectral Radiance Image Cube Detached Header File Format

Each L1B spectral radiance image cube file will be accompanied by a detached header file. A detached header provides compatibility with ENVI (version 4.4) software. The header file is a separate ASCII text file that contains information ENVI uses to read an image data file.

The header file provides the following information:

- The dimensions of the image
- The embedded header, if present
- The data format
- Other pertinent information

The detached header file will include the following text (see Table 3-3 for a description of the fields):

3.2.1.3.1. Target Mode

```
ENVI
description = {}
samples = 608
lines = N*
bands = 256
header offset = 0
file type = ENVI
data type = 4
interleave = bil
byte order = 0
wavelength = {}
fwhm = {}
```

**N equals the number of image lines of the output file.*

3.2.1.3.2. Global Mode

```
ENVI
description = {}
samples = 304
lines = N*
bands = 85
header offset = 0
file type = ENVI
data type = 4
interleave = bil
byte order = 0
wavelength = {}
fwhm = {}
```

**N equals the number of image lines of the output file*

3.2.1.4. Level 1B Spectral Radiance Image Cube Label Description

A spectral radiance image cube label (*_L1B.LBL) is detached and points to the following L1B data products:

- the single multi-band image (*_RDN.IMG) and its respective detached header file (*_RDN.HDR),
- the pixel location data (*_LOC.IMG) and its respective detached header file (*_LOC.HDR),
- the observation geometry data (*_OBS.IMG) and its respective detached header file (*_OBS.HDR),
- the UTC timing data (*_TIM.TAB)

An example Level 1B spectral radiance image cube label is located in Appendix B.

3.2.1.5. Pixel Location File Format

The pixel location data for each image are stored in a three-band, band-interleaved-by-line, binary file of double precision 8-byte values, in little-endian byte order. The three bands of the file, in order, are as follows:

4) longitude (reported in decimal degrees)
5) planetocentric latitude (reported in decimal degrees)
6) radius (reported in meters from the Moon center)

There are no embedded headers or other data in the file. Each location file will be accompanied by a detached header file. A detached header provides compatibility with ENVI software. The location file is, in essence, a three-band set of “detached backplanes” that match the sample and line spatial extent of the spectral radiance

image cube data. No map correction or resampling is applied to the radiance image cube; the file only reports the surface locations of the unadjusted pixel centers.

3.2.1.6. Pixel Location Detached Header File Format

Each location image cube file will be accompanied by a detached header file. A detached header provides compatibility with ENVI software. The header file is a separate ASCII text file that contains information ENVI uses to read an image data file.

The header file provides the following information:
- The dimensions of the image
- The embedded header, if present
- The data format
- Other pertinent information

The detached header file will include the following text (see Table 3-3 for a description of the fields):

3.2.1.6.1. Target Mode

```
ENVI
description = {}
samples = 608
lines = N*
bands = 3
header offset = 0
file type = ENVI
data type = 5
interleave = bil
byte order = 0
wavelength units = Unknown
band names = {longitude (deg), latitude (deg), radius (m)}
```

**N equals the number of image lines of the output file.*

3.2.1.6.2. Global Mode

```
ENVI
description = {}
samples = 304
lines = N*
bands = 3
header offset = 0
file type = ENVI
data type = 5
interleave = bil
byte order = 0
wavelength units = Unknown
band names = {longitude (deg), latitude (deg), radius (m)}
```

N equals the number of image lines of the output file.

3.2.1.7. Observation Geometry File Format

The observation geometry data for each image are provided in a ten-band, band-interleaved-by-line, binary file of single precision 4-byte values, in little-endian byte order. The ten bands of the file, in order, are as follows:

I) to-sun azimuth angle (decimal degrees, clockwise from local north)

II) to-sun zenith angle (decimal degrees, zero at zenith)

III) to-sensor azimuth angle (decimal degrees, clockwise from local north)

IV) to-sensor zenith angle (decimal degrees, zero at zenith)

V) observation phase angle (decimal degrees, in plane of to-sun and to-sensor rays)

VI) to-sun path length (decimal au with scene mean subtracted and noted in PDS label)

VII) to-sensor path length (decimal meters)

VIII) surface slope from DEM (decimal degrees, zero at horizontal)

IX) surface aspect from DEM (decimal degrees, clockwise from local north)

X) local cosine i (unitless, cosine of angle between to-sun and local DEM facet normal vectors)

Similar to the location data, these files are, in essence, ten-band set of “detached backplanes” that match the sample and line spatial extent of the spectral radiance image cube data. No map correction or resampling is applied to the radiance image cube; the file only reports the observation parameters of the unadjusted pixel centers.

3.2.1.8. Observation Geometry Detached Header File Format

Each observation geometry data file will be accompanied by a detached header file. A detached header provides compatibility with ENVI software.

The detached header file is an ASCII file will include the following text:

3.2.1.8.1. Target Mode

```
ENVI
description = {
M3 Level 1B Observation Parameters (scene mean To-Sun Path
Length subtracted from Band 6 (au):1.013437249601 IAU au defined
as 149597870691 meters}
samples = 608
```

```
lines = N*
bands = 10
header offset = 0
file type = ENVI Standard
data type = 4
interleave = bil
byte order = 0
wavelength units = Unknown
band names = {
To-Sun Azimuth (deg), To-Sun Zenith (deg), To-M3 Azimuth(deg),
To-M3 Zenith (deg), Phase (deg), To-Sun Path Length (au-
1.013437249601), To-M3 Path Length (m), Facet Slope (deg), Facet
Aspect (deg), Facet Cos(i) (unitless)}
```

**N equals the number of image lines of the output file.*

3.2.1.8.2. Global Mode

```
ENVI
description = {
M3 Level 1B Observation Parameters (scene mean To-Sun Path
Length subtracted from Band 6 (au):1.013437249601 IAU au defined
as 149597870691 meters)}
samples = 304
lines = N*
bands = 10
header offset = 0
file type = ENVI Standard
data type = 4
interleave = bil
byte order = 0
wavelength units = Unknown
band names = {
To-Sun Azimuth (deg), To-Sun Zenith (deg), To-M3 Azimuth(deg),
To-M3 Zenith (deg), Phase (deg), To-Sun Path Length (au-
1.013437249601), To-M3 Path Length (m), Facet Slope (deg), Facet
Aspect (deg), Facet Cos(i) (unitless)}
```

**N equals the number of image lines of the output file.*

3.2.1.9. Observation Timing File Format

The timing file (*TIM.TAB) is an ASCII file with four columns of data. The first column lists the line number of the multiple-band spectral radiance image cube (*RDN.IMG). The second column lists the corresponding UTC time for the middle of the integration period for each spectral radiance image cube line or major frame of the data and is expressed as:

YYYY-MM-DDTHH:MM:SS.SSSSSS.

The third column lists Year reference of Decimal Day of Year (DDOY) as extracted from the earliest time of each spectral radiance image cube line expressed as: YYYY.

The fourth column lists DDOY that represents the number of days elapsed since 00:00 UTC of January 1 of the year associated with the time stamp of the first image line. The DDOY format is as follows: DDD.ddddddddddd where DDD represents the integer number of days and ddddddddddd represent the fractional part of the day of year value.

Note that the times listed in the timing file may differ from those reported in the L0 image frame header. See Section 3.1.1.2 for details.

3.3. M^3 Level 2 Data Products

3.3.1. Data Product Structure and Organization

3.3.1.1. Level 2 Spectral Reflectance Product and Label Description

A Level 2 spectral reflectance product consists of a detached label (*_L2.LBL) that points to the following Level 2 data files:

- the single multi-band reflectance image (*_RFL.IMG) and its respective ENVI header file (*_RFL.HDR),
- the supplementary data file for the reflectance image (*_SUP.IMG) and its respective ENVI header file (*_SUP.HDR).

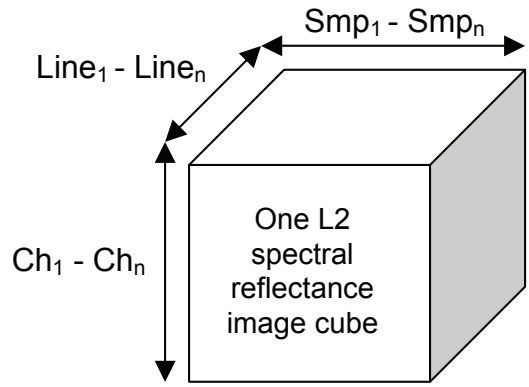
Example Level 2 spectral radiance product label is in Appendix D. For pixel locations, observational geometry, and timing information, users must refer to the L1B data products.

3.3.1.2. L2 Spectral Reflectance Image Cube File Format Overview

The L2 multiple-band spectral reflectance image cube (*_RFL.IMG) has the same dimensions of sample, line, and channel as the Level 1B spectral radiance image cube from which it was derived. This is illustrated in Figures 3-5 and 3-6. As with Level 1B, the size and format of the M^3 spectral reflectance image cube depends on the observation (global/target – see Table 2-4 for details).

Because Level 2 products are generated from Level 1B, these reflectance data are inherently standardized to remove the different effects of the four possible orbit limb and flight yaw mode combinations: descending/forward; descending/reverse; ascending/forward and ascending/reverse. In ascending limb data the lines/times are reversed, so all Level 2 images have the northernmost image line first. In descending/reverse and ascending/forward modes the samples are reversed, so the first sample is on the west side of the image and do not appear left-right mirrored. In descending/forward no changes in lines or samples are performed; this is the only case that matches the Level 0 data. Refer to the ORBIT_LIMB_DIRECTION and SPACECRAFT_YAW_DIRECTION keywords in the PDS label (*_L2.LBL - See Appendix D for more details) to reconcile a specific Level 2 image product with the associated Level 0 data.

Figure 3-5. Contents of an M^3 L2 Spectral Reflectance Image Cube File



Calibrated at-sensor reflectance data

Unitless

Format = multiband image, 4-byte floating point numbers from 0 to 1 where 1.0 represents 100% reflectance. A value of -999.0 flags degraded channels or pixels could not be calibrated to reflectance.

Figure 3-6. Illustration of a Single M^3 L2 Spectral Reflectance Image Frame (Line)

Spatial Samples

Spectral Channels	1	2	…	Smp_n
1	Ch_1, Smp_1	Ch_1, Smp_1	…	Ch_1, Smp_n
.			.	
.			.	
.			.	
n	Ch_n, Smp_1	Ch_n, Smp_1	…	Ch_n, Smp_n

3.3.1.3. L2 Spectral Reflectance Image Cube Format

As with a Level 1B product, the format of the M^3 Level 2 spectral reflectance image cube depends on the instrument mode (global/target - see Table 2-4 for details) at the time the data was taken.

3.3.1.3.1. Target Mode

In target mode, the spectral reflectance image cube has the following characteristics:

32-bit floating point numbers where 1.0 represents 100% reflectance

Little endian

256 spectral channels [Ch]

608 spatial samples [Smp]

N image lines

Band interleaved by line

In the line by line file summary below, Ch_xSmp_y identifies a 32-bit floating point numbers in little endian format.

Ch_1 contains the shortest wavelength and C_{259} contains the longest wavelength.

Smp_1 is located at the left-hand side of the image and Smp_{608} is located at the right-hand side of the image.

$LINE_1$ [Ch_1Smp_1…Ch_1Smp_{608}-Ch_2Smp_1…Ch_2Smp_{608}-$Ch_{256}Smp_1$…$Ch_{256}Smp_{608}$]

.

.

.

$LINE_N$ [Ch_1Smp_1…Ch_1Smp_{608}-Ch_2Smp_1…Ch_2Smp_{608}-$Ch_{256}Smp_1$…$Ch_{256}Smp_{608}$]

3.3.1.3.2. Global Mode

In global mode, the spectral reflectance image cube has the following characteristics:

32-bit floating point numbers where 1.0 represents 100% reflectance Little endian

85 spectral channels

304 spatial samples

N image lines

Band interleaved by line

In the line by line file summary below, Ch_xSmp_y identifies a 32-bit floating point numbers in little endian format.

Ch_1 contains the shortest wavelength and Ch_{85} contains the longest wavelength.

Smp_1 is located at the left-hand side of the image and Smp_{304} is located at the right-hand side of the image.

$LINE_1$ [Ch_1Smp_1…Ch_1Smp_{304}-Ch_2Smp_1…Ch_2Smp_{304}-$Ch_{85}Smp_1$…$Ch_{85}Smp_{304}$]

.

.

.

$LINE_N$ [Ch_1Smp_1…Ch_1Smp_{304}-Ch_2Smp_1…Ch_2Smp_{304}-$Ch_{85}Smp_1$…$Ch_{85}Smp_{304}$]

3.3.1.4. L2 Spectral Reflectance Image Cube Detached Header File Format

Each L2 spectral reflectance image cube file (*_RFL.HDR) will be accompanied by a detached header file. A detached header provides compatibility with ENVI (version 4.4) software. The header file is a separate ASCII text file that contains information ENVI uses to read an image data file.

The header file provides the following information:

- The dimensions of the image
- The embedded header, if present
- The data format
- Other pertinent information such as a bad bands list (bbl)

The detached header file will include the following text (see Table 3-3 for a description of the fields):

3.3.1.4.1. Target Mode

```
ENVI
description = {}
samples = 608
lines = N*
bands = 256
header offset = 0
file type = ENVI
data type = 4
interleave = bil
byte order = 0
wavelength = {}
fwhm = {}
bbl = {}
```

**N equals the number of image lines of the output file.*

3.3.1.4.2. Global Mode

```
ENVI
description = {}
samples = 304
lines = N*
bands = 85
header offset = 0
file type = ENVI
data type = 4
interleave = bil
byte order = 0
wavelength = {}
fwhm = {}
bbl = {}
```

**N equals the number of image lines of the output file.*

3.3.1.5. Reflectance Supplemental File Format

The supplementary data for each reflectance image are provided in a three-band, band-interleaved-by-line, binary file (*_SUP.IMG) of single precision 4-byte values, in little-endian byte order. The three bands or images in this file, in order, are:

1. A single band (at 1489 nm) 2-dimensional reflectance image that is photometrically corrected relative to a sphere is stored as the first image. This product corrects broad latitudinal variations, but retains the effects of topography (including shadows and gradients) and features are readily recognized at the scale of the measurement. A stored value of 1.0, unitless, represents 100% reflectance
2. A thermal map of the scene as estimated by the Level 2 thermal correction process where the stored temperatures are in units of Kelvin.
3. The longest wavelength band of the Level 1B radiance image (*RDN.IMG) that is scientifically useful. This band contains both reflected solar and thermal emitted components and is highly sensitive to local topography. The L1B radiance band number 84 is stored for global mode; band number 253 is stored for target mode. None of the Level 2 steps is applied to this supplemental radiance band, and units are L1B at-sensor radiance of W/(m^2 μm sr) per pixel.

Each image in a *_SUP.IMG file matches the sample and line spatial extent of the spectral reflectance image cube data (*_RFL.IMG).

3.3.1.6. Reflectance Supplemental Detached Header File Format

Each reflectance supplemental data file is accompanied by a detached header file (*_SUP.HDR). A detached header provides compatibility with ENVI software.

The detached header file is an ASCII file and includes the following text:

3.3.1.6.1. Target Mode

```
ENVI
samples = 608
lines   = N*
bands   = 3
header offset = 0
file type = ENVI Standard
data type = 4
interleave = bil
byte order = 0
band names = {
 1489 RFL with PHOTOM RELATIVE TO SPHERE (reflectance),
 ESTIMATED SURFACE TEMPERATURE (degK),
 RDN BAND 253 (radiance)
}
```

**N equals the number of image lines of the output file.*

3.3.1.6.2. Global Mode

```
ENVI
samples = 304
lines   = 28289
bands   = 3
header offset = 0
file type = ENVI Standard
data type = 4
interleave = bil
byte order = 0
band names = {
 1489 RFL with PHOTOM RELATIVE TO SPHERE (reflectance),
 ESTIMATED SURFACE TEMPERATURE (degK),
 RDN BAND 84  (radiance)
}
```

**N equals the number of image lines of the output file*

4. Applicable Software

4.1. Utility Programs

The M^3 team uses the commercial software packages ENVI and IDL to display and analyze M^3 data products. ENVI and IDL are distributed by ITT Visual Information Solutions (VIS) and are available at http://www.ittvis.com/. ITT VIS no longer provides a free tool, ENVI Freelook, which allows for basic image viewing. However free version of ENVI Freelook maybe be available at http://software.geocomm.com/viewers/raster/. Also the commercial package ACT-REACT, distributed by Applied Coherent

Technologies Corporation (http://www.actgate.com), can be used to display and analyze M^3 data products.

In addition, PDS' NASAView Image Display Software can also be used for basic image viewing of M^3 L1B data products: http://pds.nasa.gov/tools/nasa-view.shtml.

Nevertheless, the data do not have a proprietary format. Instead they are arranged as simply and as openly as possible. The provision of both ENVI and PDS labels will guarantee the data will be readily accessible to the widest possible audience.

4.2. Applicable PDS Software Tools

The M^3 team uses no PDS software to view, manipulate or process the data. However, the images are stored and labeled using the PDS IMAGE standard structure and any tool that understands that structure should be able to view them.

Appendix A Detailed Description of Format and Usage of M^3 Raw Time Data

This text describes how the 22 bytes of timing data are formatted and can be converted into the three clock tick values.

The 22 bytes of raw clock data are embedded in consecutive bytes of the 1280-byte prefix that precedes each M^3 image frame in the L0 data images. The 22 bytes start at byte 641 (using 1-based indexing, i.e. 1 to 1280) in each frame prefix. All other bytes in the 1280-byte frame prefixes are zero values.

A detailed example is given below where the 22 bytes of raw timing data are: `112, 199, 165, 30, 116, 78, 0, 0, 251, 154, 2, 228, 65, 110, 0, 0, 251, 156, 3, 140, 8, 44.`

I) CH-1 Clock Ticks at Sync Mark

The first six bytes are the raw CH-1 clock tick at the most recent once-per-minute sync pulse, encoded in MIL-STD-1750a Extended Precision Float format. These are bytes `641-646` of the 1280-byte frame prefix.

Bytes `1, 2, 3` are the most significant part of the mantissa in 2's-complement format.

Byte `4` is the 2's-complement format exponent.

Bytes `5, 6` are the least significant portion of the mantissa in 2's-complement format.

A detailed example of building the value follows for a six-byte set of values of `112, 199, 165, 30, 116` and `78`, in order. Since we expect only positive values for the mantissa and exponent, bytes `1` and `4` should never exceed `127`.

```
The mantissa is built from bytes 1, 2, 3, 5, 6 in order of most significant to least significant.

The exponent is byte 4.

Mantissa = (112 * 2^32 + 199 * 2^24 + 165 * 2^16 + 116 * 2^8 + 78 * 2^0) / 2^39 = 4311810305 / 549755813888 = 0.881092721738

Exponent = 30

Value = Mantissa * 2^Exponent = 0.881092721738 * 2^30 = 946066106.15234375
```

This value represents the CH-1 clock tick count at the most recent sync pulse. The nominal CH-1 tick rate is 1000Hz, but fractional ticks are reported suggesting the real clock had higher precision intervals. The CH-1 clock rolled over to zero every 21 days

`(modulo 1814400000 = 21 days/cycle * 24 hours/day * 3600 seconds/hour * 1000 ticks/second).`

II) M^3 Clock Ticks at Sync Mark

The next eight bytes in the frame prefix (bytes 647-654) encode the M^3 clock tick at the most recent sync pulse. The value is encoded as an integer but in a non-standard

manner across the eight bytes. The first and second set of four bytes in the eight-byte sequence are used to form two long integers. Then the first is promoted by 2^{26} as it counts the number of times the M^3 tick counter rolls over at that value. The second integer is the least significant part and rolls over to zero at 2^{26} - 1, when the upper integer is correspondingly incremented.

A detailed example of building the tick count value follows for an eight-byte set of values of `0, 0, 251, 154, 2, 228, 65` and `110`, in order.

The most significant part is formed from promoting the long integer of bytes `1, 2, 3, 4` by a factor of 2^{26}.

The least significant portion is the long integer formed by the last four bytes `(5, 6, 7, 8)`.

The value is the sum of these two integers.

$$\text{Most Significant Part} = (0 * 2^{24} + 0 * 2^{16} + 251 * 2^{8} + 154 * 2^{0}) * 2^{26} = 64410 * 67108864 = 4322481930240$$

$$\text{Least Significant Part} = 2 * 2^{24} + 228 * 2^{16} + 65 * 2^{8} + 110 * 2^{0} = 48513390$$

$$\text{Value} = \text{Most Significant Part} + \text{Least Significant Part} = 4322481930240 + 48513390 = 4322530443630$$

The nominal M^3 tick rate was 12MHz. The M^3 clock did not rollover during the mission.

III) M^3 Clock Ticks at Frame Time

The final eight bytes of the 22 raw timing bytes (bytes `655-662`) encode the M^3 clock tick at the image frame time.

The value is encoded in the exact manner as the M^3 Clock at Sync Mark previously described.

In the example being worked for clarity, these eight bytes are `0, 0, 251, 156, 3, 140, 8, 44`.

$$\text{Most Significant Part} = (0 * 2^{24} + 0 * 2^{16} + 251 * 2^{8} + 156 * 2^{0}) * 2^{26} = 64412 * 67108864 = 4322616147968$$

$$\text{Least Significant Part} = 2 * 2^{24} + 228 * 2^{16} + 65 * 2^{8} + 110 * 2^{0} = 59508780$$

$$\text{Value} = \text{Most Significant Part} + \text{Least Significant Part} = 4322616147968 + 59508780 = 4322675656748$$

This frame is approximately 12.101093 seconds after the most recent sync pulse, using the nominal 12 MHz M^3 clock rate.

$$(4322675656748 - 4322530443630) / 12000000 = 12.101093$$

In practice, we use a per-image regression between M^3 ticks and CH-1 ticks to convert the per-frame M^3 ticks to equivalent CH-1 ticks.

This regression accommodates any drift in the relative clock rates and their stability.

Then the derived CH-1 ticks are converted to real time via the clock kernel (*.TSC), in the Level 1B PDS Archive that relates CH-1 ticks to TDT time.

Appendix B Example L0 Data Product PDS Label

```
PDS_VERSION_ID                = PDS3
LABEL_REVISION_NOTE           = "2010-02-09, S. Lundeen"
DATA_SET_ID                   = "CH1-ORB-L-M3-2-L0-RAW-V1.0"
PRODUCT_ID                    = "M3G20090213T221852_V01_L0"
RECORD_TYPE                   = UNDEFINED

MISSION_ID                    = "CH1"
MISSION_NAME                  = "CHANDRAYAAN-1"
INSTRUMENT_HOST_ID            = "CH1-ORB"
INSTRUMENT_HOST_NAME          = "CHANDRAYAAN-1 ORBITER"
INSTRUMENT_NAME               = "MOON MINERALOGY MAPPER"
INSTRUMENT_ID                 = M3
TARGET_NAME                   = "MOON"
TARGET_TYPE                   = "SATELLITE"
MISSION_PHASE_NAME            = "PRIMARY MISSION"
PRODUCT_TYPE                  = RAW_IMAGE
PRODUCT_CREATION_TIME         = 2009-06-18T15:45:31
START_TIME                    = 2009-02-13T22:18:52
STOP_TIME                     = 2009-02-13T22:49:01
SPACECRAFT_CLOCK_START_COUNT  = "6/858109.126"
SPACECRAFT_CLOCK_STOP_COUNT   = "6/859917.905"
ORBIT_NUMBER                  = 01179
PRODUCT_VERSION_TYPE          = "PRELIMINARY"

PRODUCER_INSTITUTION_NAME     = "JET PROPULSION LABORATORY"
SOFTWARE_NAME                 = "m3_igds_l0_v18.pl"
SOFTWARE_VERSION_ID           = "18"
DESCRIPTION                   = "M3 Level 0 data product which consists  of
raw science data, reassembled into time-sequenced data in units of digital
numbers."

/* Level 0 Image Instrument and Observation Parameters */

INSTRUMENT_MODE_ID            = "GLOBAL"
DETECTOR_TEMPERATURE          = 146.97
CH1:SWATH_WIDTH               = 320 <PIXELS>
CH1:SWATH_LENGTH              = 17776 <LINES>

/* Description of Level 0 IMAGE file, containing both multi-banded image */
/* data described with the IMAGE object and line prefix information */
/* described with the TABLE object. */

OBJECT                  = L0_FILE
  ^L0_LINE_PREFIX_TABLE = "M3G20090213T221852_V01_L0.IMG"
  ^L0_IMAGE             = "M3G20090213T221852_V01_L0.IMG"
  RECORD_TYPE           = FIXED_LENGTH
  RECORD_BYTES          = 56320
  FILE_RECORDS          = 17776

  OBJECT                      = L0_LINE_PREFIX_TABLE
    INTERCHANGE_FORMAT        = BINARY
    ROWS                      = 17776
    COLUMNS                   = 9
    ROW_BYTES                 = 1280
    ROW_SUFFIX_BYTES          = 55040
```

```
    ^STRUCTURE               = "LN_PRFX_HDR.FMT"
  END_OBJECT                 = L0_LINE_PREFIX_TABLE

  OBJECT                     = L0_IMAGE
    LINES                    = 17776
    LINE_SAMPLES             = 320
    LINE_PREFIX_BYTES        = 1280
    SAMPLE_TYPE              = LSB_INTEGER
    SAMPLE_BITS              = 16
    UNIT                     = "DN"
    BANDS                    = 86
    BAND_STORAGE_TYPE        = LINE_INTERLEAVED
    LINE_DISPLAY_DIRECTION   = DOWN
    SAMPLE_DISPLAY_DIRECTION = RIGHT
  END_OBJECT                 = L0_IMAGE

END_OBJECT = L0_FILE

/* Description of Level 0 HEADER file */

OBJECT             = L0_HDR_FILE
  ^L0_ENVI_HEADER  = "M3G20090213T221852_V01_L0.HDR"
  RECORD_TYPE      = VARIABLE_LENGTH
  FILE_RECORDS     = 11

  OBJECT               = L0_ENVI_HEADER
    INTERCHANGE_FORMAT = "ASCII"
    BYTES              = 306
    HEADER_TYPE        = ENVI
    DESCRIPTION        = "Header file for compatibility with the commercial
                          software package ENVI."
  END_OBJECT           = L0_ENVI_HEADER

END_OBJECT = L0_HDR_FILE

END
```

Appendix C Example L1B Data Product PDS Label

```
PDS_VERSION_ID                 = PDS3
LABEL_REVISION_NOTE            = "2009-01-26, S. Lundeen,
                                  2010-12-07, S. Lundeen,
                                  2011-09-13, S. Lundeen"
DATA_SET_ID                    = "CH1-ORB-L-M3-4-L1B-RADIANCE-V3.0"
PRODUCT_ID                     = "M3G20090415T202222_V03_RDN"
RECORD_TYPE                    = UNDEFINED

MISSION_ID                     = "CH1"
MISSION_NAME                   = "CHANDRAYAAN-1"
INSTRUMENT_HOST_ID             = "CH1-ORB"
INSTRUMENT_HOST_NAME           = "CHANDRAYAAN-1 ORBITER"
INSTRUMENT_NAME                = "MOON MINERALOGY MAPPER"
INSTRUMENT_ID                  = M3
TARGET_NAME                    = "MOON"
TARGET_TYPE                    = "SATELLITE"
MISSION_PHASE_NAME             = "PRIMARY MISSION"
PRODUCT_TYPE                   = CALIBRATED_IMAGE
PRODUCT_CREATION_TIME          = 2011-09-01T02:15:01
START_TIME                     = 2009-04-15T20:22:22
STOP_TIME                      = 2009-04-15T21:10:21
SPACECRAFT_CLOCK_START_COUNT   = "9/678325.178"
SPACECRAFT_CLOCK_STOP_COUNT    = "9/681203.738"
ORBIT_NUMBER                   =  01922
PRODUCT_VERSION_TYPE           = "ACTUAL"
PRODUCT_VERSION_ID             = "3.0"
SOURCE_PRODUCT_ID              = "M3G20090415T202222_V01_L0.IMG"
PRODUCER_INSTITUTION_NAME      = "JET PROPULSION LABORATORY"
SOFTWARE_NAME                  = "m3g_l1b_v04.exe"
SOFTWARE_VERSION_ID            = "04"
DESCRIPTION                    = "M3 Level 1B data product which contains
pixel located, radiometrically-calibrated data."

/* Calibrated Image Instrument and Observation Parameters */

SOLAR_DISTANCE                 = 1.004322080839 <AU>
INSTRUMENT_MODE_ID             = "GLOBAL"
DETECTOR_TEMPERATURE           = 145.81
CH1:SWATH_WIDTH                = 304 <pixel>
CH1:SWATH_LENGTH               = 28289 <pixel>
CH1:SPACECRAFT_YAW_DIRECTION   = "REVERSE"
CH1:ORBIT_LIMB_DIRECTION       = "ASCENDING"
SPACECRAFT_ORIENTATION         = (0.260342787417,0.366499902896,
                                  180.963779333551)
CH1:INITIAL_SC_ORIENTATION     = ("N/A","N/A",
                                  "N/A")
CH1:SC_ORIENTATION_EPOCH_TDB_TIME = "N/A"
CH1:SC_ORIENTATION_RATE        = ("N/A","N/A",
                                  "N/A")
CH1:SC_ROTATION_AXIS_VECTOR    = ("N/A","N/A",
                                  "N/A")
CH1:SC_ROTATION_RATE           = "N/A"

^DESCRIPTION              = "L1B_NAV_DESC.ASC"
```

```
/* Spectral calibration parameters and radiometric gain factor data */

CH1:SPECTRAL_CALIBRATION_FILE_NAME      = "M3G20081211_RDN_SPC.TAB"
CH1:RAD_GAIN_FACTOR_FILE_NAME           = "M3G20081211_RDN_GAIN.TAB"
CH1:GLOBAL_BANDPASS_FILE_NAME           = "M3G20081211_RDN_BPF.IMG"

/* Description of Radiance-corrected image file */

OBJECT          = RDN_FILE
  ^RDN_IMAGE    = "M3G20090415T202222_V03_RDN.IMG"
  RECORD_TYPE   = FIXED_LENGTH
  RECORD_BYTES  = 103360
  FILE_RECORDS  = 28289

  OBJECT                     = RDN_IMAGE
    LINES                    = 28289
    LINE_SAMPLES             = 304
    SAMPLE_TYPE              = PC_REAL
    SAMPLE_BITS              = 32
    UNIT                     = "W/(m^2 um sr)"
    BANDS                    = 85
    BAND_STORAGE_TYPE        = LINE_INTERLEAVED
    LINE_DISPLAY_DIRECTION   = DOWN
    SAMPLE_DISPLAY_DIRECTION = RIGHT
  END_OBJECT                 = RDN_IMAGE

END_OBJECT = RDN_FILE


/* Description of Radiance-corrected header file */

OBJECT              = RDN_HDR_FILE
  ^RDN_ENVI_HEADER  = "M3G20090415T202222_V03_RDN.HDR"
  RECORD_TYPE       = VARIABLE_LENGTH
  FILE_RECORDS      = 1146

  OBJECT               = RDN_ENVI_HEADER
    INTERCHANGE_FORMAT = "ASCII"
    BYTES              = 35657
    HEADER_TYPE        = ENVI
    DESCRIPTION = "Header file for compatibility with the commercial software
                   package ENVI."
  END_OBJECT = RDN_ENVI_HEADER

END_OBJECT = RDN_HDR_FILE

/* Description of selenolocation data file */

OBJECT          = LOC_FILE
  ^LOC_IMAGE    = "M3G20090415T202222_V03_LOC.IMG"
  RECORD_TYPE   = FIXED_LENGTH
  RECORD_BYTES  = 7296
  FILE_RECORDS  = 28289

  OBJECT                     = LOC_IMAGE
    LINES                    = 28289 /* (same as RDN image) */
    LINE_SAMPLES             = 304 /* (same as RDN image) */
    SAMPLE_TYPE              = PC_REAL
```

```
    SAMPLE_BITS              = 64
    BANDS                    = 3
    BAND_STORAGE_TYPE        = LINE_INTERLEAVED
    BAND_NAME                = ("Longitude",
                                "Latitude",
                                "Radius")
    LINE_DISPLAY_DIRECTION   = DOWN
    SAMPLE_DISPLAY_DIRECTION = RIGHT
  END_OBJECT                 = LOC_IMAGE

END_OBJECT = LOC_FILE

/* Description of selenolocation header file */

OBJECT              = LOC_HDR_FILE
  ^LOC_ENVI_HEADER  = "M3G20090415T202222_V03_LOC.HDR"
  RECORD_TYPE       = VARIABLE_LENGTH
  FILE_RECORDS      = 16

  OBJECT               = LOC_ENVI_HEADER
    INTERCHANGE_FORMAT = "ASCII"
    BYTES              = 373
    HEADER_TYPE        = ENVI
    DESCRIPTION        = "Header file for compatibility with the commercial
                          software package ENVI."
  END_OBJECT = LOC_ENVI_HEADER

END_OBJECT = LOC_HDR_FILE

/* Description of observation geometry data file */

OBJECT          = OBS_FILE
  ^OBS_IMAGE    = "M3G20090415T202222_V03_OBS.IMG"
  RECORD_TYPE   = FIXED_LENGTH
  RECORD_BYTES  = 12160
  FILE_RECORDS  = 28289

  OBJECT                     = OBS_IMAGE
    LINES                    = 28289 /* (same as RDN image) */
    LINE_SAMPLES             = 304 /* (same as RDN image) */
    SAMPLE_TYPE              = PC_REAL
    SAMPLE_BITS              = 32
    BANDS                    = 10
    BAND_STORAGE_TYPE        = LINE_INTERLEAVED
    BAND_NAME                = ("To-Sun AZM",
                                "To-Sun Zenith",
                                "To-Inst AZM",
                                "To-Inst Zenith",
                                "Phase-angle",
                                "To-Sun Path Length",
                                "To-Inst Path Length",
                                "Facet Slope",
                                "Facet Aspect",
                                "Facet Cos i")
    LINE_DISPLAY_DIRECTION   = DOWN
    SAMPLE_DISPLAY_DIRECTION = RIGHT
  END_OBJECT = OBS_IMAGE
```

```
END_OBJECT = OBS_FILE

/* Description of observation geometry header file */

OBJECT              = OBS_HDR_FILE
  ^OBS_ENVI_HEADER  = "M3G20090415T202222_V03_OBS.HDR"
  RECORD_TYPE       = VARIABLE_LENGTH
  FILE_RECORDS      = 21

  OBJECT               = OBS_ENVI_HEADER
    INTERCHANGE_FORMAT = "ASCII"
    BYTES              = 708
    HEADER_TYPE        = ENVI
    DESCRIPTION        = "Header file for compatibility with the commercial
                          software package ENVI."
  END_OBJECT           = OBS_ENVI_HEADER

END_OBJECT = OBS_HDR_FILE

/* Description of UTC timing data file */

OBJECT            = UTC_FILE
  ^UTC_TIME_TABLE = "M3G20090415T202222_V03_TIM.TAB"
  RECORD_TYPE     = FIXED_LENGTH
  RECORD_BYTES    = 57
  FILE_RECORDS    = 28289 /* (same as RDN image) */

  OBJECT                 = UTC_TIME_TABLE
    NAME                 = "UTC OBSERVATION TIMING DATA"
    INTERCHANGE_FORMAT   = "ASCII"
    ROWS                 = 28289 /* (same as RDN image) */
    COLUMNS              = 4
    ROW_BYTES            = 57
    OBJECT                 = COLUMN
      COLUMN_NUMBER      = 1
      NAME               = "LINE NUMBER"
      DATA_TYPE          = ASCII_INTEGER
      START_BYTE         = 1
      BYTES              = 6
      FORMAT             = "I6"
      DESCRIPTION        = "Record number for each RDN image line"
    END_OBJECT             = COLUMN

    OBJECT                 = COLUMN
      COLUMN_NUMBER      = 2
      NAME               = "UTC_TIME"
      DATA_TYPE          = TIME
      START_BYTE         = 8
      BYTES              = 26
      FORMAT             = "A26"
      DESCRIPTION        = "UTC Time for the middle of the integration period
                            for each RDN image line expressed as
                            YYYY-MM-DDTHH:MM:SS.SSSSSS"
    END_OBJECT             = COLUMN

    OBJECT                 = COLUMN
      COLUMN_NUMBER      = 3
      NAME               = "YEAR"
```

```
      DATA_TYPE          = CHARACTER
      START_BYTE         = 35
      BYTES              = 4
      FORMAT             = "I4"
      DESCRIPTION        = "Decimal Day of Year (DDOY) Year reference
                            extracted from the earliest time of each RDN
                            image line"
    END_OBJECT             = COLUMN

    OBJECT                 = COLUMN
      COLUMN_NUMBER      = 4
      NAME               = "DDOY"
      DATA_TYPE          = DATE
      START_BYTE         = 40
      BYTES              = 16
      FORMAT             = "F16.12"
      DESCRIPTION        = "Decimal Day of Year represented as the number of
                            days elapsed since 00:00 UTC of January 1 of the
                            year associated with the time stamp of the first
                            line of the RDN image file. DDOY is expressed
                            using seventeen characters where 1-3 = three
                            characters that contain the integer number of
                            days; 4 = a decimal point; 5-16 = twelve charact-
                            ers after the decimal for the fractional part of
                            the day of year value."
    END_OBJECT             = COLUMN

  END_OBJECT = UTC_TIME_TABLE

END_OBJECT = UTC_FILE

END
```

Appendix D Example L2 Data Product PDS Label

```
PDS_VERSION_ID                = PDS3
LABEL_REVISION_NOTE           = "2011-03-31  UMD/ACT  Original RLFL product."
DATA_SET_ID                   = "CH1-ORB-L-M3-4-L2-REFLECTANCE-V1.0"
PRODUCT_ID                    = "M3G20090719T121342_V01_RFL"
RECORD_TYPE                   = UNDEFINED

MISSION_ID                    = "CH1"
MISSION_NAME                  = "CHANDRAYAAN-1"
INSTRUMENT_HOST_ID            = "CH1-ORB"
INSTRUMENT_HOST_NAME          = "CHANDRAYAAN-1 ORBITER"
INSTRUMENT_NAME               = "MOON MINERALOGY MAPPER"
INSTRUMENT_ID                 = M3
TARGET_NAME                   = "MOON"
TARGET_TYPE                   = "SATELLITE"
MISSION_PHASE_NAME            = "PRIMARY MISSION"
PRODUCT_TYPE                  = REFLECTANCE_IMAGE
PRODUCT_CREATION_TIME         = 2011-09-01T02:15:01
START_TIME                    = 2009-07-19T12:13:42
STOP_TIME                     = 2009-07-19T12:27:09
SPACECRAFT_CLOCK_START_COUNT  = "13/1599402.861"
SPACECRAFT_CLOCK_STOP_COUNT   = "13/1600209.714"
ORBIT_NUMBER                  =  03018
PRODUCT_VERSION_TYPE          = "ACTUAL"

PRODUCER_INSTITUTION_NAME     = "APPLIED COHERENT TECHNOLOGY CORP."
SOFTWARE_NAME                 = "PIPE_REACT_m3v01_"
SOFTWARE_VERSION_ID           = "01"
DESCRIPTION                   = "M3 Level 2 data product which contains
  pixel located, thermal corrected, photometry corrected, reflectance data."

/* Calibrated Image Instrument and Observation Parameters */

SOLAR_DISTANCE                = 1.014261577555 <AU>
INSTRUMENT_MODE_ID            = "GLOBAL"
DETECTOR_TEMPERATURE          = 156.90
CH1:SWATH_WIDTH               = 304 <pixel>
CH1:SWATH_LENGTH              = 7857 <pixel>
CH1:SPACECRAFT_YAW_DIRECTION  = "FORWARD"
CH1:ORBIT_LIMB_DIRECTION      = "ASCENDING"
SPACECRAFT_ORIENTATION        = ("N/A","N/A",
                                 "N/A")
CH1:INITIAL_SC_ORIENTATION    = (00.598425449997,-1.473570574616,
                                 -002.470917908078)
CH1:SC_ORIENTATION_EPOCH_TDB_TIME = 301273517.138000
CH1:SC_ORIENTATION_RATE       = ("N/A","N/A",
                                 "N/A")
CH1:SC_ROTATION_AXIS_VECTOR   = (0.074279503622,-0.996568815929,
                                 0.036512332982)
CH1:SC_ROTATION_RATE          = 0.047390003003

^DESCRIPTION             = "L1B_NAV_DESC.ASC"

/* Spectral calibration parameters and radiometric gain factor data */

CH1:SPECTRAL_CALIBRATION_FILE_NAME      = "M3G20081211_RDN_SPC.TAB"
CH1:RAD_GAIN_FACTOR_FILE_NAME           = "M3G20081211_RDN_GAIN.TAB"
```

```
CH1:GLOBAL_BANDPASS_FILE_NAME          = "M3G20081211_RDN_BPF.IMG"

/* Level 1B radiance image product and the associated observational  */
/* geometry and pixel location (longitude, latitude, and radius)    */
/* files used as sources for this reflectance product.               */

SOURCE_DATA_SET_ID                     = "CH1-ORB-L-M3-4-L1B-RADIANCE-V3.0"
SOURCE_PRODUCT_ID                      = "M3G20090719T121342_V03_RDN"
CH1:RADIANCE_IMAGE_FILE_NAME           = "M3G20090719T121342_V03_RDN.IMG"
CH1:OBS_GEOMETRY_FILE_NAME             = "M3G20090719T121342_V03_OBS.IMG"
CH1:PIXEL_LOCATION_FILE_NAME           = "M3G20090719T121342_V03_LOC.IMG"


/* Calibration files and factors applied to the Level 1B radiance   */
/* image product to generate this reflectance product.              */

CH1:SOLAR_SPECTRUM_FILE_NAME           = "M3G20110224_RFL_SOLAR_SPEC.TAB"
CH1:STATISTICAL_POLISHER_FILE_NAME     = "M3G20110830_RFL_STAT_POL_n.TAB"
CH1:THERMAL_CORRECTION_FLAG            = "Y"
CH1:PHOTOMETRY_CORR_FILE_NAME          = "M3G20111109_RFL_F_APLHA_HIL.TAB"
CH1:GROUND_TRUTH_CORR_FILE_NAME        = "M3G20111111_RFL_GRND_TRU_n.TAB"

/* Description of the photometrically-corrected (from local topography) and */
/* reflectance-corrected data file where a stored value of 1.0, unitless,   */
/* represents 100% reflectance.                                             */

OBJECT          = RFL_FILE
  ^RFL_IMAGE    = "M3G20090719T121342_V01_RFL.IMG"
  RECORD_TYPE   = FIXED_LENGTH
  RECORD_BYTES  = 103360  /*  = LINE_SAMPLES * SAMPLE_BITS/8 * BANDS  */
  FILE_RECORDS  = 7857    /*  = Total IMG file size in bytes / RECORD_BYTES  */

  OBJECT                     = RFL_IMAGE
    LINES                    = 7857  /*  = FILE_RECORDS  */
    LINE_SAMPLES             = 304
    SAMPLE_TYPE              = PC_REAL
    SAMPLE_BITS              = 32
    BANDS                    = 85
    BAND_STORAGE_TYPE        = LINE_INTERLEAVED
    LINE_DISPLAY_DIRECTION   = DOWN
    SAMPLE_DISPLAY_DIRECTION = RIGHT
    INVALID_CONSTANT         = -999.0
  END_OBJECT                 = RFL_IMAGE

END_OBJECT = RFL_FILE

/* Description of the header file for RFL_FILE */

OBJECT              = RFL_HDR_FILE
  ^RFL_ENVI_HEADER  = "M3G20090719T121342_V01_RFL.HDR"
  RECORD_TYPE       = VARIABLE_LENGTH
  FILE_RECORDS      = nnnnn     /* = # records in HDR file  */

  OBJECT               = RFL_ENVI_HEADER
    INTERCHANGE_FORMAT = "ASCII"
    BYTES              = nnnnn  /* = Total HDR file size in bytes / RECORD_BYTES */
    HEADER_TYPE        = ENVI
    DESCRIPTION        = "Header file for compatibility with the commercial
```

```
                          software package ENVI."
  END_OBJECT = RFL_ENVI_HEADER

END_OBJECT = RFL_HDR_FILE


/* Description of the supplemental data file for the RLF image above.       */
/* Band 1 provides the 1489-nm channel photometrically-corrected to a       */
/* sphere to preserve topography (i.e., photometrically-corrected albedo);  */
/* a stored value of 1.0, unitless, represents 100% reflectance.            */
/* Band 2 contains the temperature estimated and applied by the thermal     */
/* correction step of the L2 calibration process; units are kelvin.         */
/* Band 3 contains the longest wavelength band that is scientifically       */
/* useful and has topography (number 84 for global mode or 253 for target   */
/* mode) from the L1 radiance image specified by CH1:RADIANCE_IMAGE_FILE_   */
/* NAME above; none of the Level 2 steps has been applied.                  */

OBJECT          = SUPPLEMENTAL_FILE
  ^SUPPL_IMAGE  = "M3G20090719T121342_V01_SUP.IMG"
  RECORD_TYPE   = FIXED_LENGTH
  RECORD_BYTES  = 3646   /*  = LINE_SAMPLES * SAMPLE_BITS/8 * BANDS  */
  FILE_RECORDS  = 7857   /*  = Total IMG file size in bytes / RECORD_BYTES  */

  OBJECT                    = SUPPL_IMAGE
    LINES                   = 7857   /* Should be same as RFL image */
    LINE_SAMPLES            = 304    /* (same as RFL image) */
    SAMPLE_TYPE             = PC_REAL
    SAMPLE_BITS             = 32
    BANDS                   = 3
    BAND_STORAGE_TYPE       = LINE_INTERLEAVED
    BAND_NAME               = ("1489NM RFL (PHOTOM RELATIVE TO SPHERE)",
                               "ESTIMATED TEMPERATURE",
                               "RDN BAND n")
    LINE_DISPLAY_DIRECTION  = DOWN
    SAMPLE_DISPLAY_DIRECTION = RIGHT
END_OBJECT                = SUPPL_IMAGE

END_OBJECT = SUPPLEMENTAL_FILE

/* Description of the header file for SUPPLEMENTAL_FILE                     */

OBJECT              = SUPPLEMENTAL_HDR_FILE
  ^SUPPL_ENVI_HEADER = "M3G20090719T121342_V01_SUP.HDR"
  RECORD_TYPE       = VARIABLE_LENGTH
  FILE_RECORDS      = nnnnn  /* = # records in HDR file  */

  OBJECT              = SUPPL_ENVI_HEADER
    INTERCHANGE_FORMAT = "ASCII"
    BYTES              = nnnnn  /* = Total HDR file size in bytes / RECORD_BYTES */
    HEADER_TYPE        = ENVI
    DESCRIPTION        = "Header file for compatibility with the commercial
                          software package ENVI."
  END_OBJECT = SUPPL_ENVI_HEADER

END_OBJECT = SUPPLEMENTAL_HDR_FILE

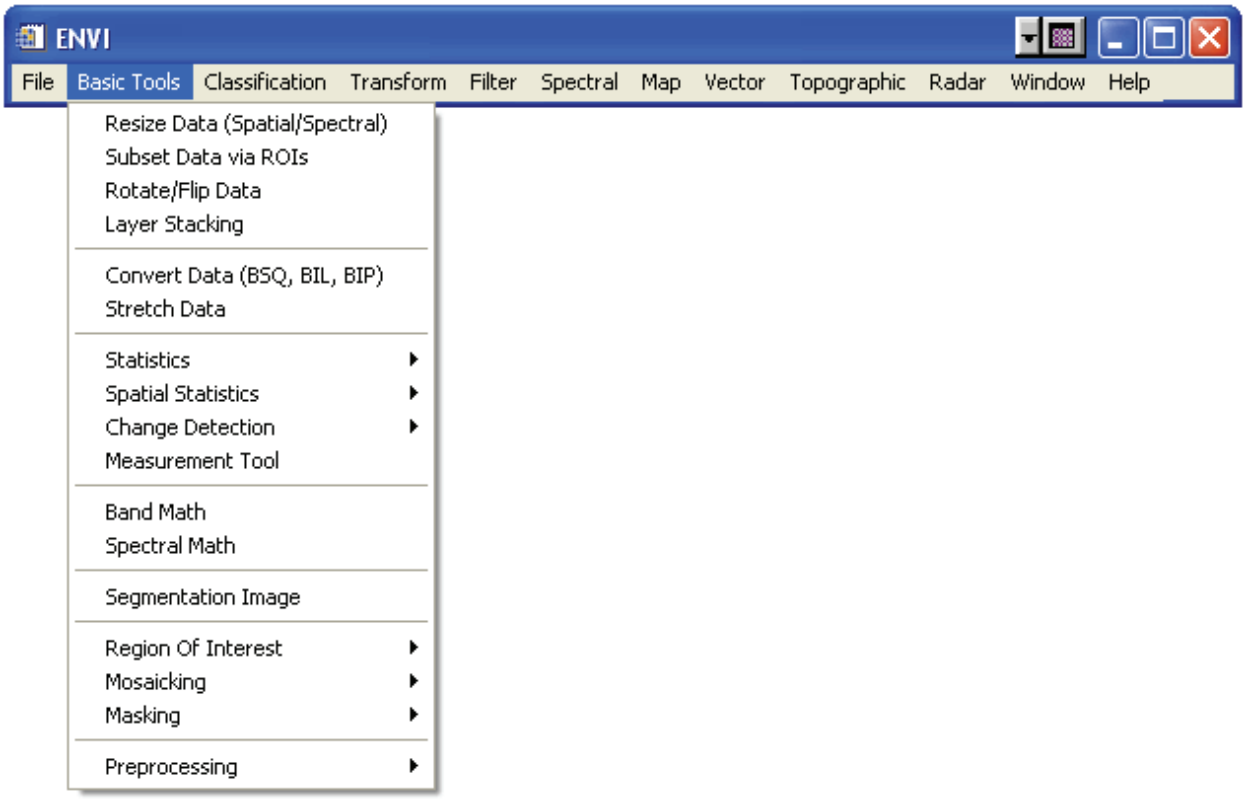
END
```

Appendix E INSTRUCTION FOR BASIC VIEWING OF AN M^3 L0/L1B/L2 Image Cube File (*.IMG) USING ENVI 4.3

**** Please note that PDS Imaging Node website provides an M^3 data tutorial at http://pds-imaging.jpl.nasa.gov/portal/chandrayaan-1_mission.html.***

1. When you start ENVI, the ENVI main menu bar appears. You initiate activities in ENVI by using the menus in the ENVI main menu bar.

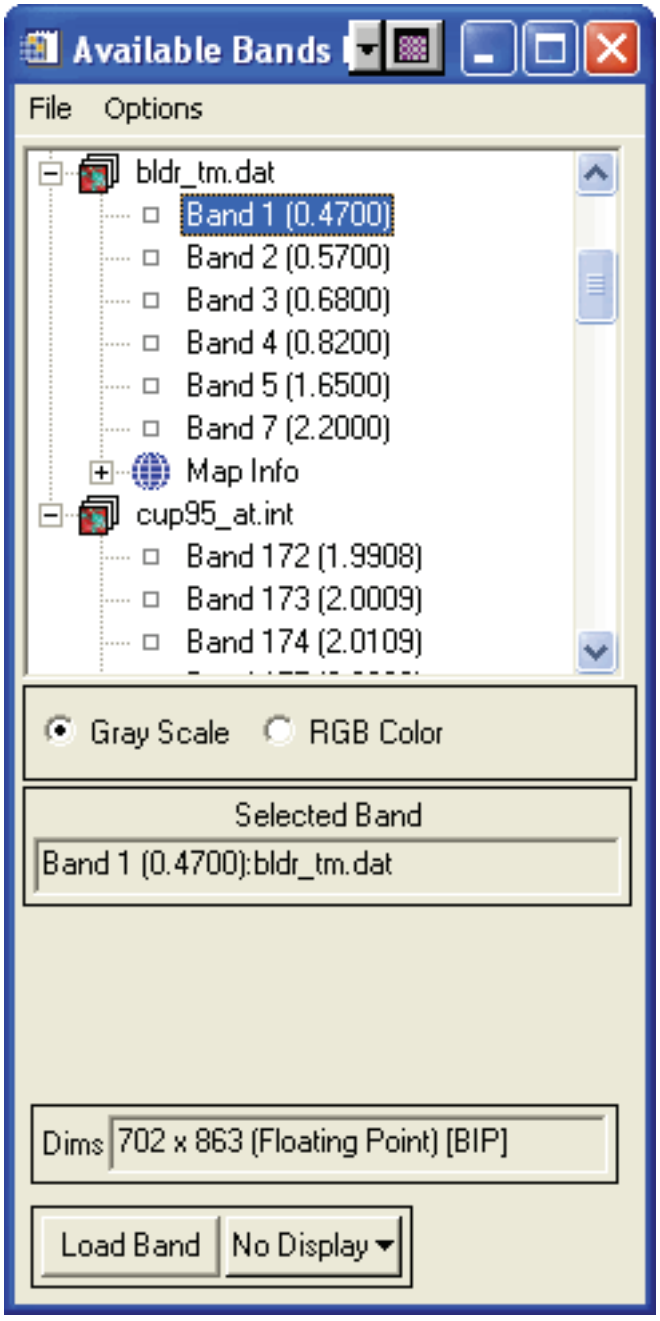
Figure D-1: ENVI Main Menu Bar



2. From the ENVI main menu bar, select **File** → **Open Image File**.
3. In the "Look in:" field, navigate to the appropriate directory containing the *.IMG file you would like to display.
4. Click **Open**. ENVI adds the filename and bands to the Available Bands List.
5. When you open a file for the first time during a session, ENVI automatically places the filename, with all of its associated bands listed beneath it, into the Available Bands List. If a file contains map information as well, a map icon also appears under the filename.

   ENVI also adds output files to the Available Bands List that are the results of processing your data using ENVI's tools.

Figure D-2: Available Bands List

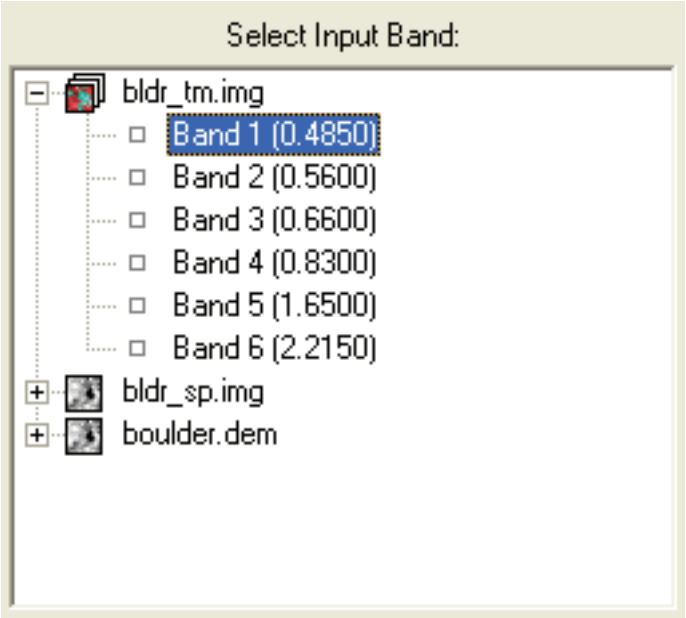


If you open multiple files, all of the files with all of their bands appear in the Available Bands List sequentially, with the most recently opened file at the top of the list. You can fold the bands displayed under each filename to shorten the list length

6. By default, data sets typically display in ENVI in an unfolded state, where a file and all of its bands are immediately visible in the list. In the Available Bands List and other band selection dialogs, many bands may be listed, particularly when

using hyperspectral data. You can fold or hide all of the bands of a data set so that they appear on only one line. This keeps the lists shorter and easier to work with.

Figure D-3: Folded and Unfolded Data Sets



To fold a data set, either:

- Click on the minus symbol (–) next to the filename.
- Double-click on the filename of the data set.
- To fold all data sets in the Available Bands List, right-click in the **Select Input Band** field and select **Fold All Files**, or from the Available Bands List menu bar, select **Options** → **Fold All Files**.

All of the bands of the data set compress and the data set appears with the plus symbol (+) next to the filename, as illustrated in the example in Figure D-3.

To unfold a data set, either:

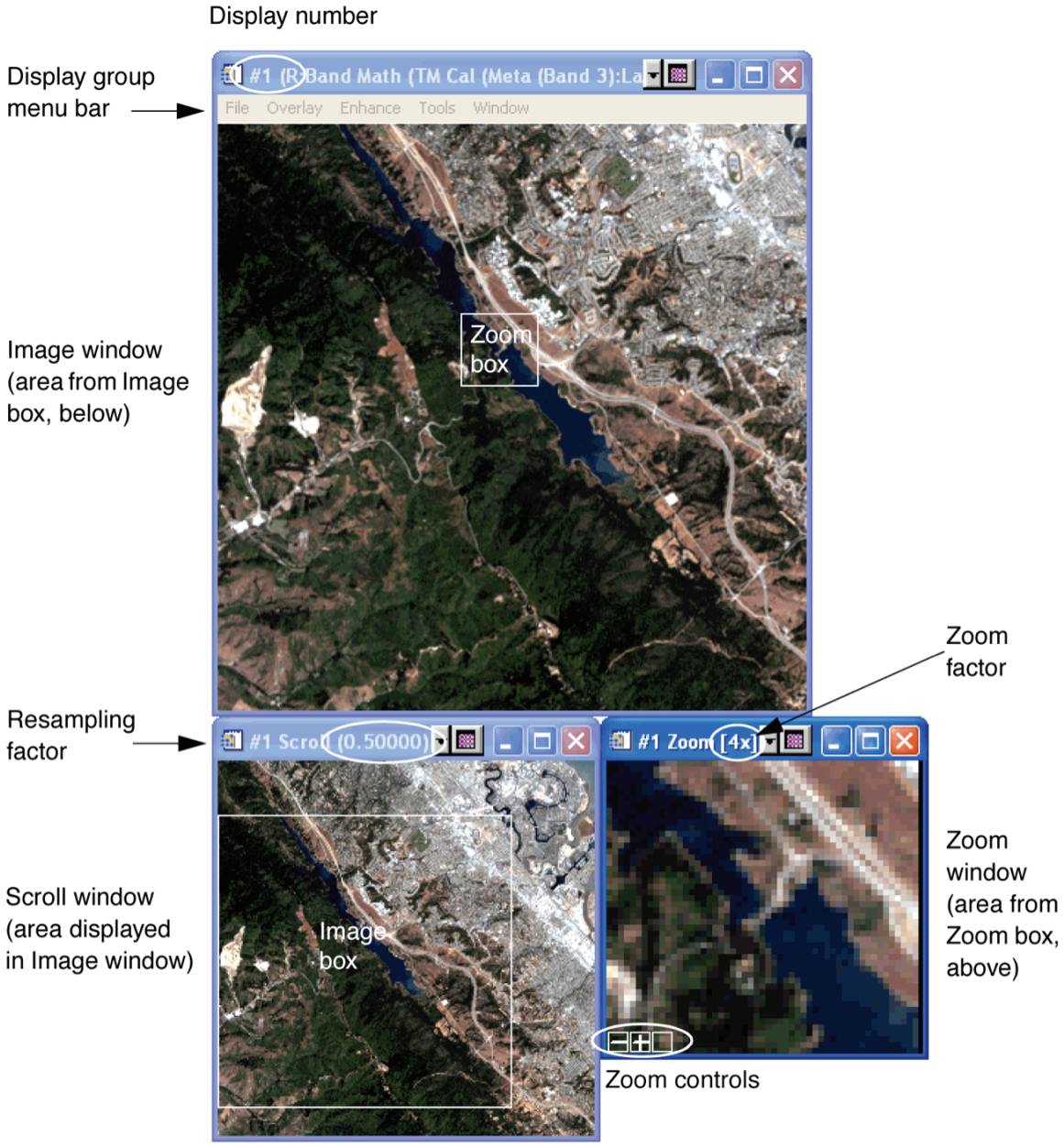
- Click on the plus symbol (+) next to the filename.
- Double-click on the filename.
- To unfold all data sets in the Available Bands List, right-click in the **Select Input Band** field and select **Unfold All Files**.

All of the bands of the data set expand and the data set appears with the minus symbol (–) next to the filename, as illustrated in the example in Figure D-3.
If a band is currently displayed as either a gray scale or RGB image, an asterisk

(*) appears next to the filename when it is folded.

7. To display an image, highlight the band you wish to display and select the “Gray Scale” radio button. The band name appears under the **Selected Band** area.
8. Click **Load Band**. ENVI loads the band into the display group.
9. When you select a file to display from the Available Bands List , a group of windows will appear on your screen allowing you to manipulate and analyze your image. This group of windows is collectively referred to as the *display group* (see Figure D-4). The default display group consists of the following:
    - Image window — Displays the image at full resolution. If the image is large, the Image window displays the subsection of the image defined by the Scroll window Image box.
    - Zoom window — Displays the subsection of the image defined by the Image window Zoom box. The resolution is at a user-defined zoom factor based on pixel replication or interpolation.
    - Scroll window — Displays the full image at subsampled resolution. This window appears only when an image is larger than what ENVI can display in the Image window at full resolution.

Figure D-4: Display Group



ENVI displays all images with a default 2% linear stretch. You can have multiple display groups open at a time, with any combination of gray scale and color images on display.

It is simple to access the location and geometry information in the *.LOC and *.OBS files and relate it to the spectra of the *.RDN files using ENVI. Open and display an image from an *.RDN file as in Step 1) listed above. Then open and display bands from the *.LOC and *.OBS files, or both, in separate windows.

Link the various windows using the **Tools** → **Link** → **Link Displays** pull-down menus. Once linked, you can interrogate spectra and simultaneously be provided the longitude, latitude and radius from the *.LOC file as well as values from all ten bands of observation geometry data in the *.OBS files.

For more detailed documentation and user's guides of ENVI and IDL software, visit the ITT Visual Solutions website, http://www.ittvis.com/.

Appendix F - M^3 Science Data Flow

