# $M^3$ Overview and Working with $M^3$ Data

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$M^3$ Data Tutorial

November, 2011

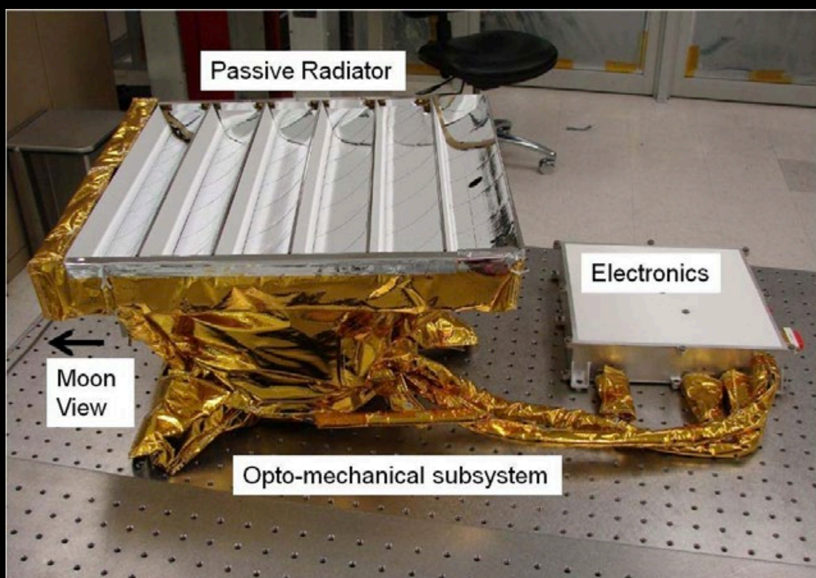
# *Topics to be discussed*

- Instrument overview
- $M^3$ observation history
- Dataset description
- Calibration pipeline
- Dataset and U2 calibration issues
- Converting radiance to I/F with ENVI

# *For Reference*

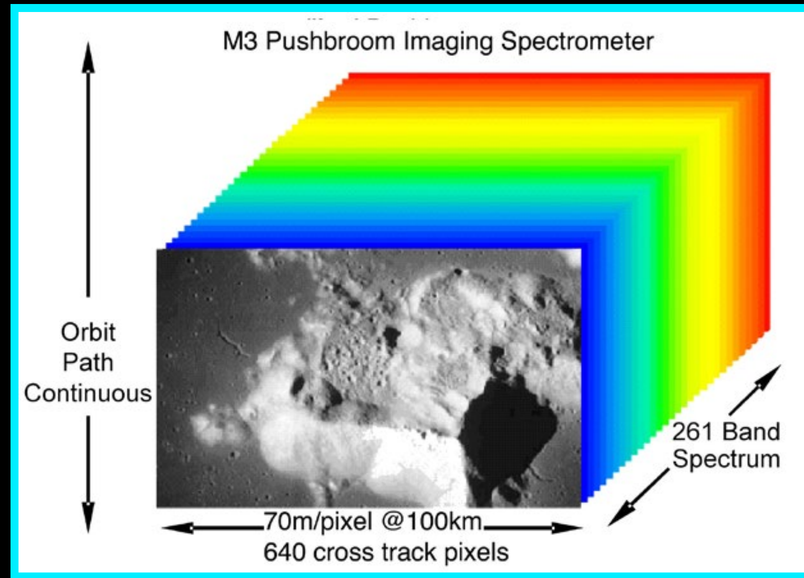
- Slides and example data from this workshop available at: http://m3.jpl.nasa.gov/m3data.html
- References for more complete description of these topics:
  - Green et al. (JGR, 2011)
  - Boardman et al. (JGR, 2011)
  - Clark et al. (JGR, 2011)
  - $M^3$ JGR Special Issue: http://www.agu.org/journals/je/special_sections.shtml?collectionCode=MOONMMI1

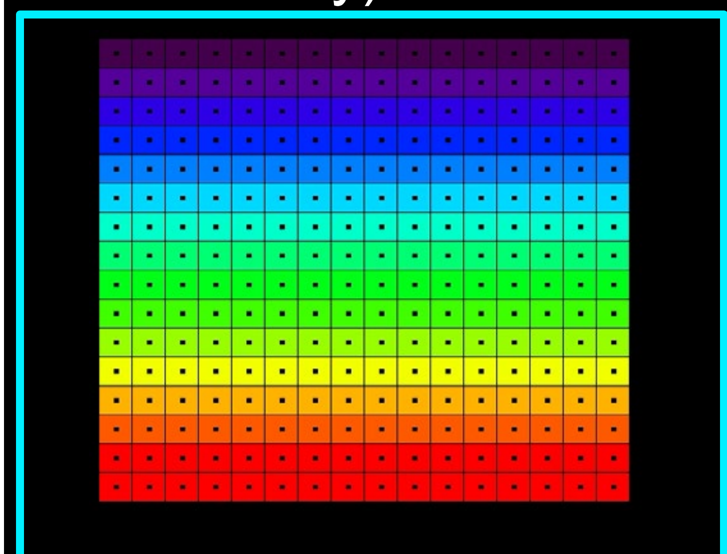
# $M^3$ Instrument

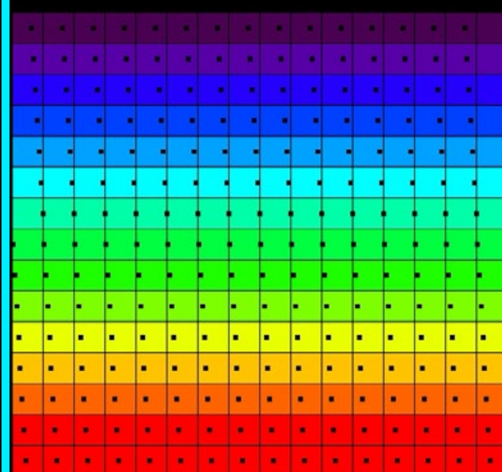


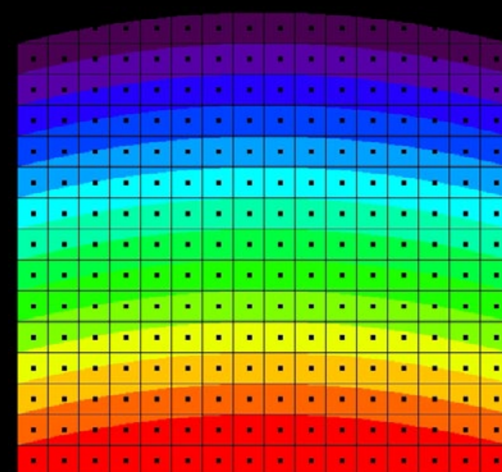

# *Instrument Design*

- Pushbroom imaging spectrometer
  - Each detector readout is 1 line of an image cube. The entire image is built as M3 moves along the ground track.
- High Spectral/Spatial Uniformity (>90% spectral crosstrack and spectral IFOV uniformity)



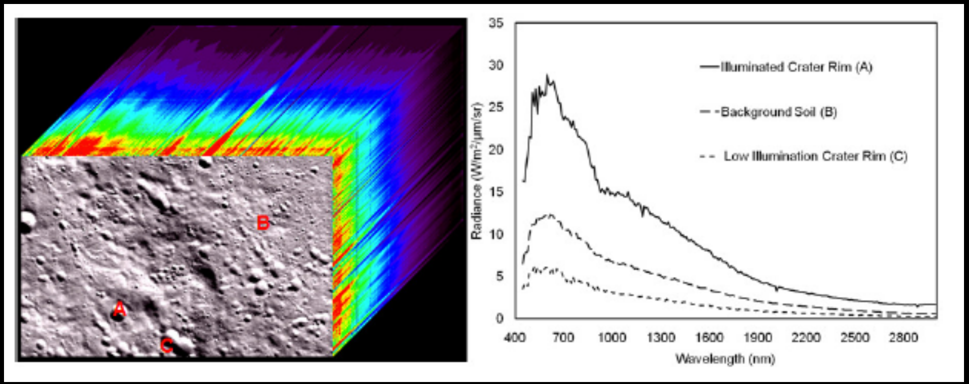



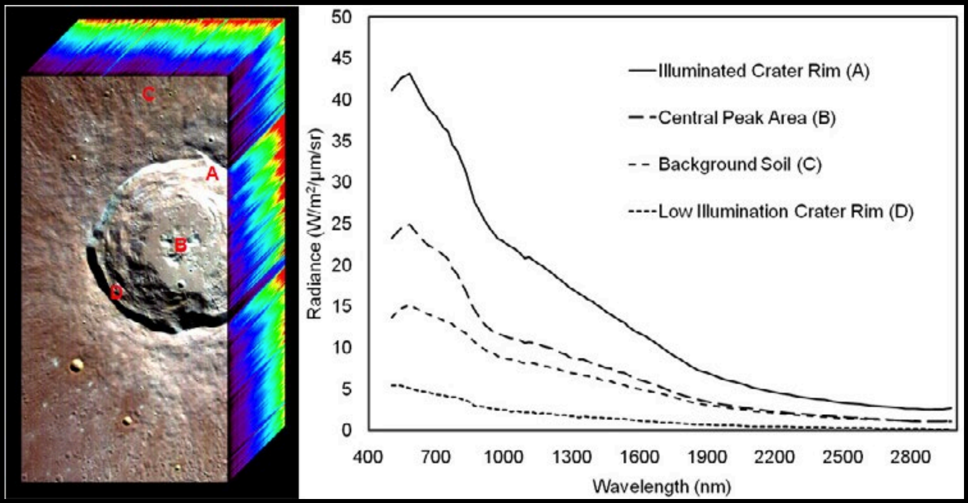




# Operational Modes

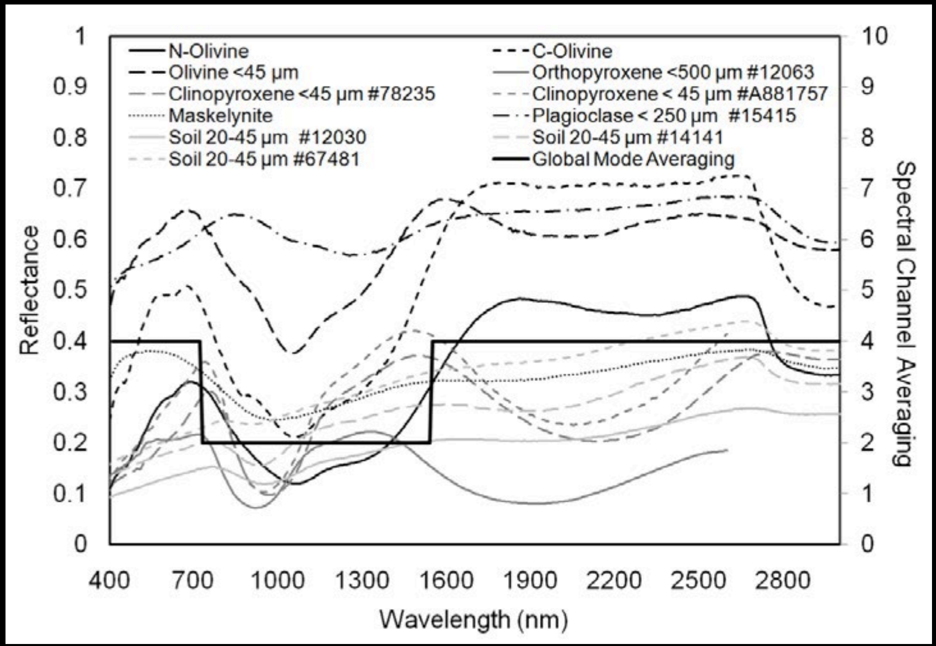
- Target
  - High spatial/spectral resolution mode for priority observations
  - Only a few target observations were actually acquired
- Global
  - $M^3$ instrument acquires full resolution data then onboard software averages data to produce reduced resolution data
  - Lower resolution (spatial & spectral) mode for mapping the entire Moon
  - <u>*Majority of the M3 data set is global data*</u>



# *Spatial and Spectral Resolution*

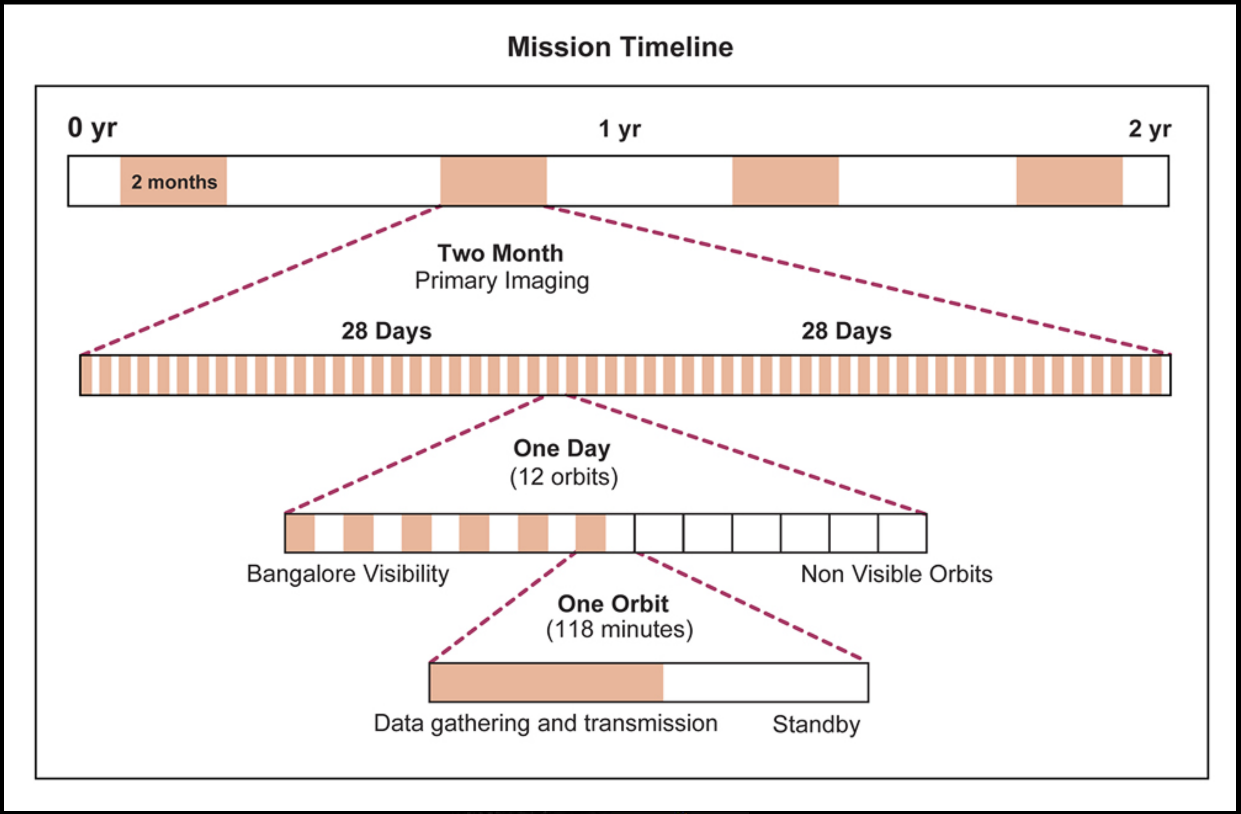
- Spectral Coverage:
  - Target: 446-3000 nm
- Spectral Resolution:
  - Target: 10nm
  - Global: 20 or 40 nm
- Spatial Resolution:
  - Target: 70 m/pixel
  - Global: 140 m/pixel
  - Doubled when from 200km orbit (see later discussion of operational history)



# *M3 Mission History*

# *Planned vs. Actual Flight*

- Planned observation time was 4 two-month optical periods defined by equatorial solar zenith of ±0-30°



# *Planned vs. Actual Flight*

- Thermal issues plagued the spacecraft as soon as it arrived at the Moon on November 8, 2008
- Lost the 1$^{st}$ of 2 star trackers before a single image was taken
- Extended commissioning phase was required, lasting into Jan 2009

# *Planned vs. Actual Flight*

- The Chandrayaan-1 Mission Operations team did a fantastic job redesigning the mission in real time throughout the mission lifetime
- Despite all the challenges, we were able to meet baseline mission requirements thanks to heroic efforts on the part of Ch-1 and M3 team members
- LOLA topography data were essential for orthorectification (early LOLA grids used)

# *Planned vs. Actual Flight*

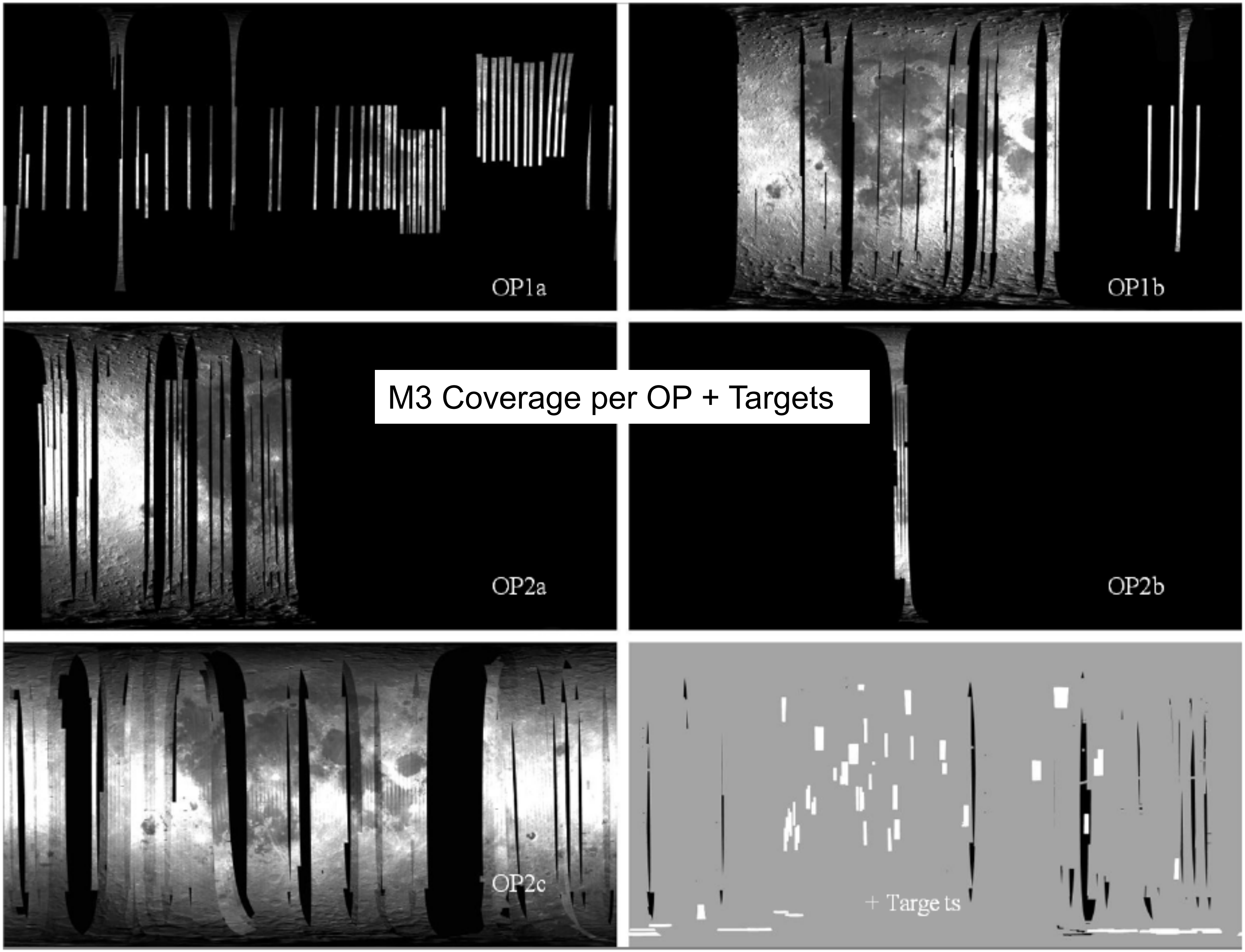
- Impact on data:
  - Instrument was operated at less favorable viewing conditions, resulting in lower reflected surface signal and increased effects of shadows.
  - The adverse changing conditions experienced in lunar orbit were beyond the range of ground calibrations for ~80% of $M^3$ data.
  - The spacecraft acquired data intermittently during two optical periods
    - Almost all M3 data were acquired in reduced resolution (“Global”) mode; very few optimal resolution (“Target”) mode observations acquired.
    - Most of 2nd optical period taken at higher orbit (200km vs 100km) and *with no star trackers.*

# M3 Optical Periods

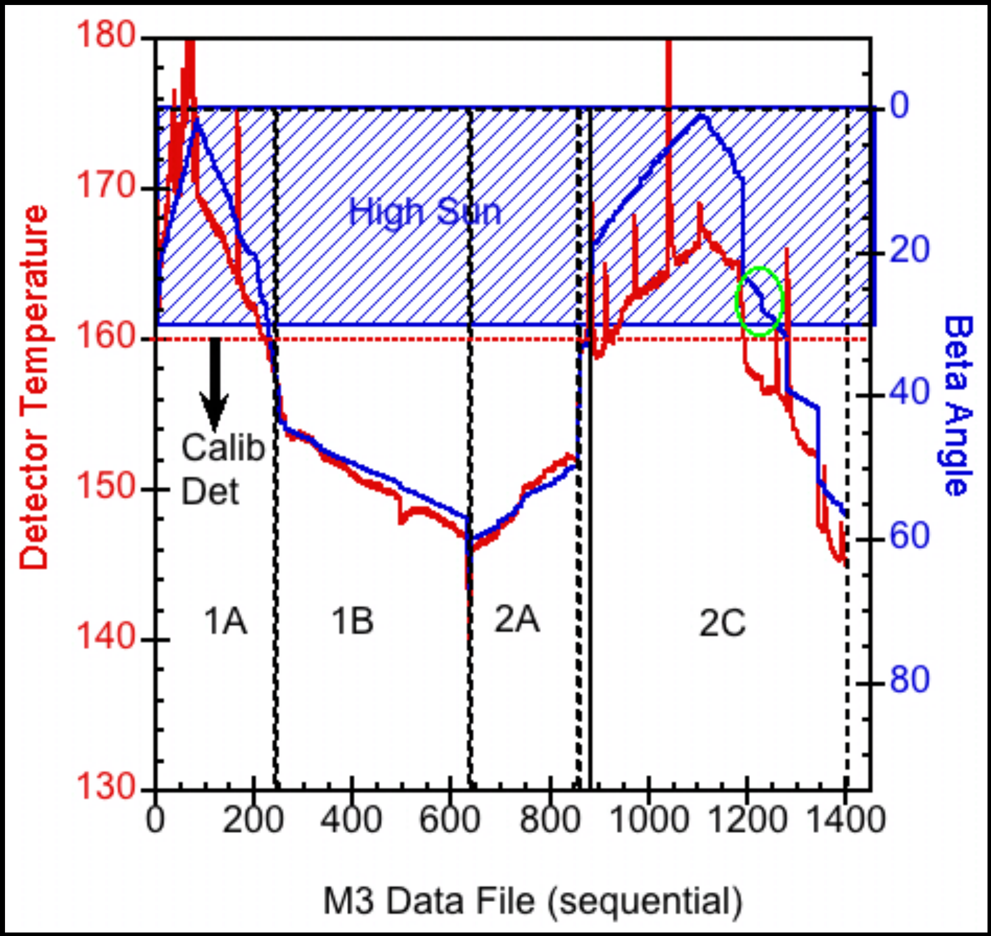
- M3 observed data during two optical periods, defined by favorable viewing conditions
- The team subdivided the optical periods based on data characteristics:

| Period | Dates | Images | Orbit | Star Sensors | Status |
|---|---|---|---|---|---|
| OP1A | Nov 18 - Jan 24 | 119 | 100 km | 1 of 2 | extended commissioning |
| **OP1B** | **Jan 25 - Feb 14** | **247** | **100 km** | **1 of 2** | **operational, high solar zenith angles** |
| OP2A | Apr 15 - Apr 27 | 197 | 100 km | 1 of 2 | operational, high solar zenith angles |
| OP2B | May 13 - May 16 | 20 | 100 km | 0 of 2 | S/C emergency, orbit raised |
| **OP2C** | **May 20 - Aug 16** | **375** | **200 km** | **0 of 2** | **operational, variable conditions** |

# M3 Coverage per OP + Targets



# M3 Optical Periods




- High detector temperatures were encountered when observations were made at optimal high sun conditions. Very low detector temperatures were only encountered during periods of very low sun angle

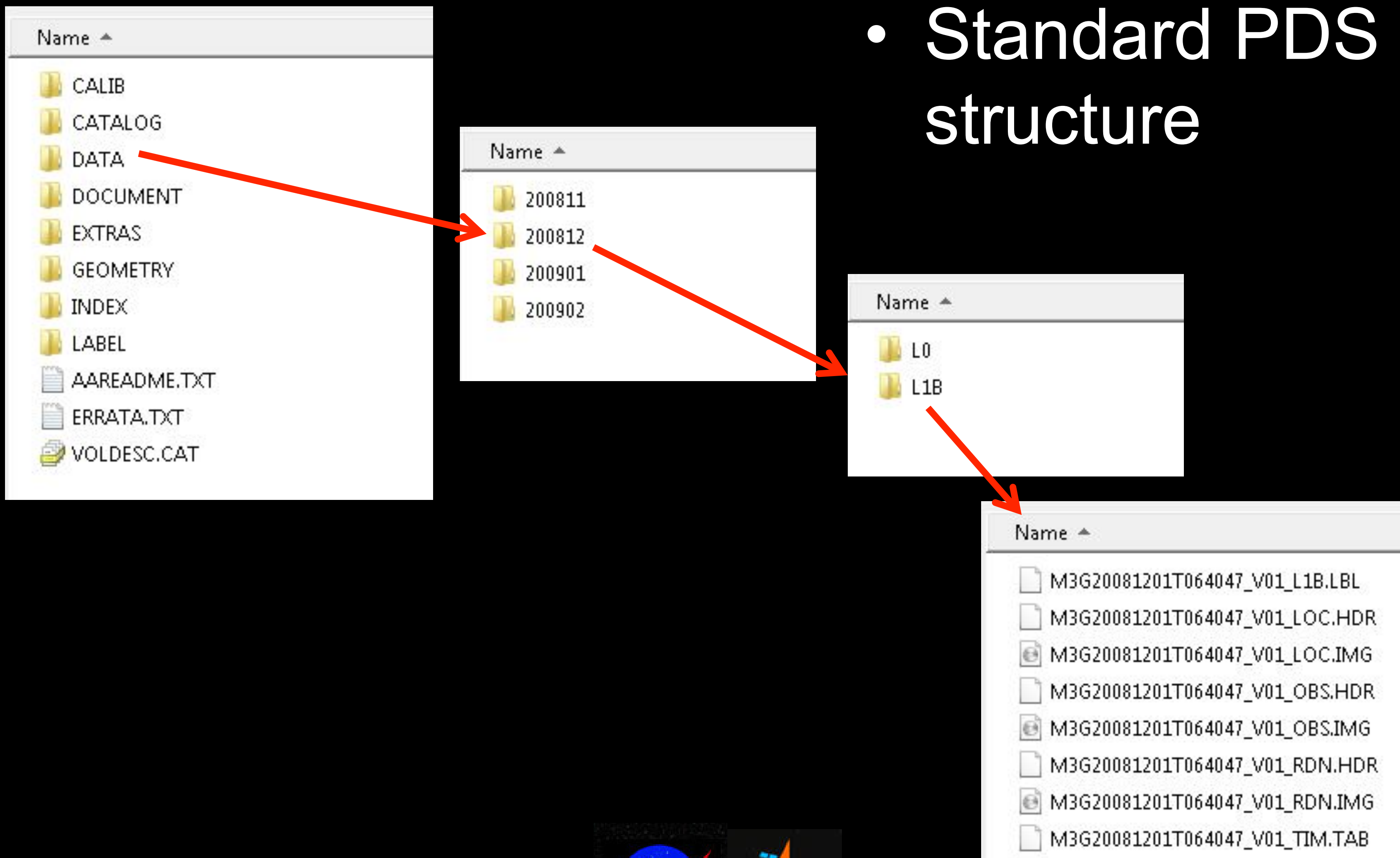
# *PDS Releases*

- Level 0 and Level 1B:
  - OP1 (R3, R4 calibration): June 2010
  - OP2 (R4 calibration): December 2010
  - *OP1 and OP2 (U2 calibration): delivered to PDS 9/30/11*
- Level 2 (U2 calibration):
  - OP1 and OP2: November 2011

L0 = raw spacecraft data, L1b=radiance + backplanes, L2 = reflectance

# M3 File Formats/PDS Structure

# PDS Directory Structure




- Standard PDS structure

# M3 File Naming Convention

M3G20090204T113444_V01_RDN.IMG

Basename | Version | Data Type | File Type

- Basename – covered next slide
- Version – gives the version of a file: final L0 is V01, final L1B is V03, and final L2 is V01
- Data type – tells you the type of information stored in the file
  - Possible values in PDS deliveries:
    - L0 – raw spacecraft data
    - RDN – L1B radiance
    - RFL – L2 reflectance
    - SUP – L2 supplemental file
    - OBS – L1B observational data (incidence, emission, phase angles, etc.)
    - LOC – L1B location data (latitude, longitude, radius)
    - TIM – L1B time of observation
- File Type – tells you the file format
  - Possible Values in PDS deliveries:
    - IMG – raw binary image data
    - HDR – ENVI header
    - LBL – PDS label
    - TAB – tabular data stored in ASCII format

# M3 File Naming Convention (cont'd)

Example Basename: M3G20090204T113444

M3 G 2009 02 04 T 11 34 44

- M3 — Always "M3"
- G — Observation type: G=Global, T=Target
- 2009 — Year
- 02 — Month
- 04 — Day
- T — Always "T"
- 11 — Hour
- 34 — Minutes
- 44 — Seconds

Note: Sorting by filename is only equivalent to sorting by observation time if you do not have global and target data mixed together. If you do have a mix of the two, remove the first three characters then sort by filename to also sort by observation time.

# *M3 image data format*

- The following applies to all M3 image data:
- Files are raw binary data (no offset)
- Interleave is BIL (line-interleaved)
- Global data have 304 samples (columns) for all image types (except L0, which has 320)
- Targeted data have 608 samples (L0 has 640)
- Number of lines (rows) is variable (determined by length of observation)
- Data type is 32-bit floating point (LOC files are 64-bit double precision floating point)
- “Backplanes” = OBS, LOC, and TIM files

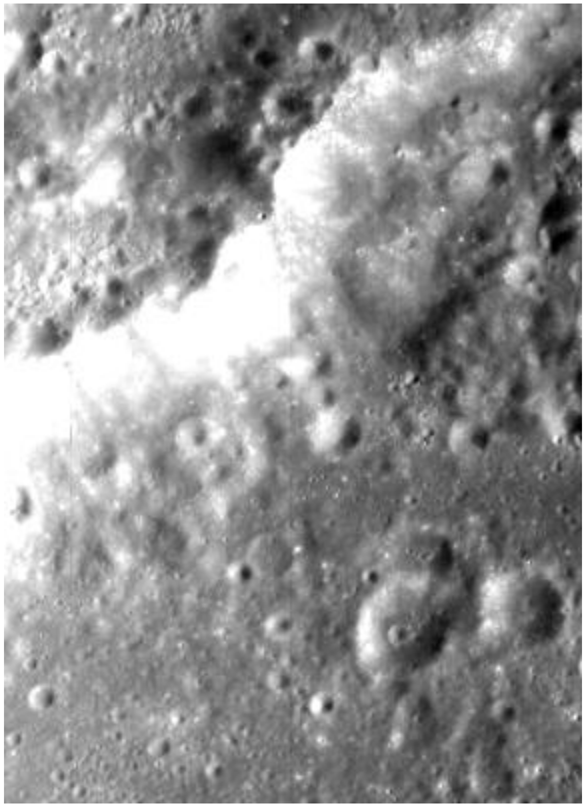
# M3 Data types: L0

M3G20090126T033545_V01_L0.IMG

- L0 is raw spacecraft data, units are DN
- 320 samples which are reduced to 304 when converted to radiance
  - The 16 columns that are removed are for monitoring dark signal level and scattered light
- Each frame has a 1280-byte header
- To directly compare L0 to radiance:
  - No sample or line flip starting Nov 16 2008
  - Sample only flip starting Dec 18 2008
  - Line only flip starting Mar 14 2009
  - Sample and line flip starting Jun 18 2009

# M3 Data Types: L1B RDN

M3G20090126T033545_V01_RDN.IMG



- Radiance data, units W/($m^2$ Sr μm)
- Steps used to create radiance described in calibration slides
- PDS label or ENVI header can be used to open files
- ENVI Header contains:
  - Calibration steps
  - Target wavelengths (averaging for global)
  - Target FWHM
  - Dark Signal Image
  - Anomalous Detector Map
  - Flat Field Image
  - Detector Temperature
  - Beta Angle
  - Sample/Line flip code

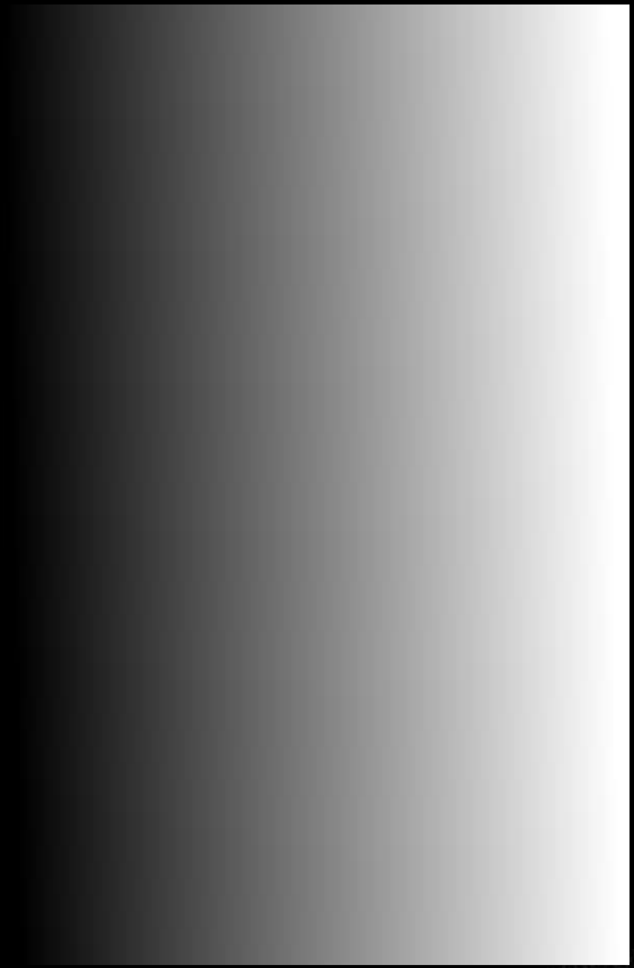
# M3 Data Types: OBS

- List of bands in OBS file:
  - To-Sun Azimuth (deg)
  - To-Sun Zenith (deg)
  - To-M3 Azimuth (deg)
  - To-M3 Zenith (deg)
  - Phase (deg)
  - To-Sun Path Length (au-0.981919816030)
  - To-M3 Path Length (m)
  - Facet Slope (deg)
  - Facet Aspect (deg)
  - Facet Cos(i) (unitless)
- Values in the To-Sun Path Length band are the difference from the scene mean path length.

Scene-mean to-Sun path length

# M3 Data Types: OBS

Phase angle band



Facet cos(i) angle band

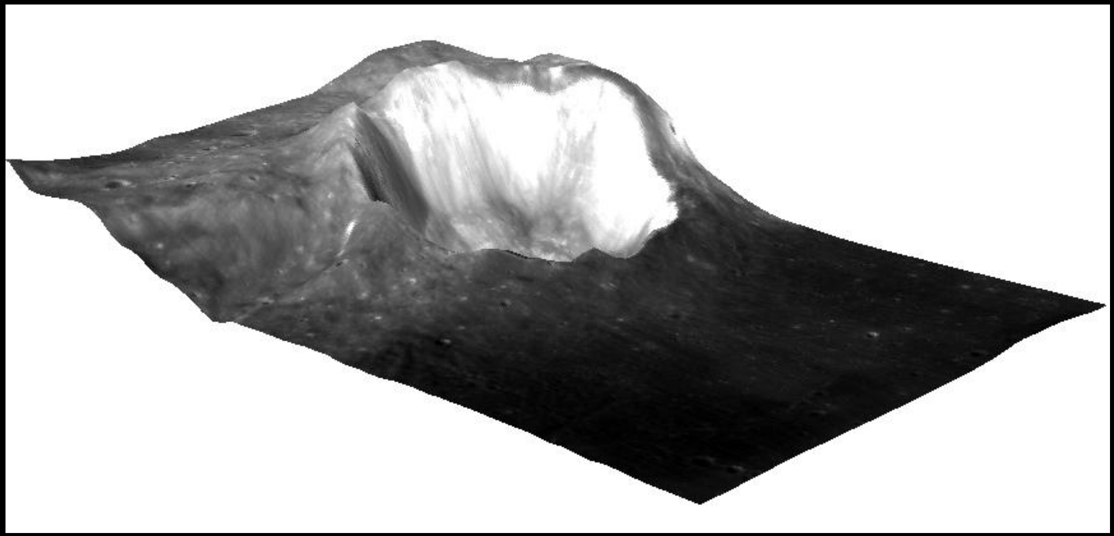
# M3 Data Types: LOC

- List of channels in LOC file:
  - Longitude
  - Latitude
  - Radius
- Subtract lunar radius of 1737400 m to get difference in elevation from reference sphere
- Based on LOLA topography (see Boardman et al., JGR 2011)
- Reference frame is Moon Mean Earth Polar Axes (MOON_ME) frame

# M3 Data Types: OBS

Band 3 “Radius”

750 nm albedo draped over “Radius” band



# M3 Data Types: TIM

## One ASCII text record per frame:

Column 1: Frame Number

Column 2: UTC Time

Column 3: Year

Column 4: Decimal Day of Year

M3G20081118T222604_V01_TIM.TAB (Z:\m3team\DATA\RRAD\DATA\20081118_20090214\200811\L1B\)

File Edit Insert Format Settings Tools Window Help

| | | | |
|---|---|---|---|
| 1 | 2008-11-18T22:26:03.491014 | 2008 | 322.934762614844 |
| 2 | 2008-11-18T22:26:03.592772 | 2008 | 322.934763792605 |
| 3 | 2008-11-18T22:26:03.694531 | 2008 | 322.934764970366 |
| 4 | 2008-11-18T22:26:03.796289 | 2008 | 322.934766148128 |
| 5 | 2008-11-18T22:26:03.898048 | 2008 | 322.934767325889 |
| 6 | 2008-11-18T22:26:03.999806 | 2008 | 322.934768503650 |
| 7 | 2008-11-18T22:26:04.101565 | 2008 | 322.934769681411 |
| 8 | 2008-11-18T22:26:04.203324 | 2008 | 322.934770859173 |
| 9 | 2008-11-18T22:26:04.305082 | 2008 | 322.934772036933 |
| 10 | 2008-11-18T22:26:04.406841 | 2008 | 322.934773214695 |
| 11 | 2008-11-18T22:26:04.508599 | 2008 | 322.934774392456 |
| 12 | 2008-11-18T22:26:04.610358 | 2008 | 322.934775570217 |
| 13 | 2008-11-18T22:26:04.712116 | 2008 | 322.934776747979 |
| 14 | 2008-11-18T22:26:04.813875 | 2008 | 322.934777925740 |
| 15 | 2008-11-18T22:26:04.915634 | 2008 | 322.934779103501 |
| 16 | 2008-11-18T22:26:05.017392 | 2008 | 322.934780281262 |
| 17 | 2008-11-18T22:26:05.119151 | 2008 | 322.934781459024 |
| 18 | 2008-11-18T22:26:05.220909 | 2008 | 322.934782636785 |
| 19 | 2008-11-18T22:26:05.322668 | 2008 | 322.934783814546 |
| 20 | 2008-11-18T22:26:05.424426 | 2008 | 322.934784992307 |
| 21 | 2008-11-18T22:26:05.526185 | 2008 | 322.934786170069 |
| 22 | 2008-11-18T22:26:05.627944 | 2008 | 322.934787347830 |
| 23 | 2008-11-18T22:26:05.729702 | 2008 | 322.934788525591 |
| 24 | 2008-11-18T22:26:05.831461 | 2008 | 322.934789703352 |
| 25 | 2008-11-18T22:26:05.933219 | 2008 | 322.934790881114 |
| 26 | 2008-11-18T22:26:06.034978 | 2008 | 322.934792058875 |
| 27 | 2008-11-18T22:26:06.136736 | 2008 | 322.934793236636 |

# *Good Stuff in the PDS Directories*

- CALIB
  - In L1B:  Record of detector temperatures, band pass functions, spectral calib. File (wavelength center positions), radiometric calibration coefficients
  - In L2:  Reflectance calibration tables providing the solar spectrum, statistical polishing factors, photometric correction factors, and ground truth correction factors.
- DOCUMENT
  - Data Product SIS document that describes all files released to PDS down to the byte level; Archive Volume SIS describes PDS directory structure
- EXTRAS
  - In L1B:  Flat fields, anomalous detector element maps, quicklooks

# *Calibration*

# *Converting L0 to L1 (Radiance)*

- M3 Global Mode Calibrated Data version r4
- Raw image;
- Dark signal subtraction;
- Anomalous detector element interpolation;
- Interpolate filter edges c13, c50;
- Interpolate detector panel edges s81, s161, s241;
- Electronic panel ghost correction;
- Dark pedestal shift correction;
- Scattered light correction;
- Laboratory flat field;
- Image based flat field w/ photometry preserved;
- Nonlinearity correction
- Apply radiometric calibration coefficients;
- Apply shape correction
- Units (W/m^2/um/sr)

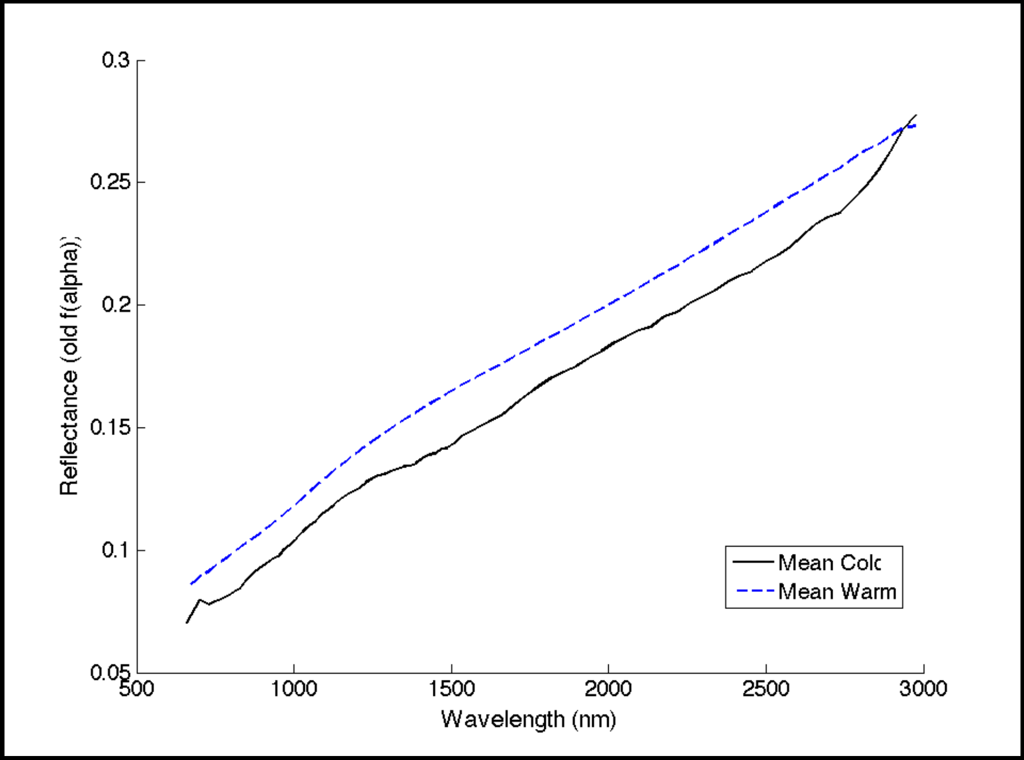
See Green et al. (JGR, 2011) and L1B SIS PDS document for more detailed description.

# Basic calibration equation

$$L_{l,s,\lambda} = RCC_{\lambda}(C_{s,\lambda}(DN_{l,s,\lambda} - \overline{DS_{s,\lambda}}))$$

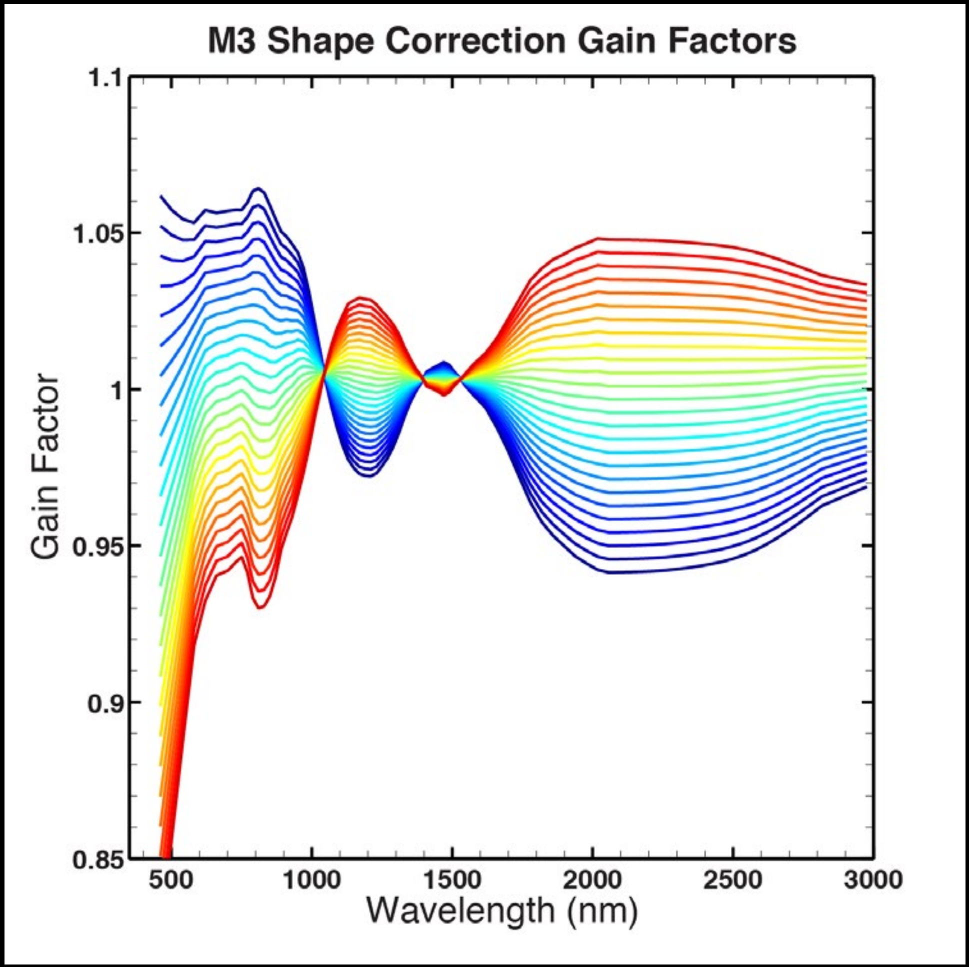
- L = calibrated radiance
- RCC = radiometric calibration coefficients
- C = term encompassing all correction factors (flat fields, etc.)
- DN = raw digital number
- DS = dark signal

# *Shape correction*




- “Raw signal” artifacts apparent in data collected under variable operational conditions
- Most apparent in ratios of spectra from identical regions but with variable detector temperatures
- Mitigation approach: scene subset covering same region under several detector temperature conditions
- Derive gain factors that force spectral ratios to be flat (ratios over the same terrain should not exhibit spectral variability)

# Shape correction

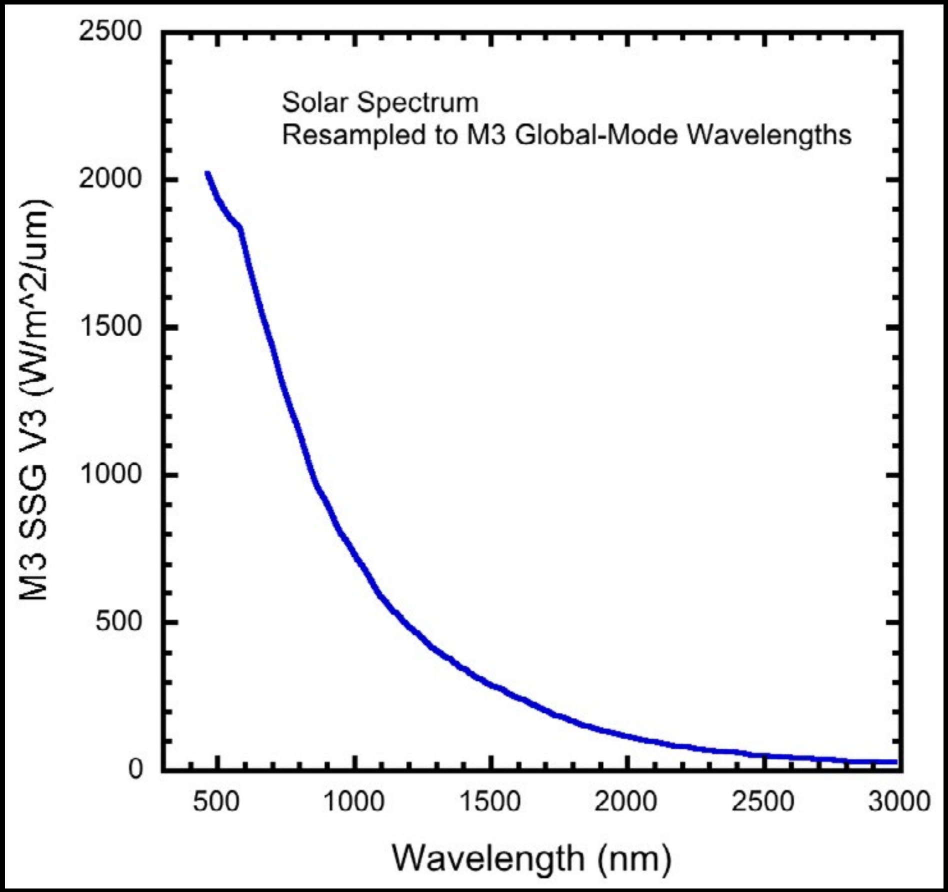



- Interpolate for full detector temperature coverage
- Applied To *delivered* U2 radiance L1B data
- Gain factor used is recorded in label files (reversible correction)
- In EXTRAS directory, individual per image (named with BASENAME_SSCADJ.TAB)
- Key difference between older R4 calibration and U2 (U2 has shape correction applied).

# *Converting L1 to L2 (Reflectance)*

- M3 Global Mode Calibrated Data version u2
- Radiance image
- Divide by solar irradiance
- Statistical polisher
- Remove thermal emission
- Photometric correction
- Ground truth correction *(NOT applied to delivered L2 data)*
- Units are reflectance (0-1)

# Division by Solar Irradiance

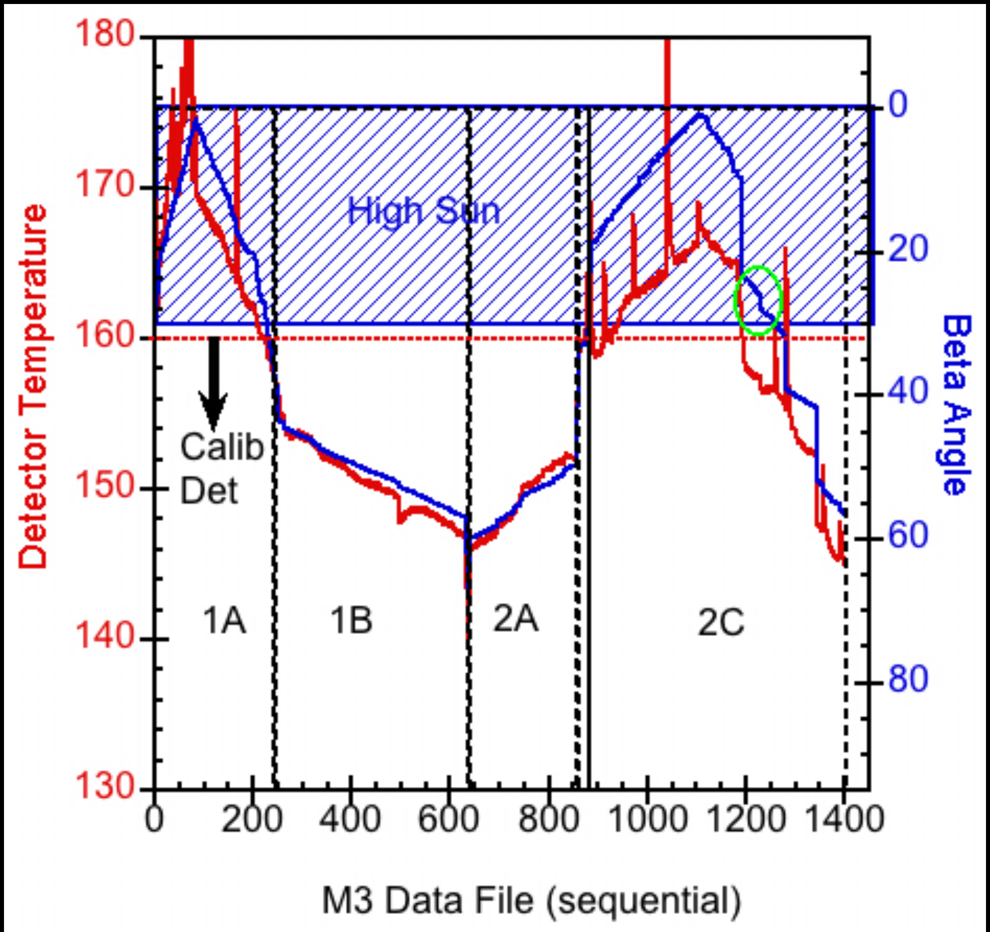



- Divide by solar irradiance to create "I/F".

$$\frac{I}{F}(\lambda) = \frac{L1B(\lambda) * \pi}{L(\lambda)/d^2}$$

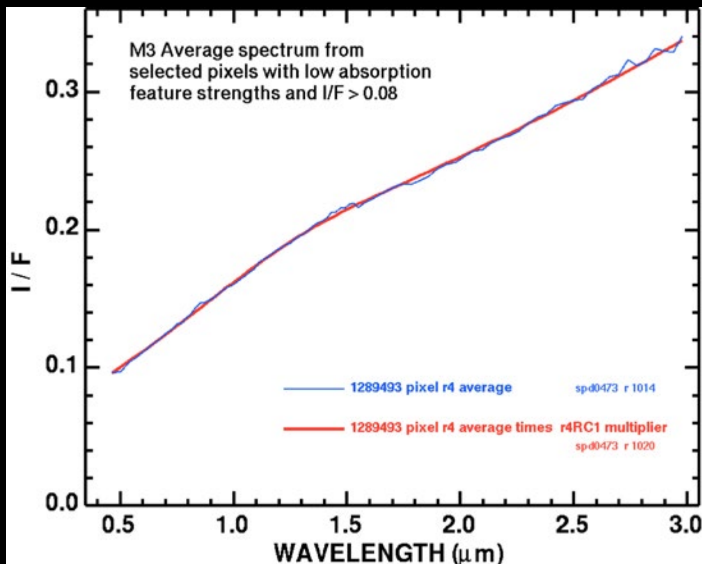
- L1B = radiance from L1B
- L = solar irradiance
- d = normalized Moon-Sun distance from L1B backplane (OBS) files
- Solar spectra stored in PDS archive (CALIB) directory
- Solar spectra also available on web (global and target modes).
  - http://m3.jpl.nasa.gov/m3data.html

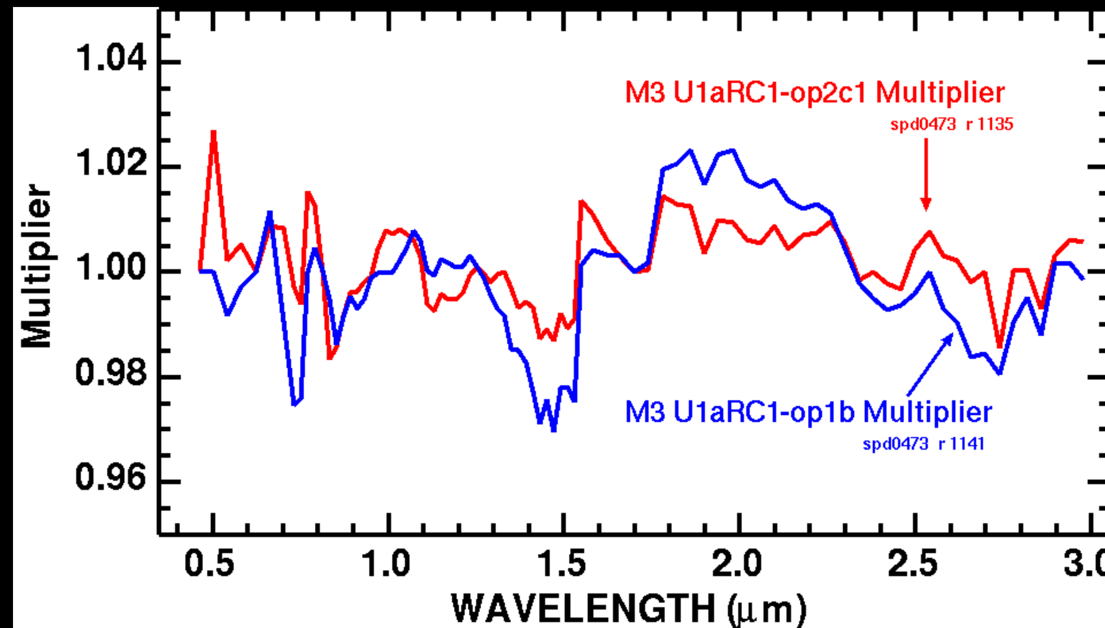
# Statistical Polishing




- Goal: remove systematic band-to-band artifacts in M3 data.
- Temperature dependence: strong temperature variations resulting from spacecraft thermal challenges require different "polishers" from different input data "suites".

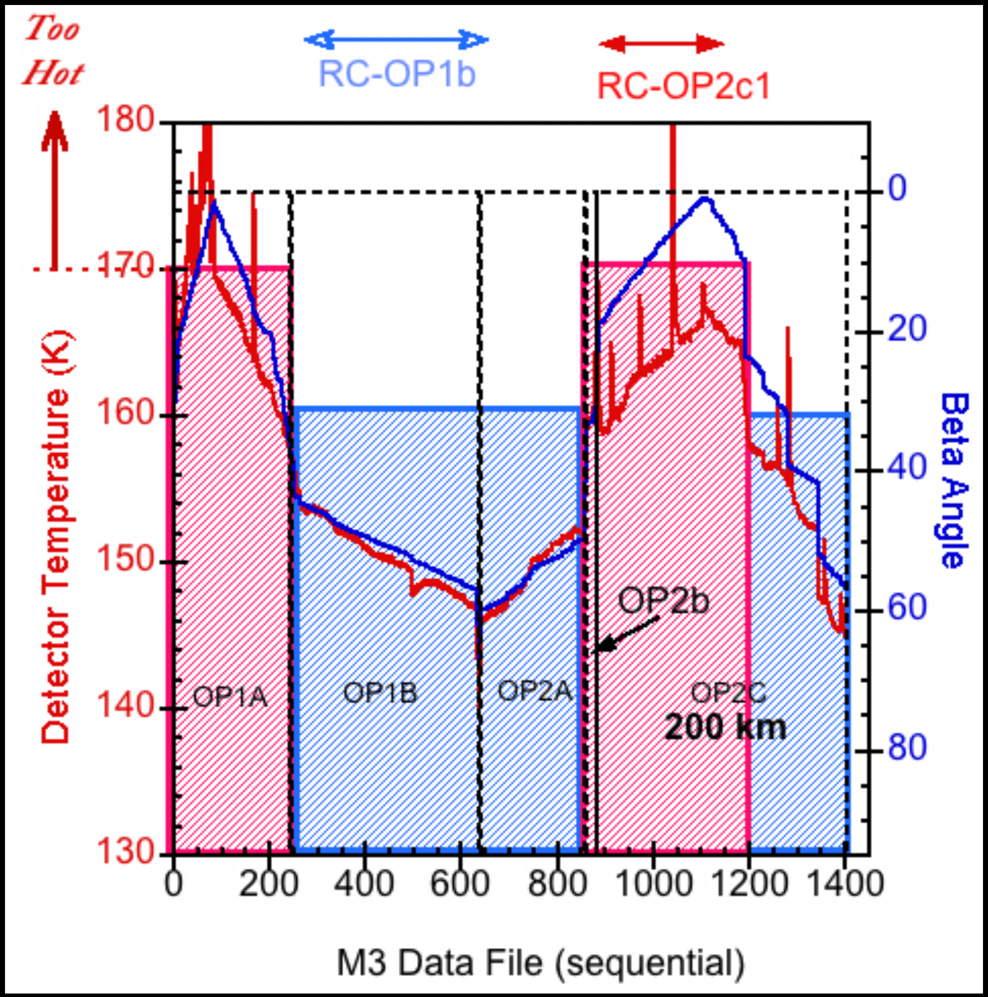
# Statistical Polishing




- Select a large suite of “featureless” spectra (A)
- Perform cubic spline fit (manual) to average spectrum (B)
- Polisher = A / B
- Temperature dependence: distinct polishers from distinct input suites
- Gain factors stored in L2 CALIB directory; pointers in label files.

# Statistical Polishing: Application




Polisher application summary:

**OP1**

HOT: 11/18/2008 – 1/18/2009

COLD: 1/19/2009 – 2/14/2009

**OP2**

COLD: 4/15/2009 – 4/27/2009

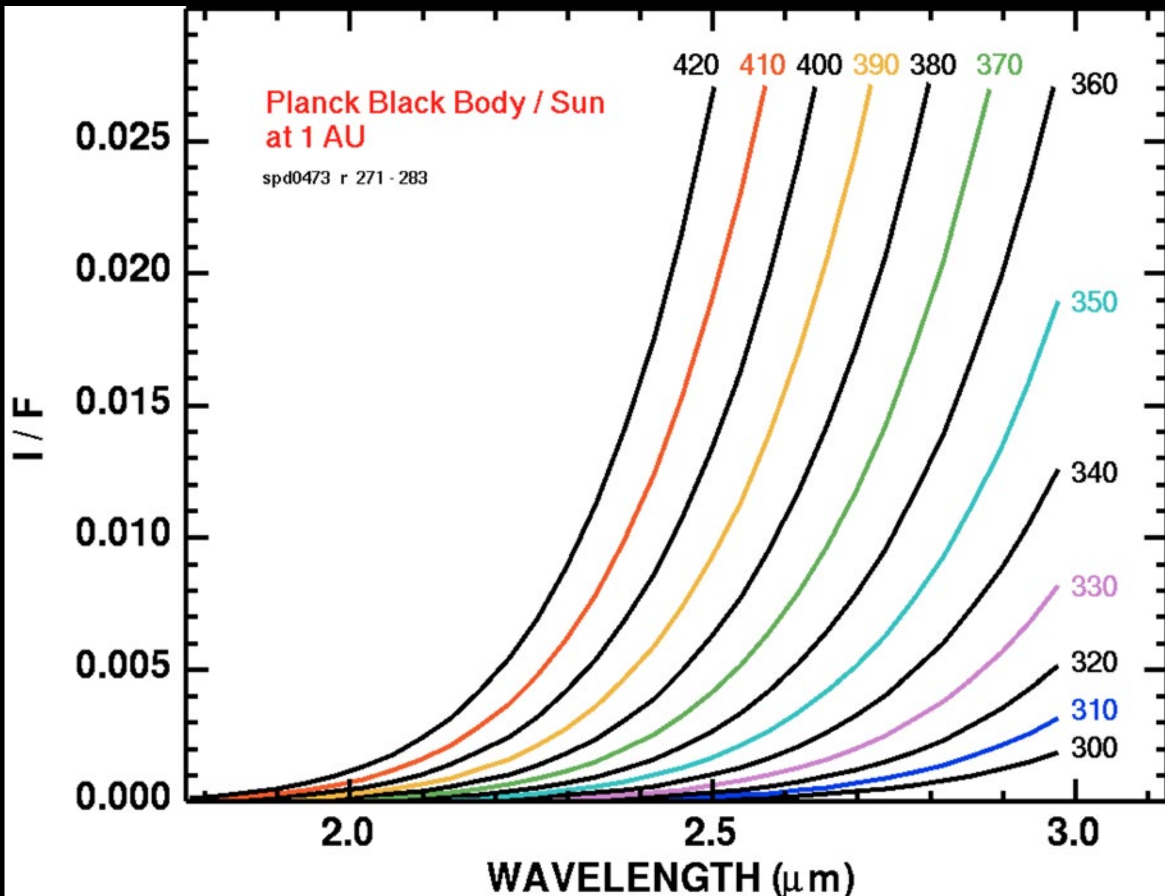
HOT: 5/13/2009 – 5/16/2009

-------altitude change-------

HOT: 5/20/2009 – 6/27/2009

COLD: 7/12/2009 – 8/16/2009

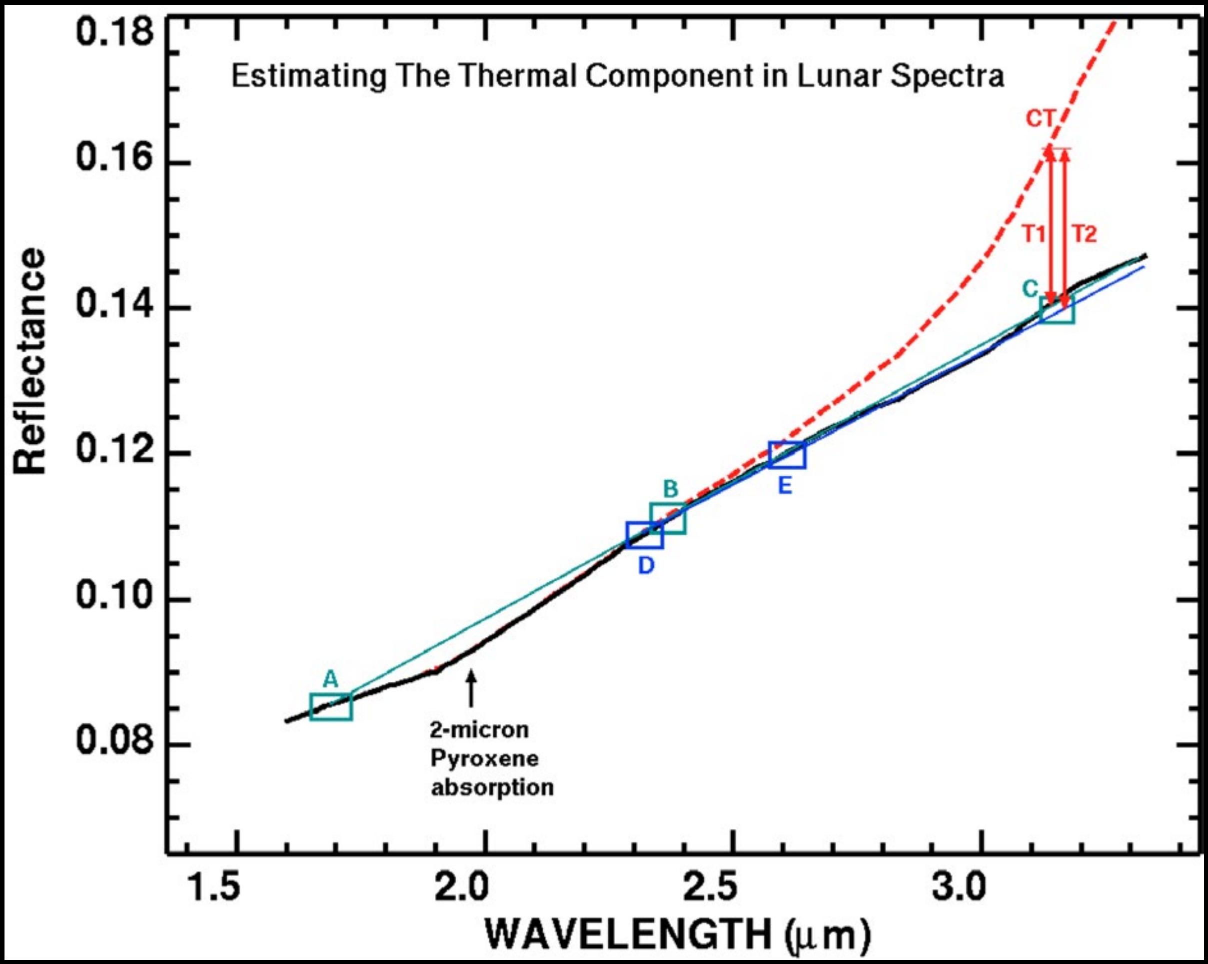
# *Thermal Removal*




Clark et al., 2011

- Thermally emitted radiation is apparent at longer M³ wavelengths for warm surfaces
- Affects long wavelength spectral character
- Team has devised an approach to remove “excess” thermal emission component (see Clark et al., 2011 JGR)

# Thermal Removal




- Project to C from A and B; remove thermal component (Planck function) T1
- Use T1-corrected spectrum, project to C from D and E, remove thermal component T2
- Third iteration (C from D and E) if derived temperatures bet. steps 1 and 2 vary by >2 K.
- Thermal emission NOT removed where no temperature derived (where no excess thermal component is detected).

Clark et al., 2011

# *Photometric correction*

- Goal of photometric correction: normalize the reflectance to standard geometry: i=30, e=0, a=30

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

  - Where XL is the limb darkening. It can be modeled by lunar-lambert (Clementine mission) or Lommel-Seeliger (LROC). We are using Lommel-Seeliger.
    - $L2_{s4}$ is photometrically-corrected reflectance, $L2_{s3}$ is the output of the thermal correction step (includes division by solar irradiance, statistical polishing, and thermal removal).

  - We use the topography derived from LOLA

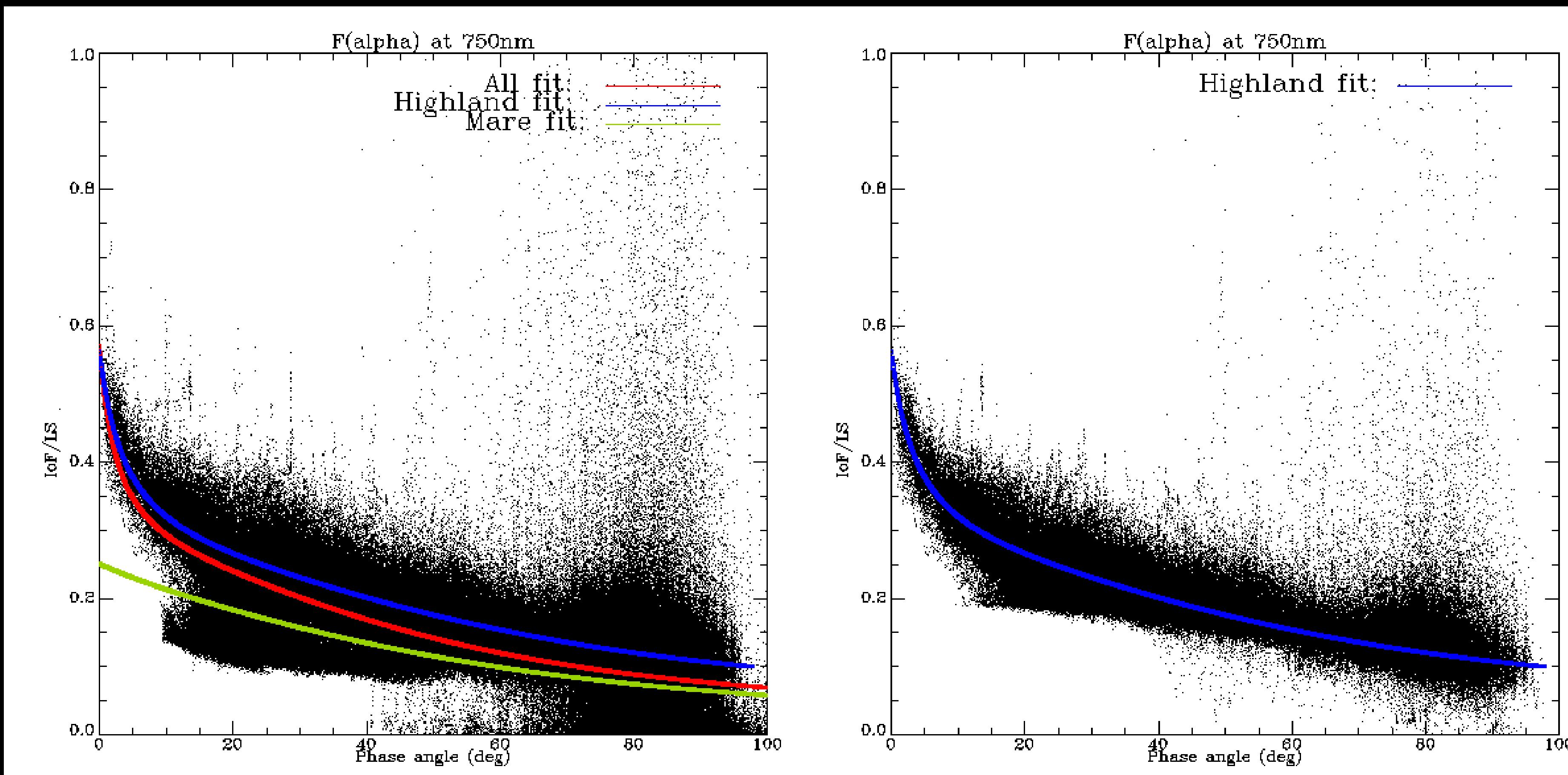
  - And the f(alpha) is determined from the data itself

# *Photometric correction*

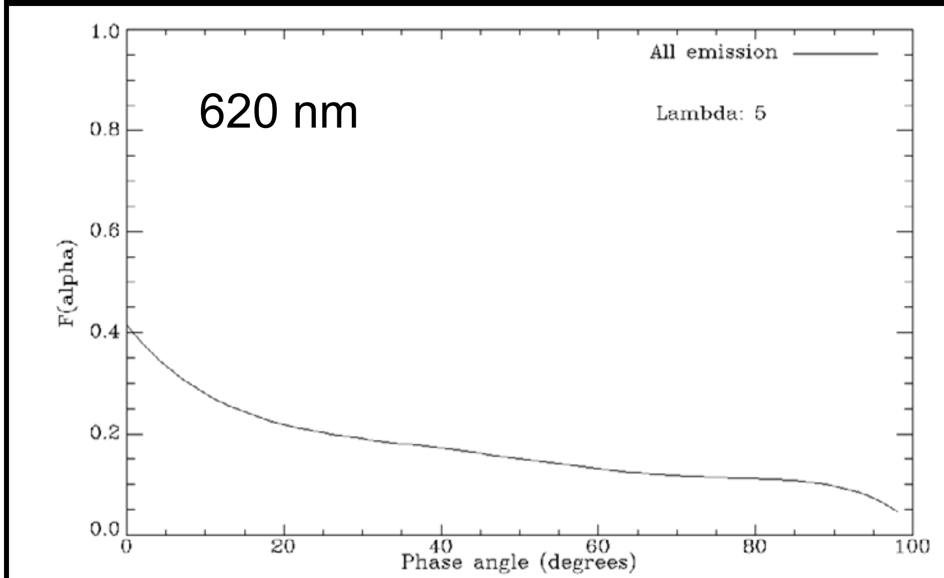
- Data used to define the F(alpha)
  - OP2C, representing ~1 full coverage of the Moon
  - Data have been thermally corrected (data subsetted by pixels where a temperature was derived in the previous step).
  - For data higher than 75° latitude, we use of all pixels because thermal emission is ~nonexistent.
  - Where i or e > 85° latitude, they are set to 85° to avoid physically unrealistic limb darkening corrections.
  - We separate highland and mare using empirical model. This model uses the reflectance at 750nm and the slope between 750 and 950 nm. Only HIGHLAND pixels are used to derive the f(alpha)
  - We obtain >100,000 spectra
  - We cover phase angle from 0 to 100 degrees
- **Then we fit with a polynomial function (fit in phase angle), and smooth in wavelength.**
- *F(alpha) table stored in CALIB directory*

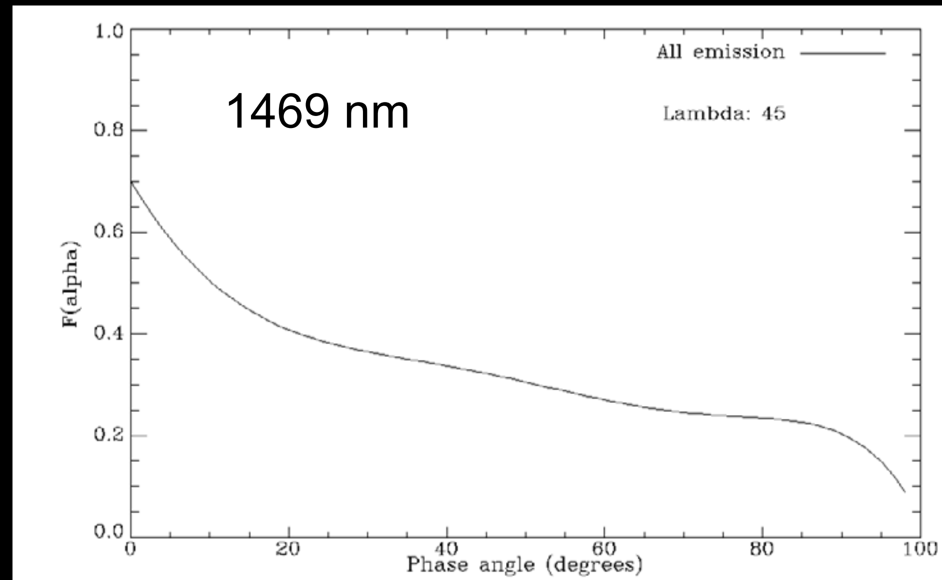
# Photometric correction

Mare & Highland | Highland only

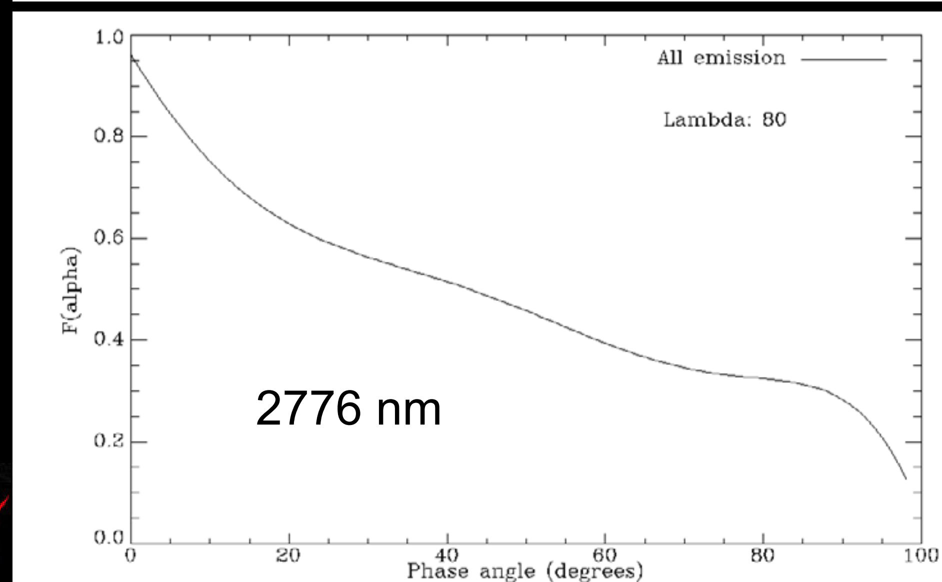


# Photometric correction

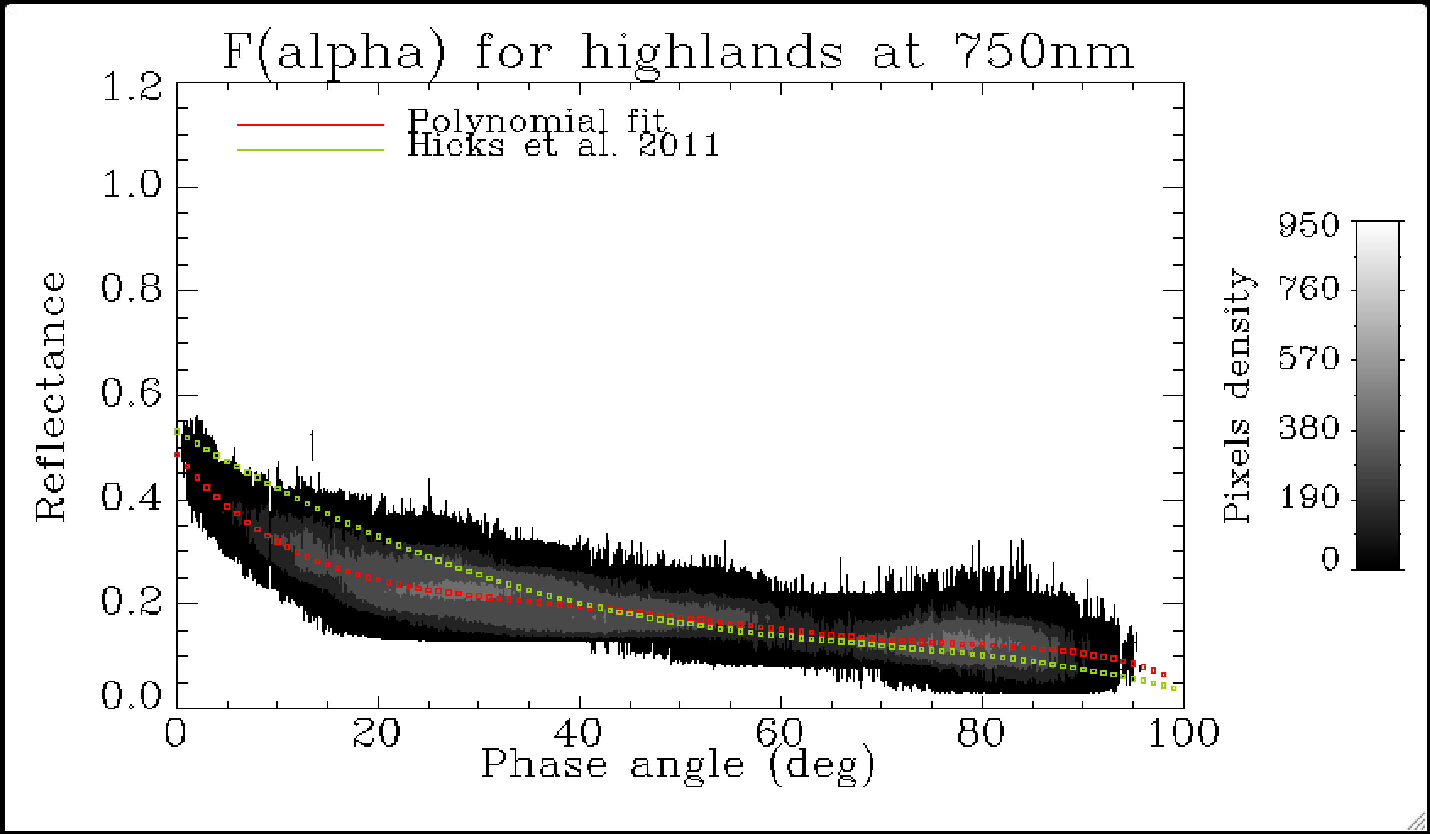



Highland fit for different wavelengths

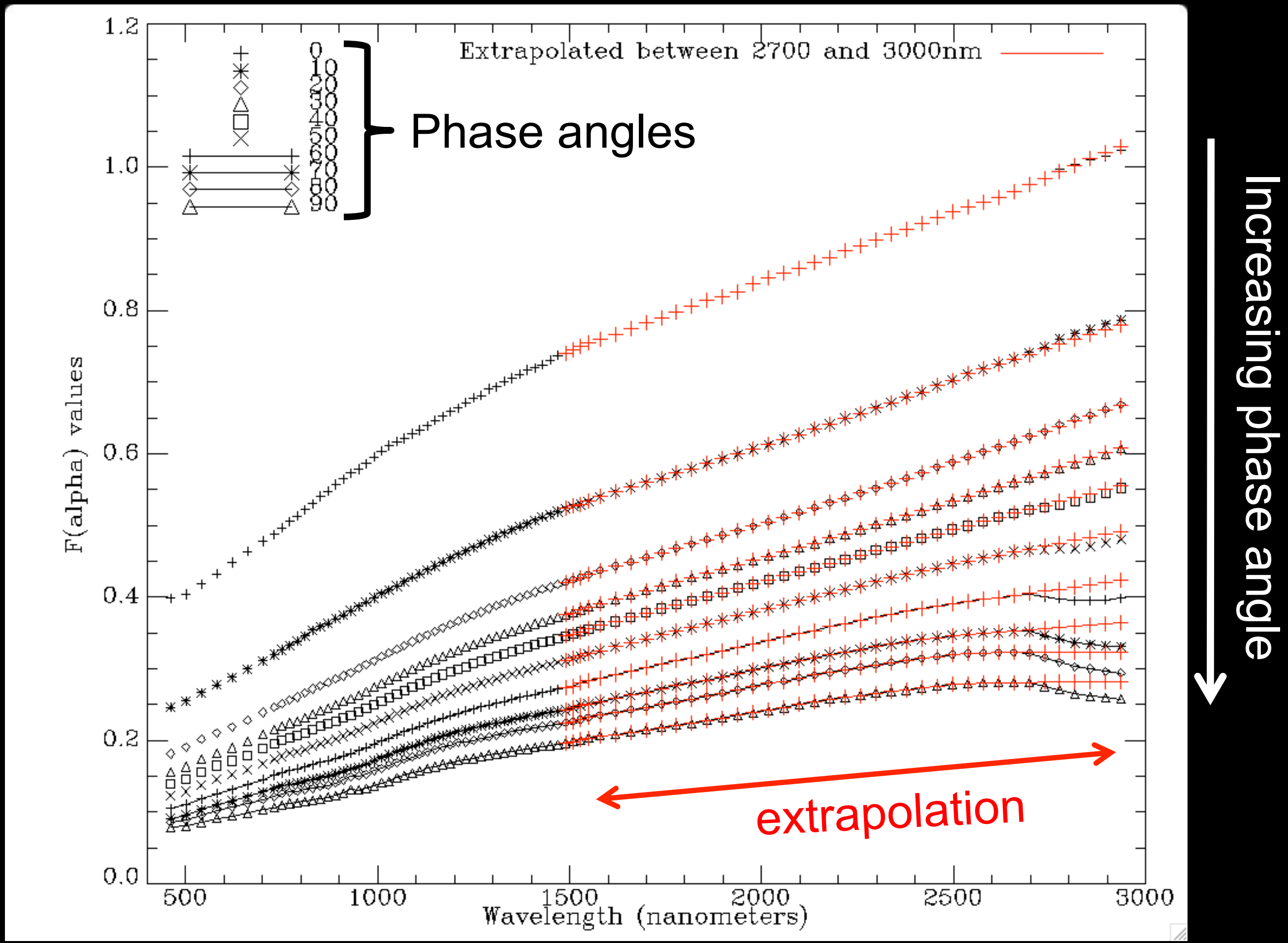


# Photometric correction



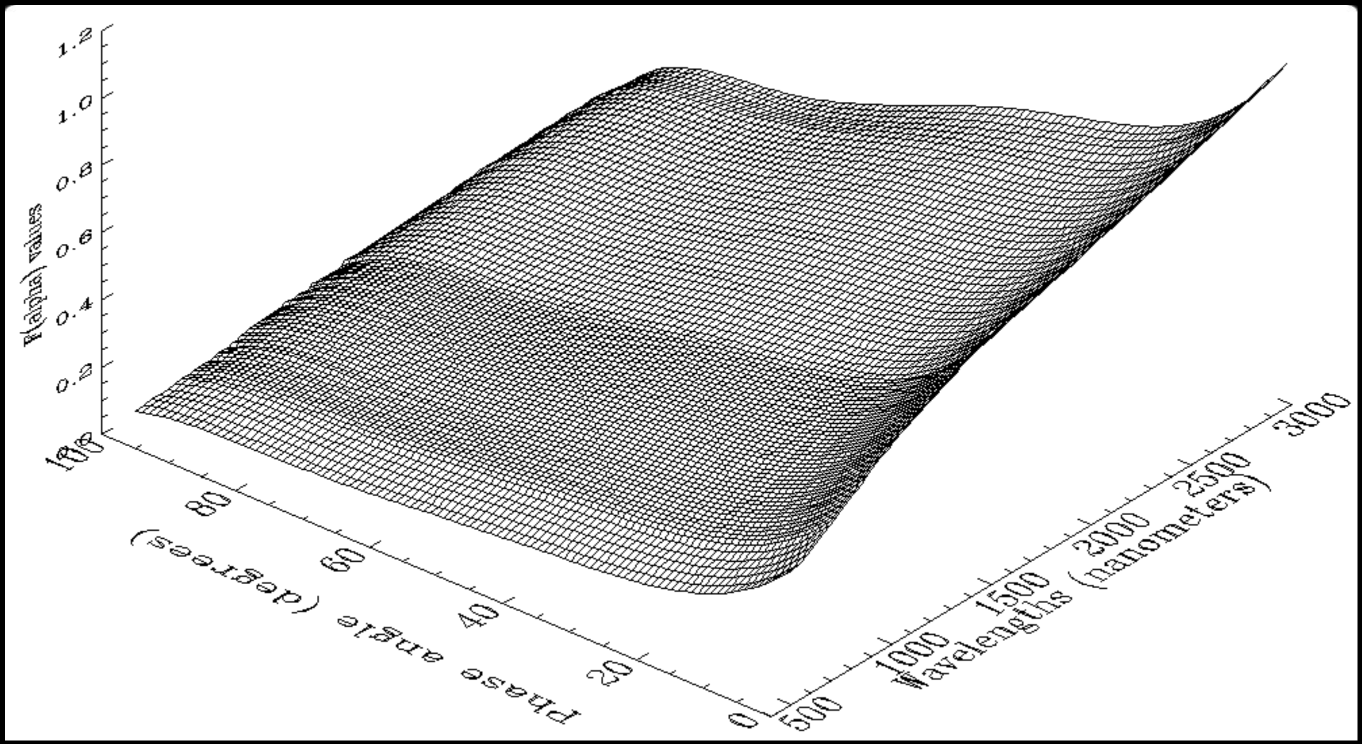

Comparison with previous model

# Photometric correction



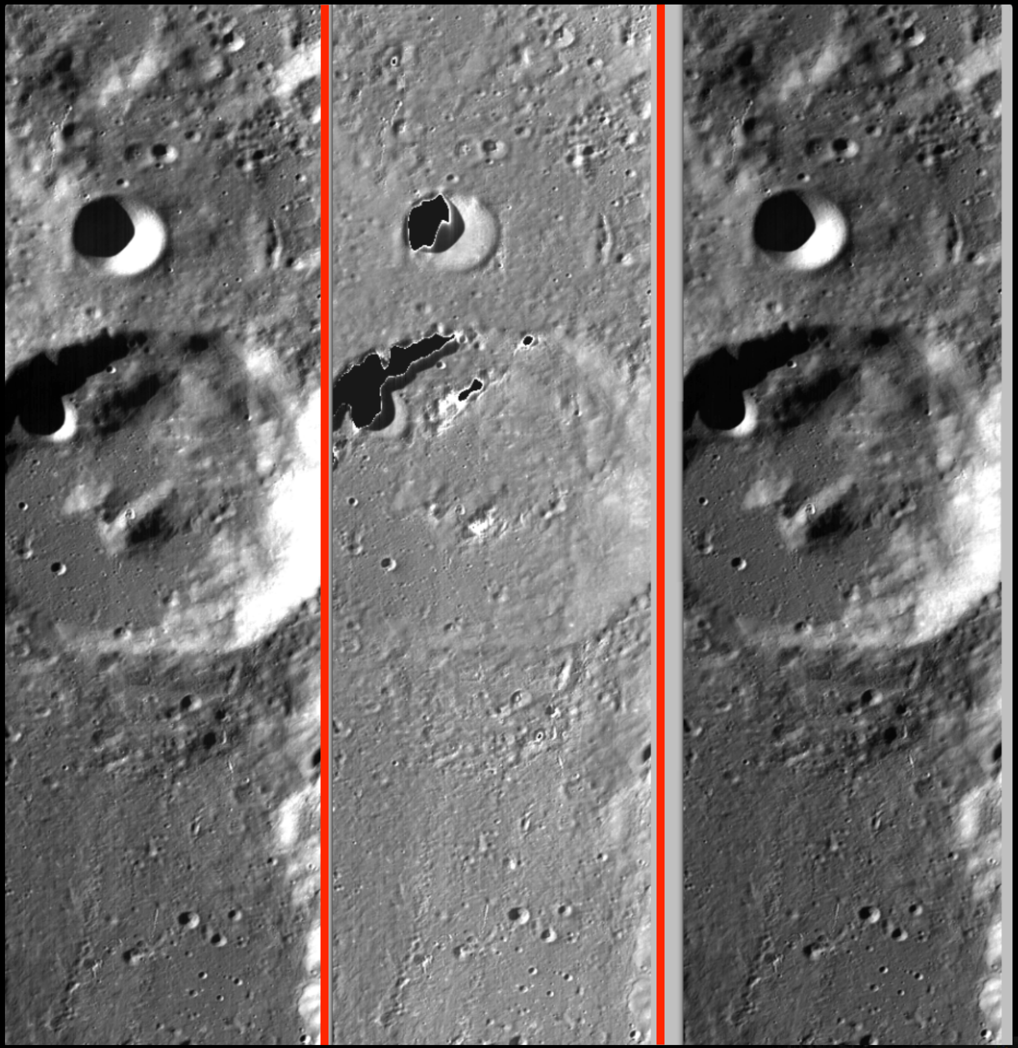

Interpolation from 2.7 to 3.0

# *Photometric correction*




3D view of the derived F(alpha) function

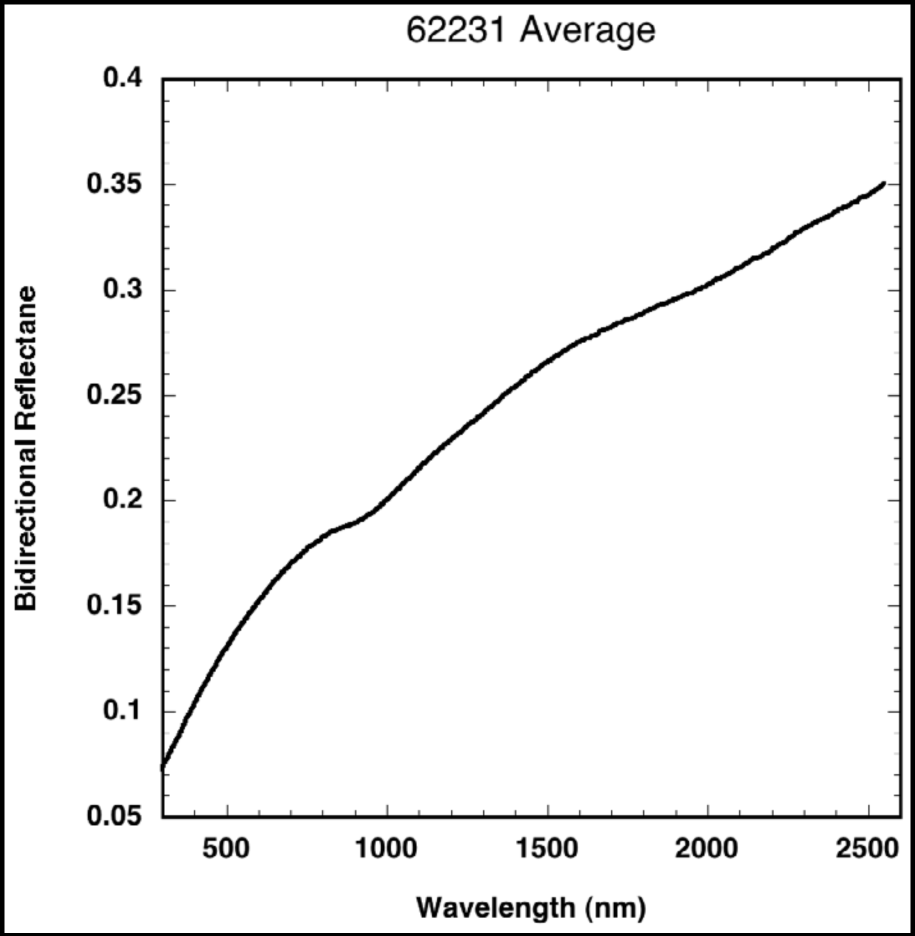
# Photometric correction



From left to right:
Reflectance
Reflectance + Photometry (topo)
Reflectance + Photometry (sphere)

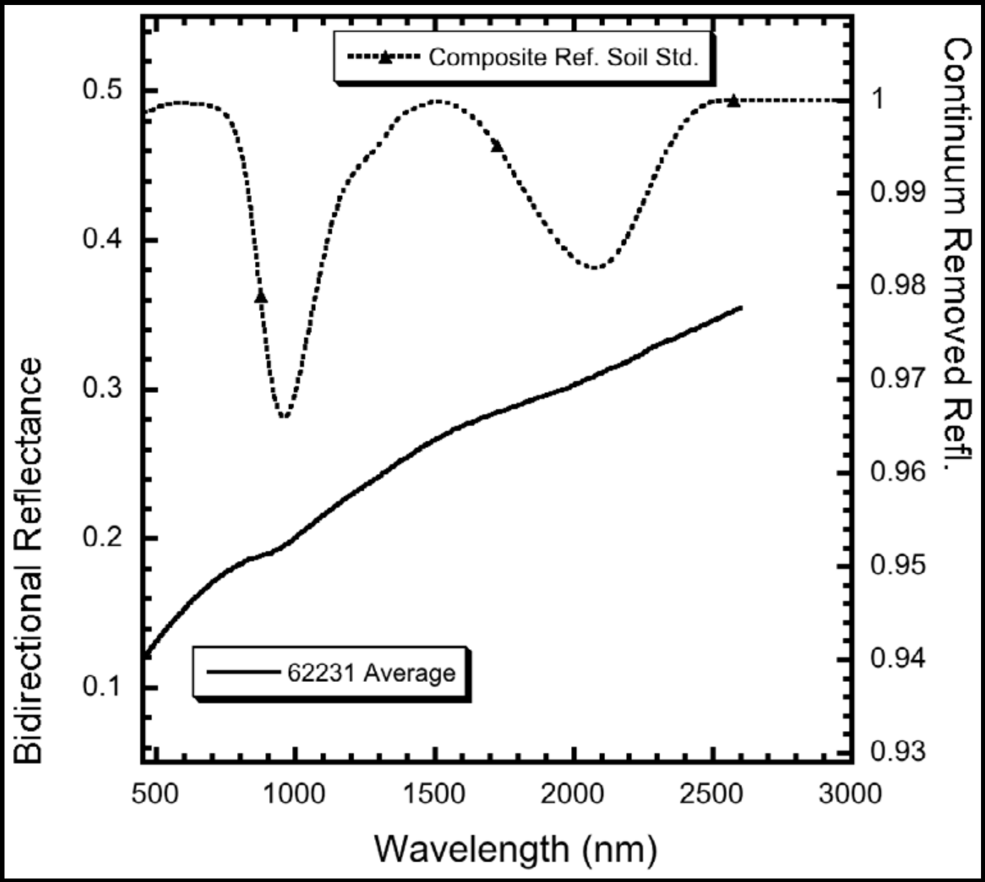
Using Photometry with i,e,a from topo,
The topography itself disapears.

# Ground truth correction



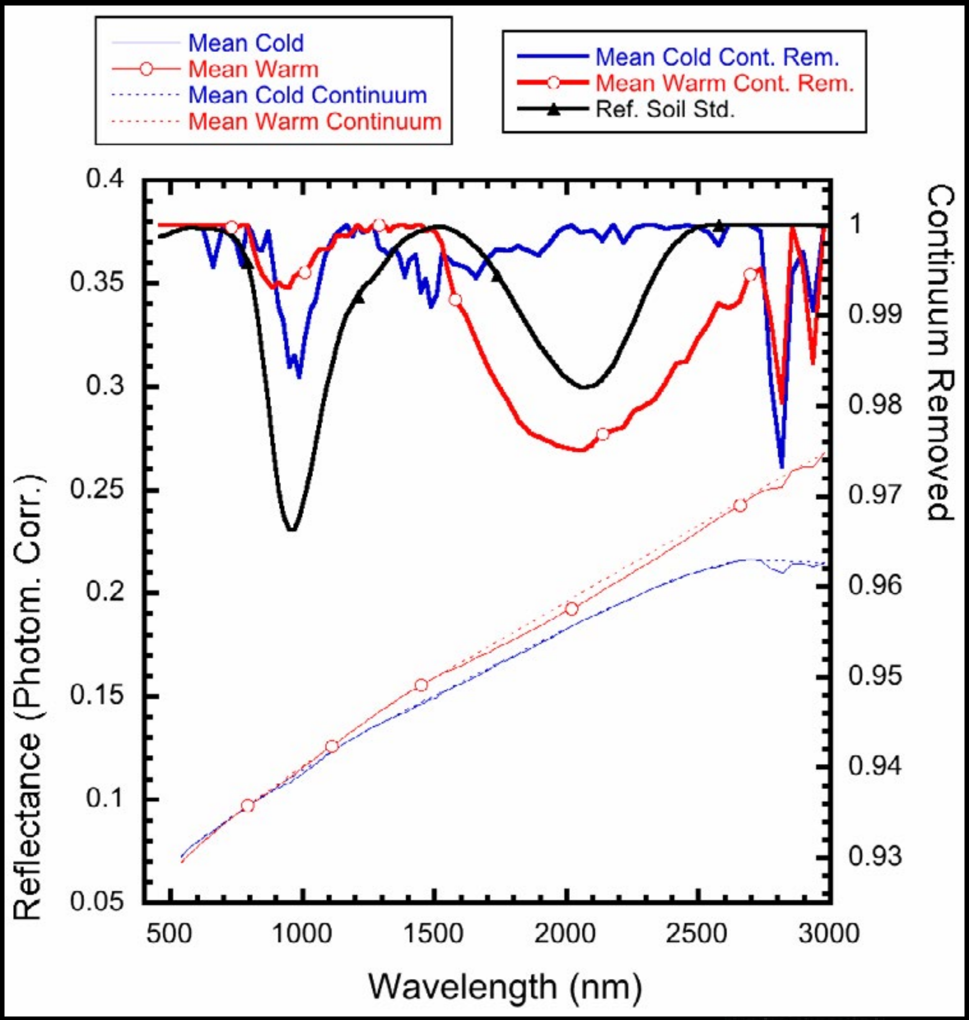

- Motivation for GT Correction: Spectral properties of mature lunar soils are well-understood from laboratory investigations.
- Ground truth correction will correct spectral character (absorption properties) for known regions and known spectral properties of mature soil.
- Ground truth correction will NOT change:
  - Absolute albedo
  - Continuum Slope

# *Ground truth correction*




- <u>Reference standard spectrum</u>
  - Based on 62231 average
  - Continuum removal (convex hull)
  - MGM fit (long wavelengths)
  - Convolution filter

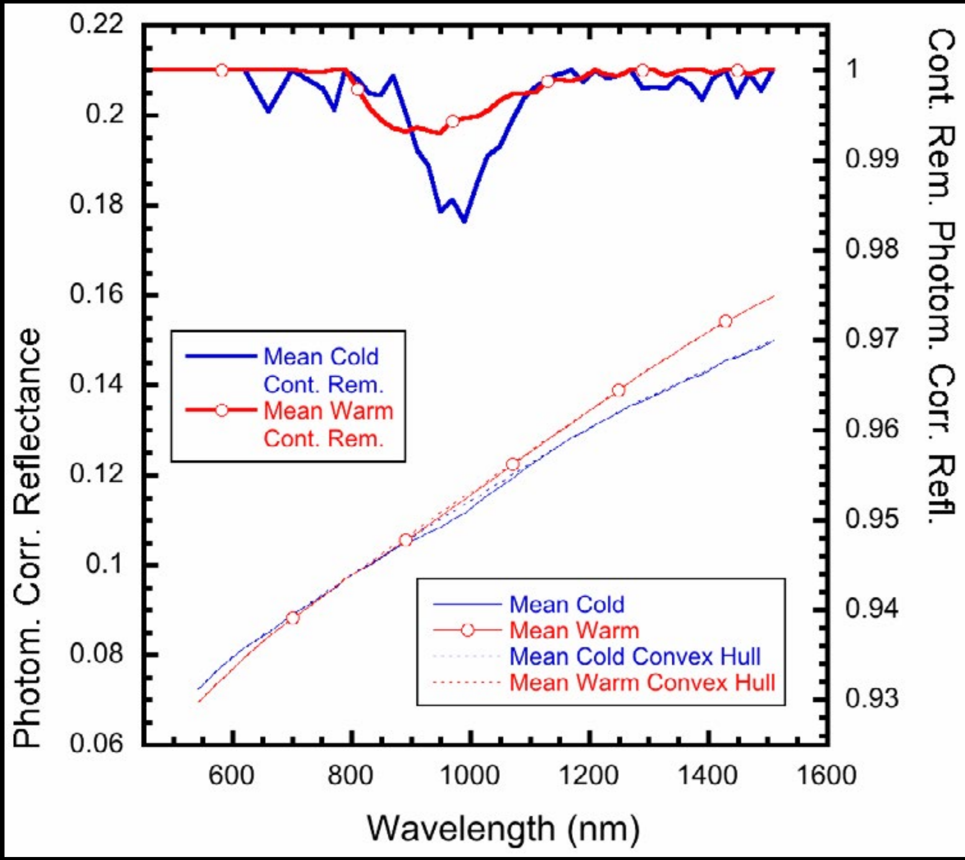
# Ground truth correction




Approach

- Average 62231 soil spectrum is the basis of the correction
- Convex hull continuum removal (both $M^3$ and lab)
- Residual artifacts from diverse operational conditions affect long wavelengths (>1500 nm)
- G.T. factors derived only for λ < 1500 nm

# Ground truth correction

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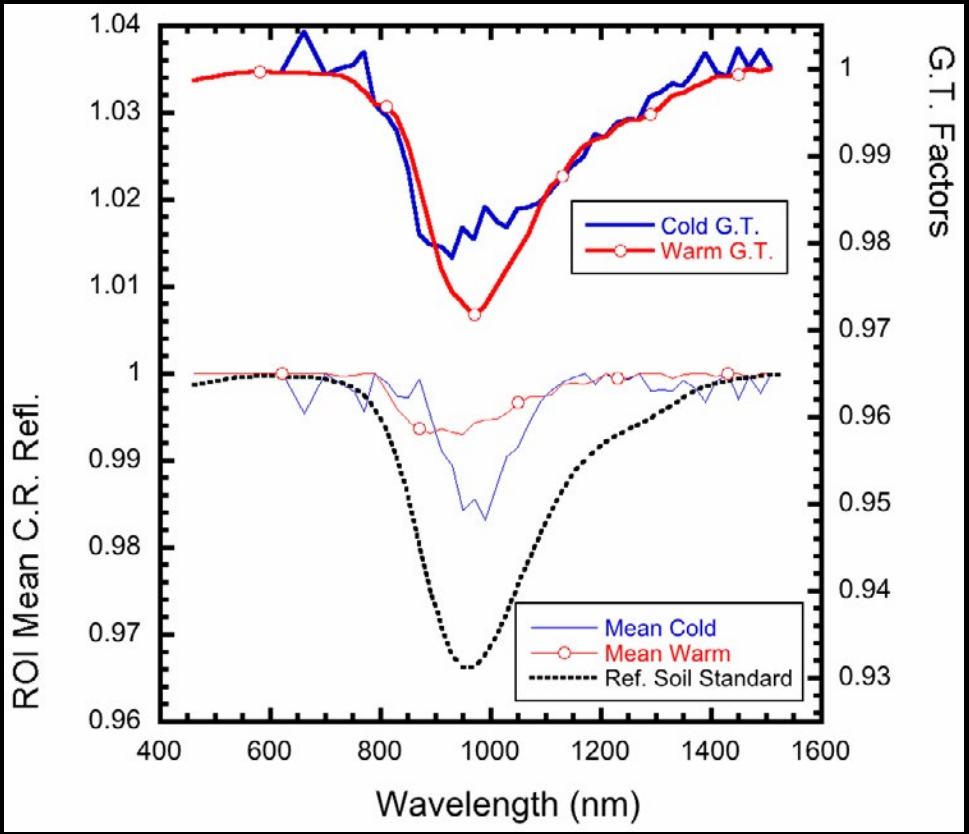
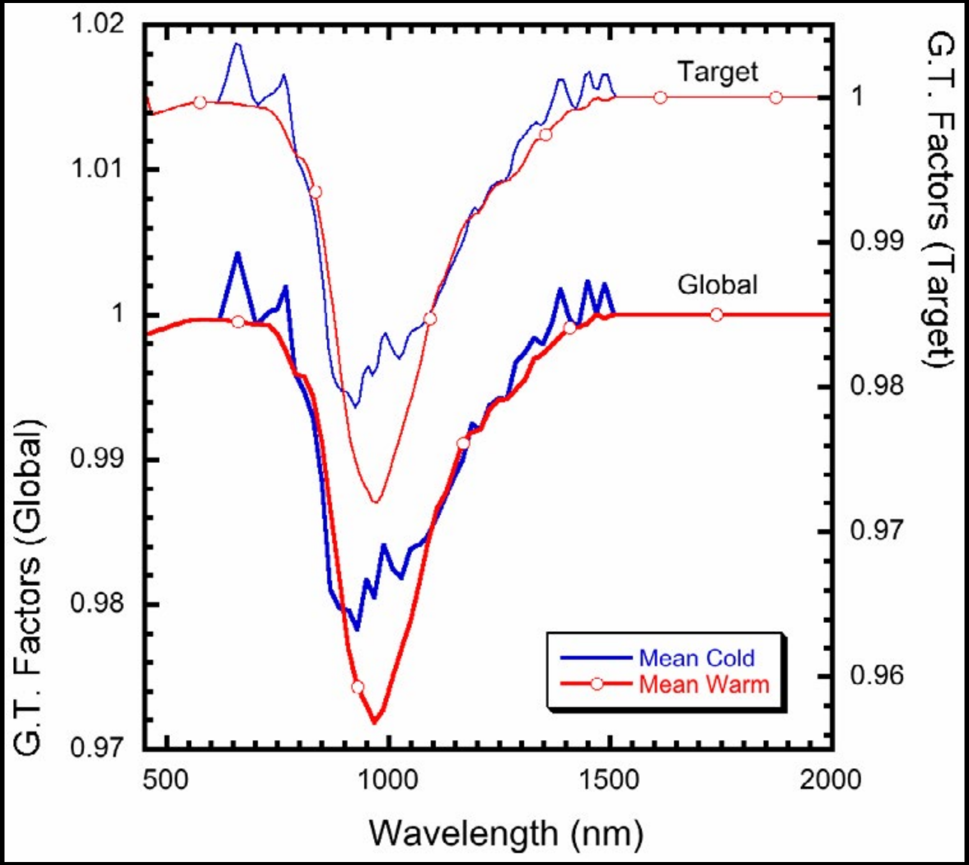
# *Ground truth correction*




Derivation of Factors

- Ratio of M3 mean spectra and reference standard
  - Continuum removed
- Factors are *multipliers*; application of factors is by multiplication of L2 image/ spectrum by the "spectrum" of G.T. factors.
  - E.g., L2 global mode spectrum s1(λ) * G.T.(λ) = L2 G.T. Corrected $s2_{GT}(\lambda)$
  - S1 can also be a L2 image (apply G.T. factors to each spectrum in a L2 image cube)

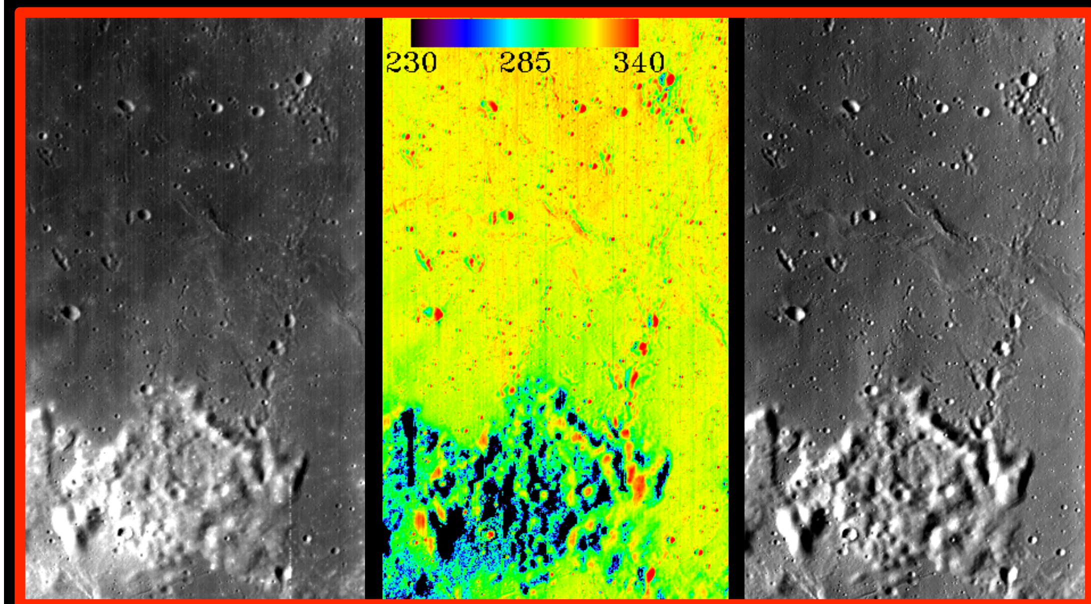
# Ground truth correction




- Ground Truth factors as delivered
- Target mode factors produced by interpolating global mode factors to target mode resolution
- Warm/cold differentiated as in statistical polishers.
- Factors delivered for all $M^3$ wavelengths; set to 1.0 above cutoff wavelength.
- ***Ground truth factors NOT applied to delivered L2 data.***
- Factors provided in CALIB directory (individual users must decide whether to apply the factors, and apply them on their own)

# *Supplemental files*

- L2 Supplemental files ("*_SUP") contain quick-look information on L2 images.
- 3-band image cube of same dimensions (samples, lines) as associated L2 image
  - 1489 nm reflectance (topography preserved, photometric correction based on a sphere for i and e)
  - Estimated surface temperature (thermal removal step)
  - Longest wavelength radiance (global band 84, target band 253); illustrates surface morphology

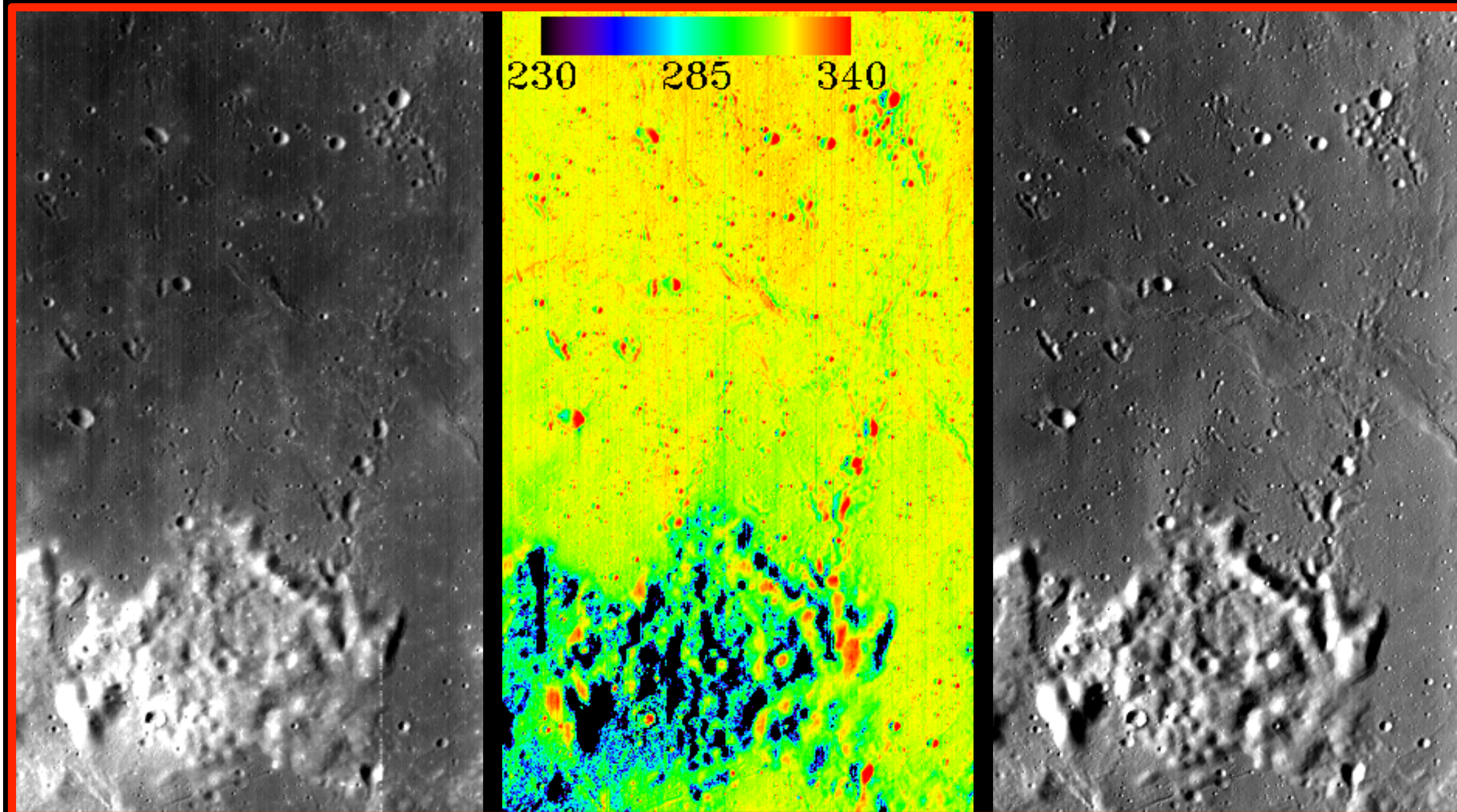



R1489, topo. preserved

Estimated temp.

Long λ radiance

# *Supplemental files*



# *Definition of “reflectance” for $M^3$ L2 dataset*

- Radiance Factor (RADF) at i=30°, e=0°
  - Hapke, 1993, p. 262, equation 10.5
- Photometry uses smoothed f($\alpha$) derived from OP2C1 [highland regions only] and applied to ALL $M^3$ data to correct to 30° phase
- M3 data are thus “normalized” as if they were all measured at i=30°, e=0°

- *Under this definition of reflectance there is NO correction of the incident light to normal incidence. I.e., no cos (30°) correction as there would be in reflectance factor.*
- *This definition is consistent with other missions (e.g. Kaguya Spectral Profiler, Dawn VIR, etc.]*

# *Summary of $M^3$ L2 data*

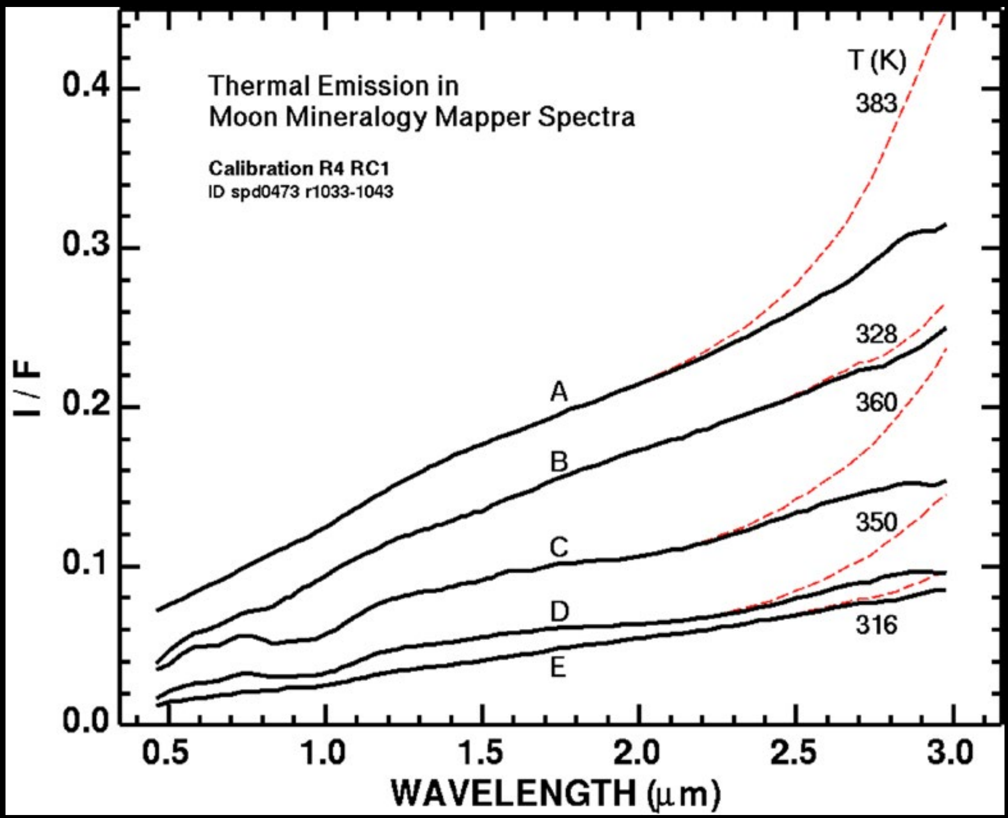
- Steps in L2 production:
  - Divide by solar irradiance
  - Statistical polishing
  - Removal of thermal emission component
  - Photometric correction
  - [Ground truth correction; not applied to delivered L2 dataset but correction factors provided in CALIB directory]
- Level 2 delivery: November 2011

Note that either PDS labels or ENVI headers can be used to open L2 files (same as L1B)

# *Words of caution regarding M3 dataset (**U2 Calibration**)*

**U2 Calibration is the version included in the Sept. 2011 Level 1 and late 2011 PDS data releases**

# *Thermal emission at long wavelengths (L1b only)*

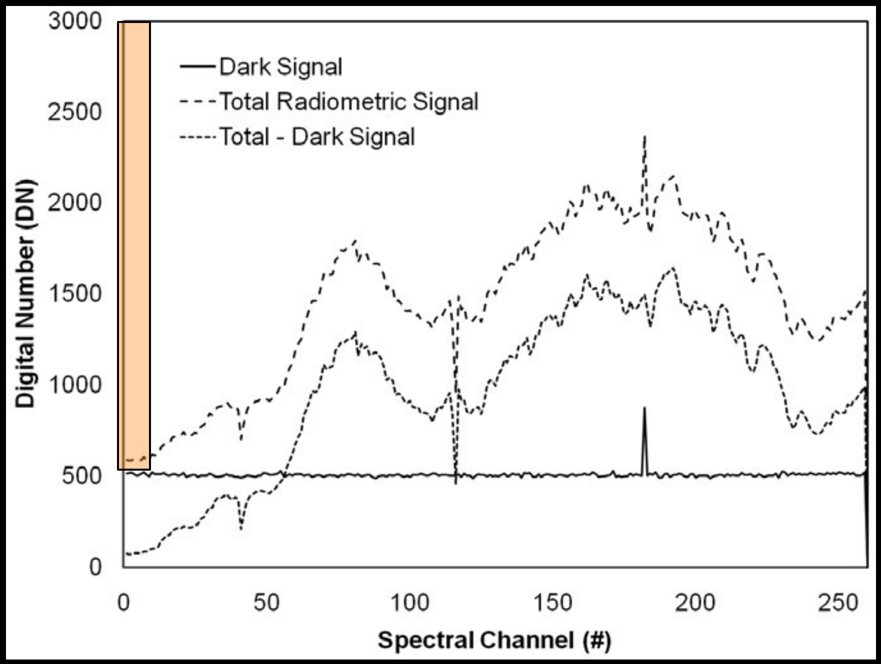



Clark et al., JGR 2011

- M3 data contain a component of emitted thermal (black body) radiation.
- More extreme for warm/hot surfaces; more notable at long wavelengths
- Removal of thermal emission is discussed by Clark et al. (2011)

# *Low signal levels at short wavelengths*

- The shortest wavelengths have the lowest overall signal. Given the unfortunate low lighting conditions for much of $M^3$ data, these channels may not be far above the dark (offset) signal, which can contribute to a range of adverse effects on M3 data.
- These wavelengths thus often contain spurious effects and should **NOT** be used in ratio images or quantitative analyses.
- *L2 data from U2 data will be delivered with unreliable channels set to null value (-999). [est. below 540 nm] (but will still contain 85 spectral bands).*
- *Last target channel is also set to null.*
  - Caution should be exercised with U2 L1B data when converting to reflectance (L1B PDS archive does not have unreliable bands set to 0!).




Green et al. 2011, JGR