LPSC 2015
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Lunar Orbiter Laser Altimeter

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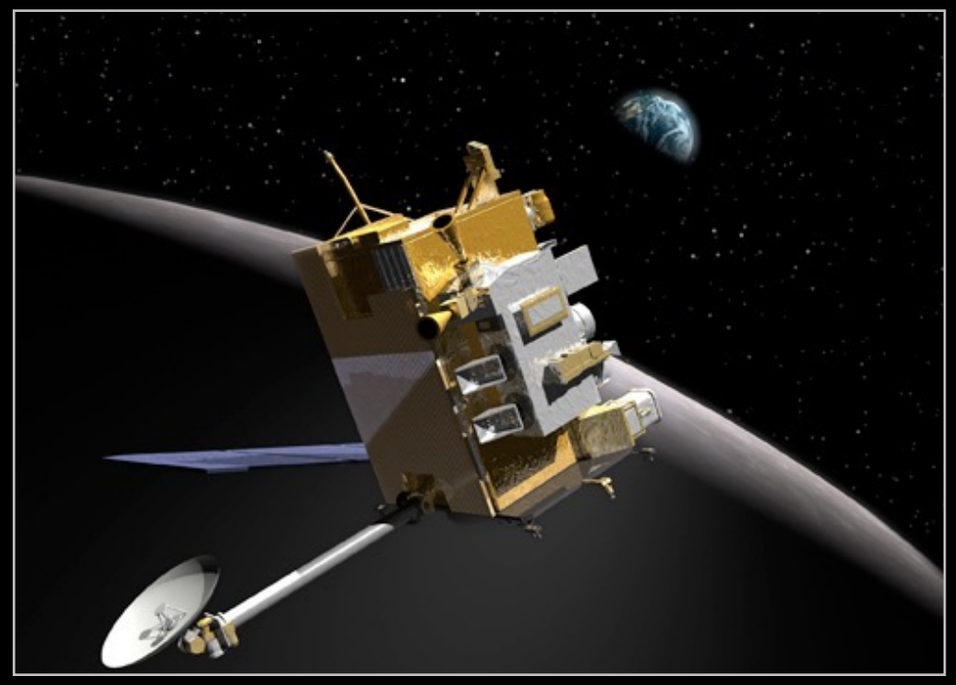
and the LOLA Science Team

LRO Data Workshop, LPSC 2015
March 15, 2015

Acronyms



- LRO = Lunar Reconnaissance Orbiter
- LOLA = Lunar Orbiter Laser Altimeter
- DOE = Diffractive Optical Element
- FOV = Field of View
- PDS = Planetary Data System
- EDR = Experimental Data Record
- RDR = Reduced Data Record
- GDR = Gridded Data Record
- SHADR = Spherical Harmonics Data Record

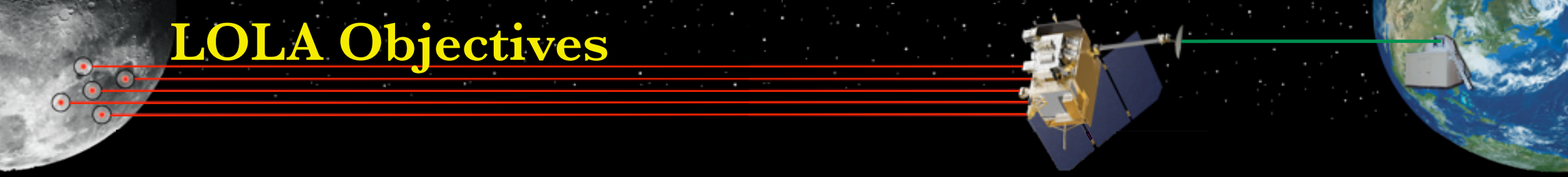
General overview

- LRO launched in June 2009
- Different orbit configurations:
  - Commissioning: June - September 2009 [30x200km elliptical]
  - Nominal: September 2009 - December 2011 [50km near-circular]
  - Near-frozen: December 2011 - present [30x200km elliptical]

- LOLA has collected over 6.75 billion range measurements with vertical precision ~ 10 cm and accuracy ~ 1 m => the current geodetically-controlled topographic reference for the Moon

- The LRO orbit inclination has been changing (secularly), so currently the LRO groundtrack does not go over the pole.

LOLA Objectives

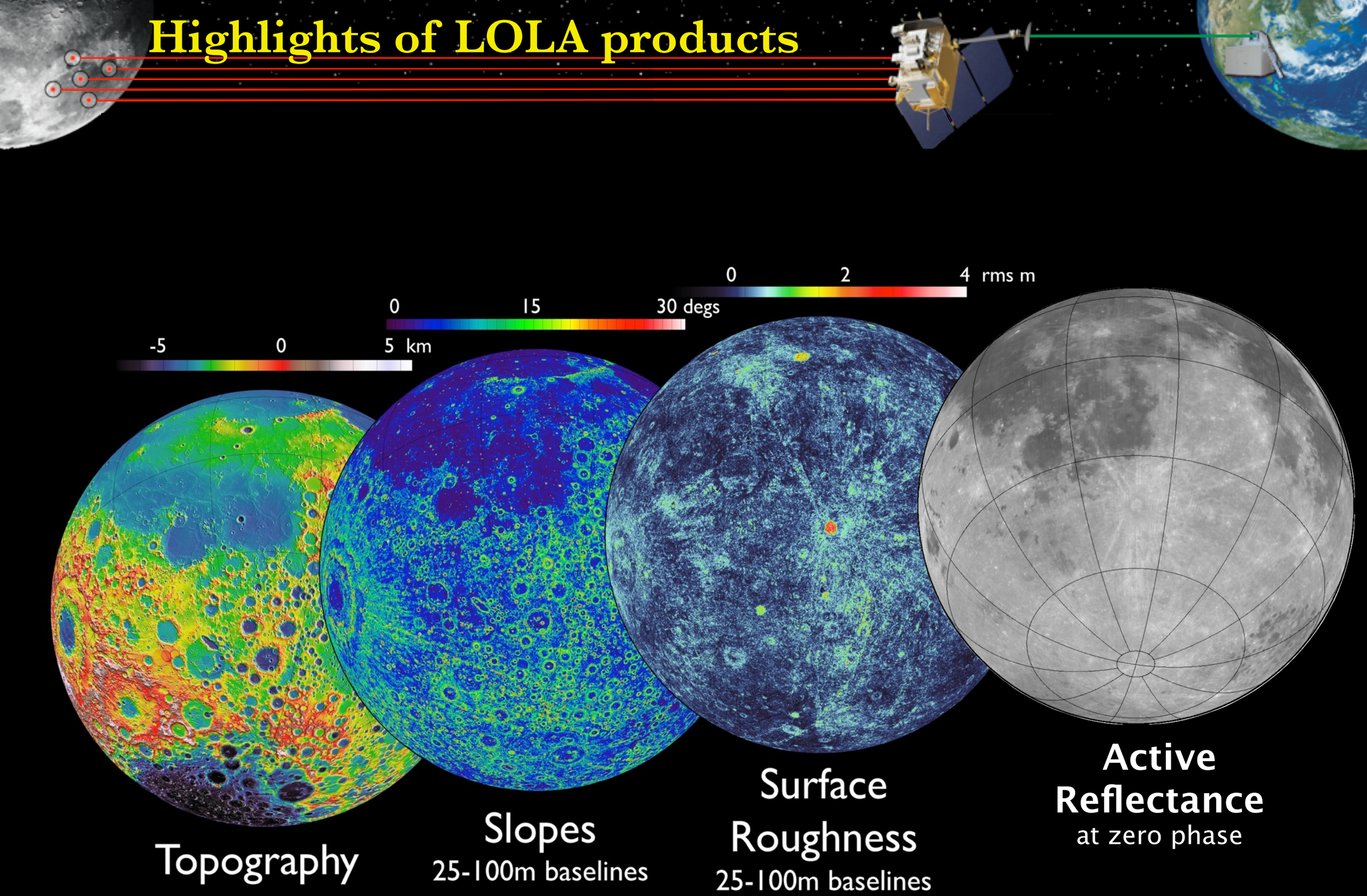


- High-resolution global topographic model and geodetic framework
  - Precise targeting, safe landing, and safe mobility for future exploration

- Characterize polar illumination conditions
  - Image permanently shadowed regions to identify possible locations of ice

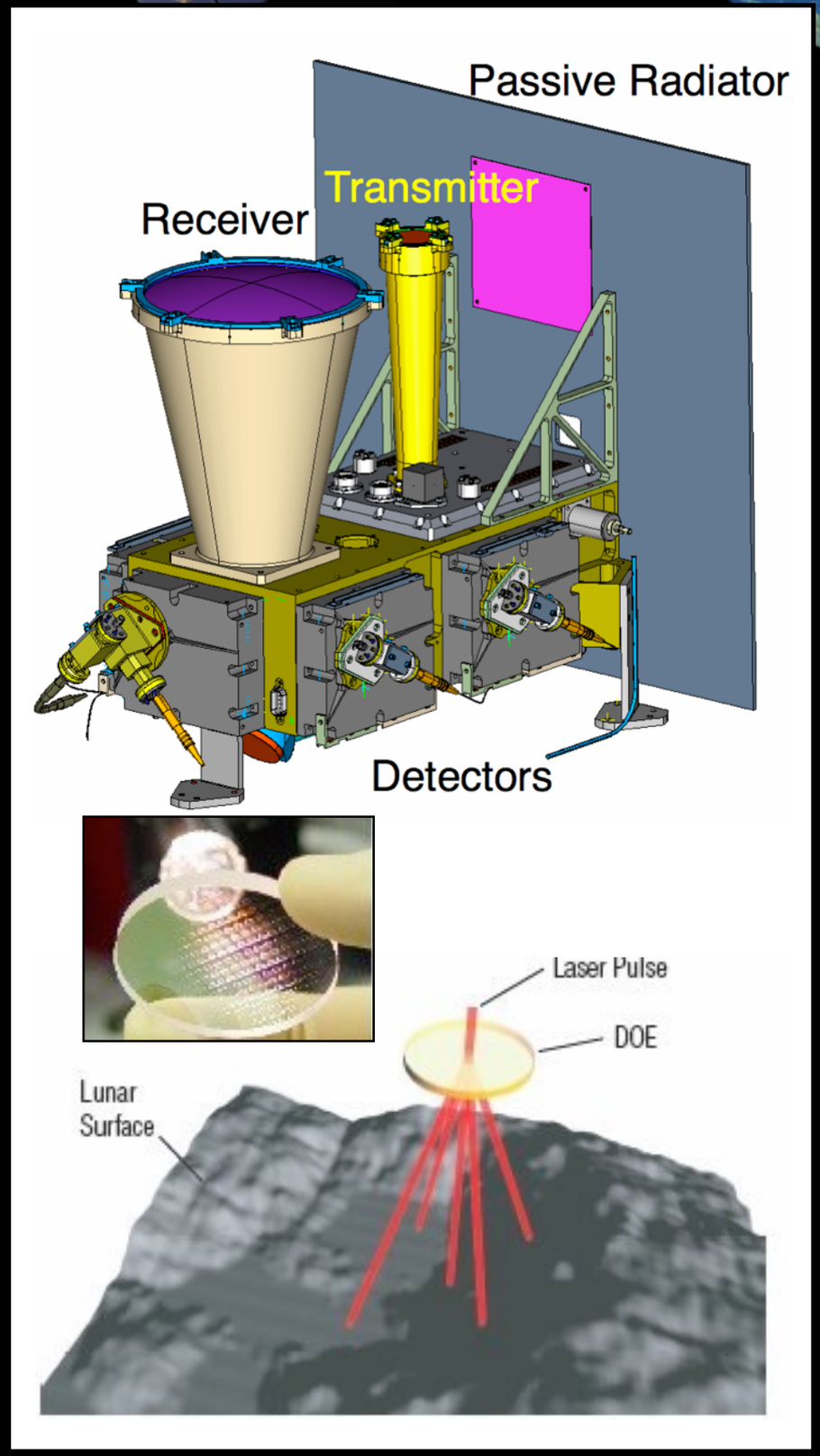
- Science measurements:
  - The distance between the surface and LRO (shape)
  - The spreading of the returned laser pulse (roughness)
  - The transmitted and returned laser energies (reflectance)

Highlights of LOLA products



The LOLA instrument

- instrument built at NASA/GSFC
- 5 beams, 28Hz laser firing frequency
- each 5-m spot provides:
  - range to surface (10-cm precision)
  - footprint-scale surface roughness
  - 1064-nm surface reflectance
- transmitter energy (2 lasers): 2.7/3.2 mJ
- beam FOV: 100-µrad divergence (red)
- receiver FOV: 400-µrad each spot (green)
- continuous operation since July 13, 2009
  - 6.75+ billion altimetric measurements
  - <400m median long. gap at equator
  - >80° lat. : coverage effective <50m res.
  - max. cross-track gap ~4km



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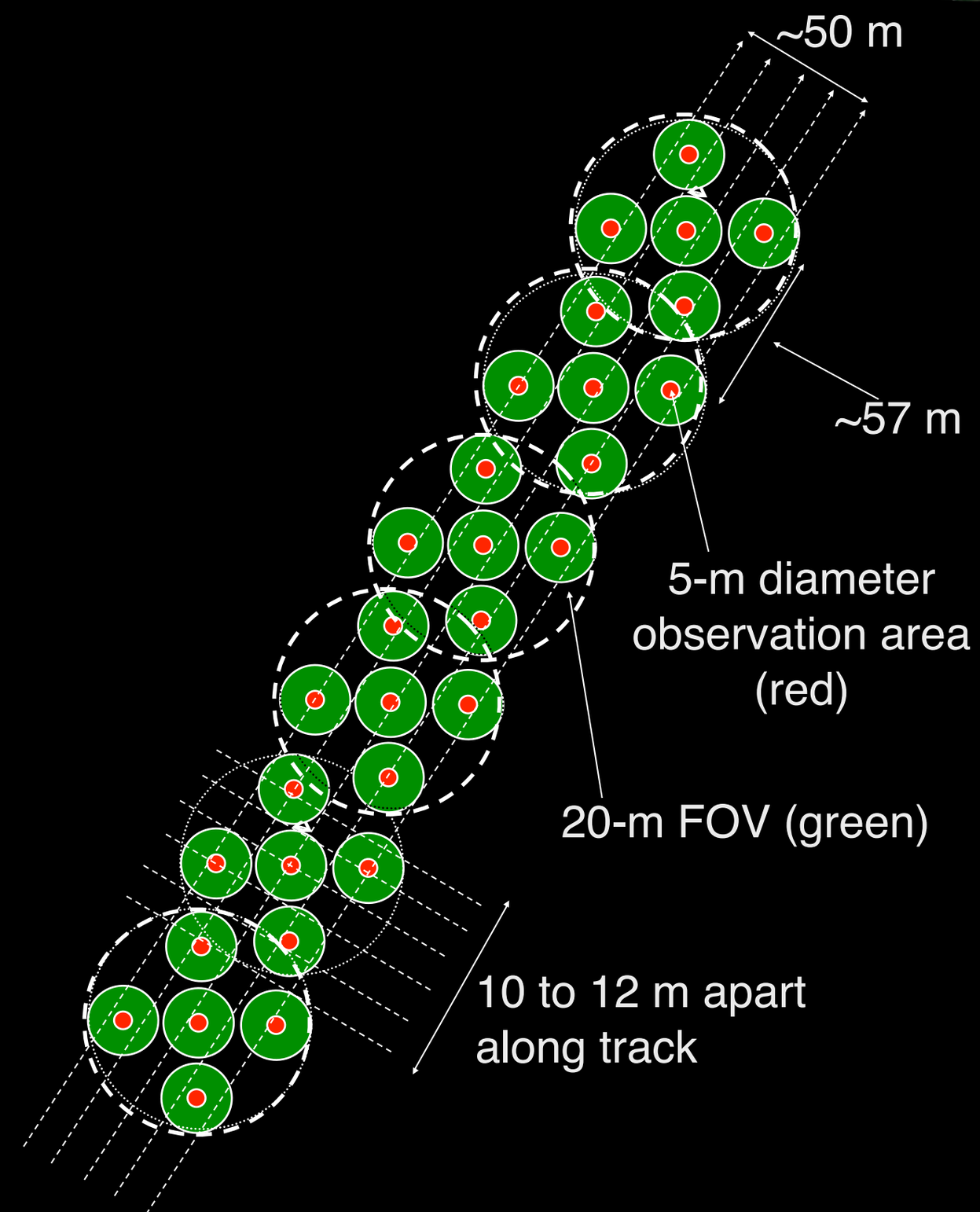
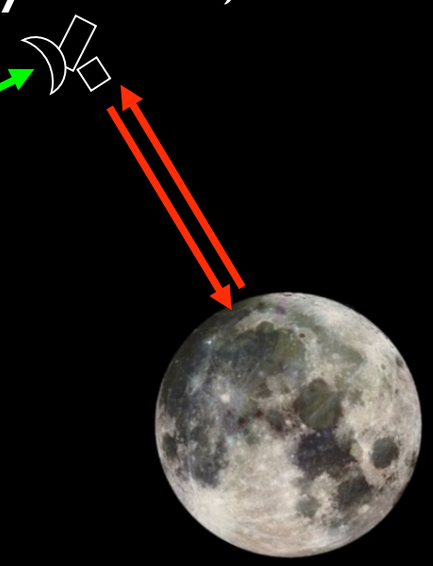


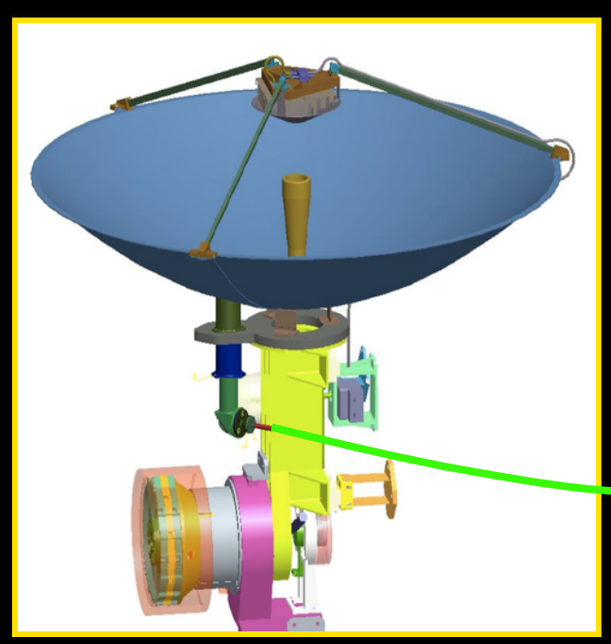
The LOLA instrument
Laser Ranging Data

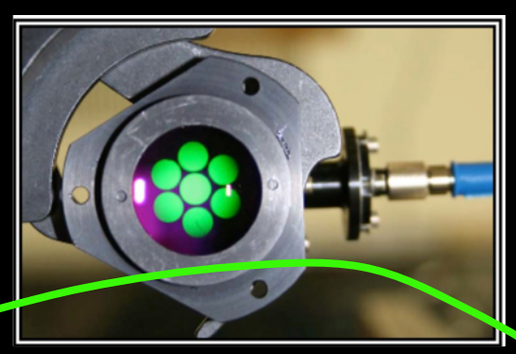
LOLA: 10-cm range accuracy 28 Hz, 1064 nm

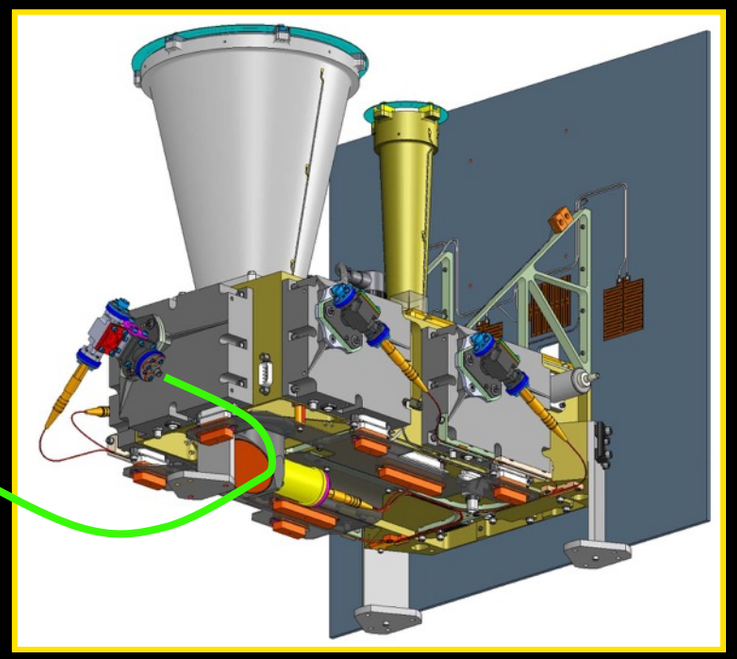
LR: 10-cm range precision 28 Hz, 532 nm



~1000 hours of LR tracking







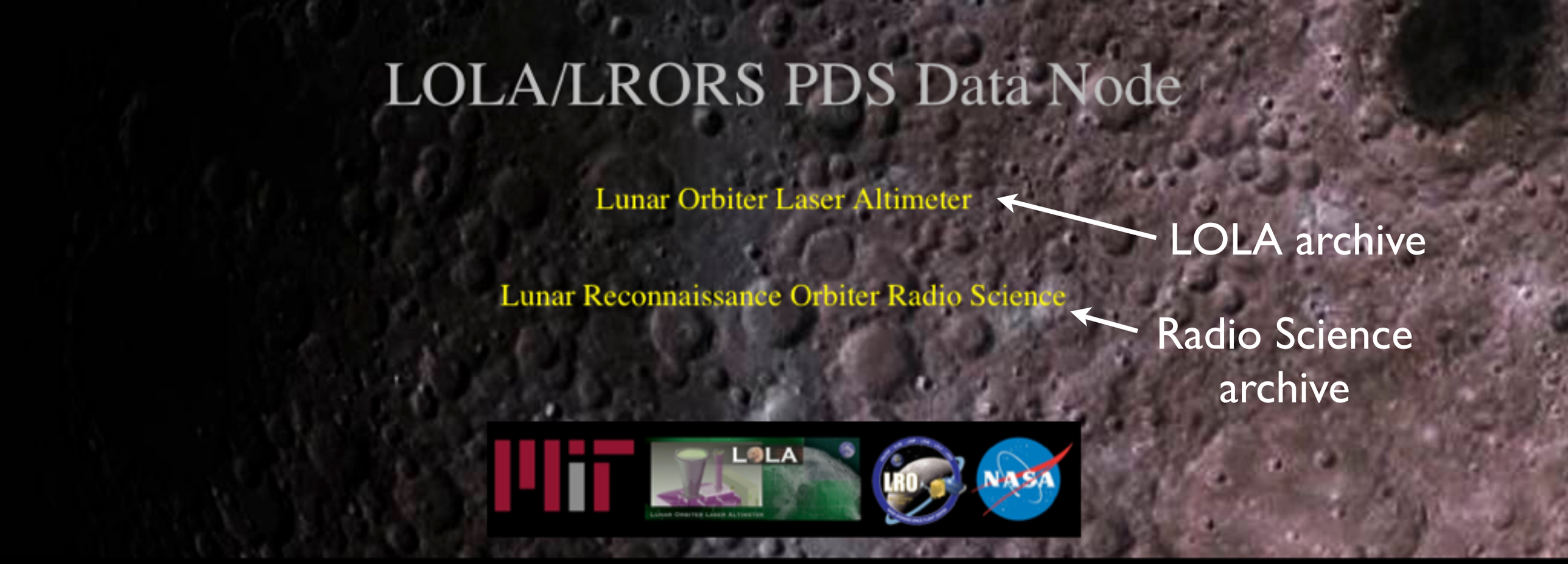
10-m fiber optic bundle carries LR Earth laser signal to LOLA channel-1 detector

Zuber et al. [2010]

The LOLA Data

- Where can you get the data ?
  - LOLA Data Node: http://imbrium.mit.edu - Most recent data.
  - Lunar Orbital Data Explorer: http://ode.rsl.wustl.edu/moon/ - Web interface for querying the LOLA Data Node. Useful for selecting data by geographic location.
  - PDS Geosciences Node: http://pds-geosciences.wustl.edu - Updated every 3 months.

→ quarterly updates with new and updated data ←



http://imbrium.mit.edu

LOLA Data Archive

This archive contains raw, reduced, and higher-level instrument altimetry data acquired during Lunar Reconaissance Orbiter (LRO) spacecraft operations. The observations are carried out using the Lunar Orbiter Laser Altimeter (LOLA) instrument.

The LOLA archive is stored on two volumes. Raw data are stored on this volume, designated LRO

designated LR

Earth ranges

ed Ranging Data recor

Quick-look images for internet browsing

Data products: EDR, RDR, GDR, SHADR

AAREADME.TXT BROWSE/ CALIB/ CATALOG/ DATA/ DOCUMENT/

EXTRAS/ GEOMETRY/ INDEX/ LABEL/ SOFTWARE/ VOLDESC.CAT

Unsupported extras: geoid, illumination, Hurst exponent

Documentation on instrument, data archive, data formats, etc.

Utilities for reading the data

Experimental Data Records (EDRs)

- Time series collection of uncalibrated science and housekeeping data
- One EDR per orbit (~ 7000 s), starting at each ascending equator crossing
- Each EDR consists of 2 files:
  - Data stored in PDS compliant binary table
  - PDS ASCII label (ending in .LBL) describing table content and formats
- Useful if you want to do your own calibration and geolocation

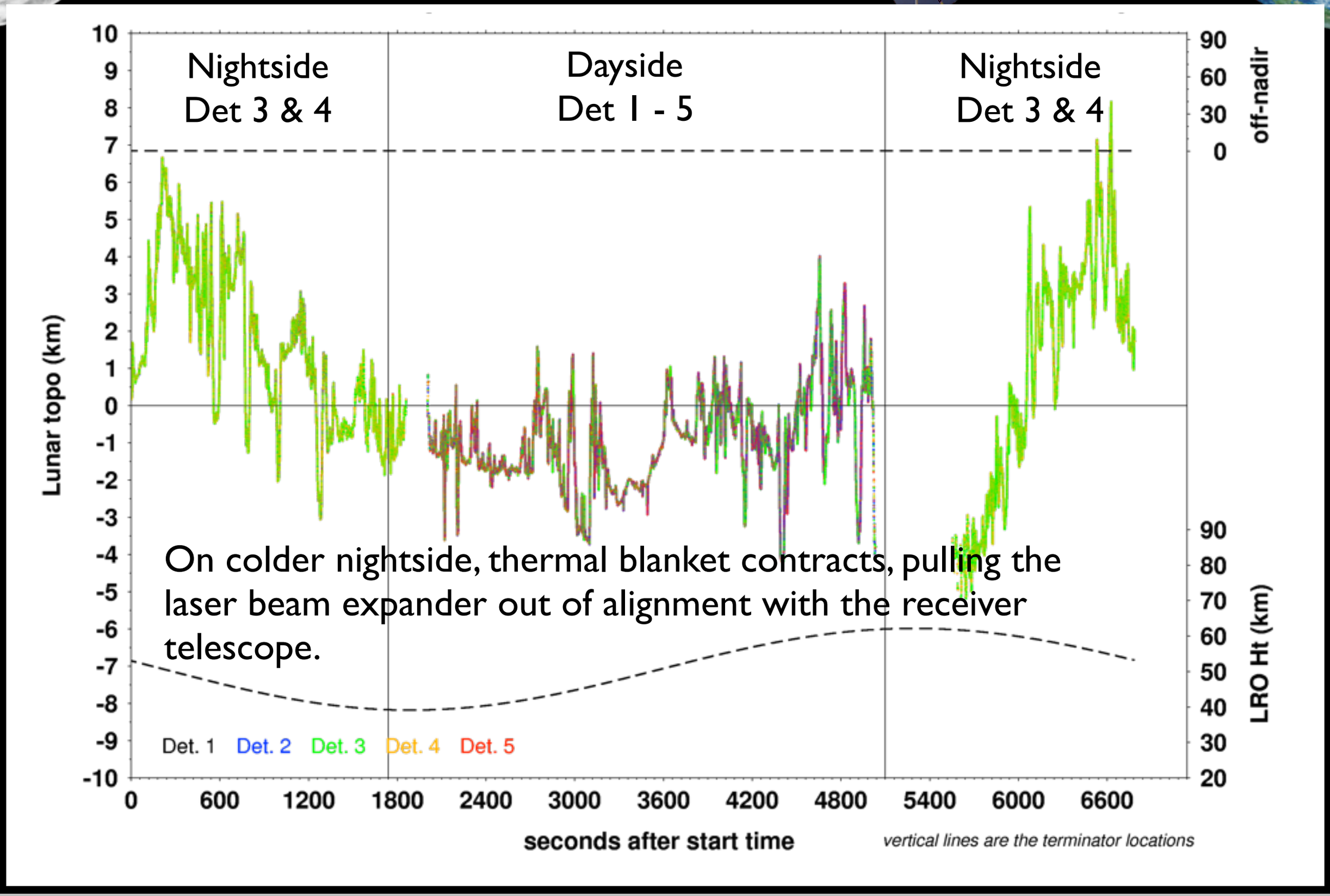
→ Please read the labels first ! ←

Reduced Data Records (RDRs)

- Time-ordered **calibrated and geolocated** measurements per orbit, using our best orbits (now based on GSFC GRAIL gravity field GRGM900B)
- Each topographic return is located with respect to the lunar center of mass in a body-fixed (rotating) coordinate frame (Mean Earth per LRO standard)
- Elevation is expressed relative to reference sphere of radius 1737.4 km
- Each RDR consists of a PDS label and compliant binary table
- Each table row represents one 28-Hz LOLA minor frame with 5 spots
- Useful for plotting and analyzing individual altimetry tracks at **full resolution**

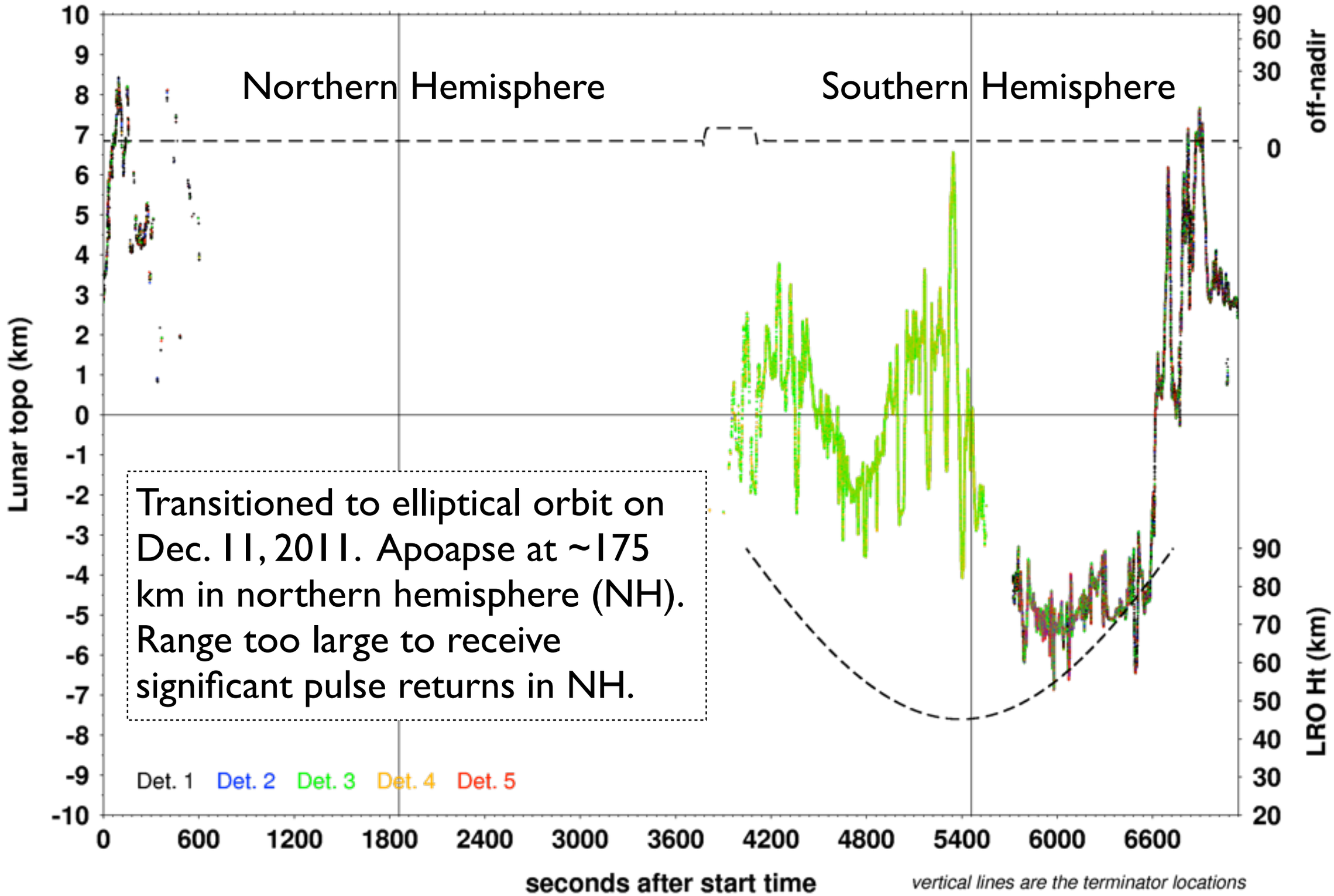
elevation ≠ topography

Example RDR output
Elevation time series



On colder nightside, thermal blanket contracts, pulling the laser beam expander out of alignment with the receiver telescope.

Example RDR output
Elevation time series



Transitioned to elliptical orbit on Dec. 11, 2011. Apoapse at ~175 km in northern hemisphere (NH). Range too large to receive significant pulse returns in NH.

Gridded Data Records (GDRs)

- Lunar Digital Elevation Models (**LDEMs**) formatted as **IMG binary** images with detached labels
  - 16-bit integer, with 50cm quantization (e.g. divide DN by 2 to get meters!)
  - new release also contains IMGs with 32-bit 'float'
  - various resolutions and projections:
    - global (cylindrical) from 4ppd (~8km/px) to 1024ppd (~30m/px)
    - polar stereographic from 5/px to 400m/px
  - owing to the large file sizes, several tiling schemes are employed for the high-resolution maps (256+ppd)
  - also stored in JPEG2000 lossless compressed format, compatible with many mapping software tools (e.g., ArcGIS, GDAL, Global Mapper, etc.)
- Additional GDRs: counts, slope, roughness
- EXTRAS: geoid height, Hurst exponent (Rosenburg et al. 2011), polar illumination (Mazarico et al. 2011)

Gridded Data Records (GDRs)

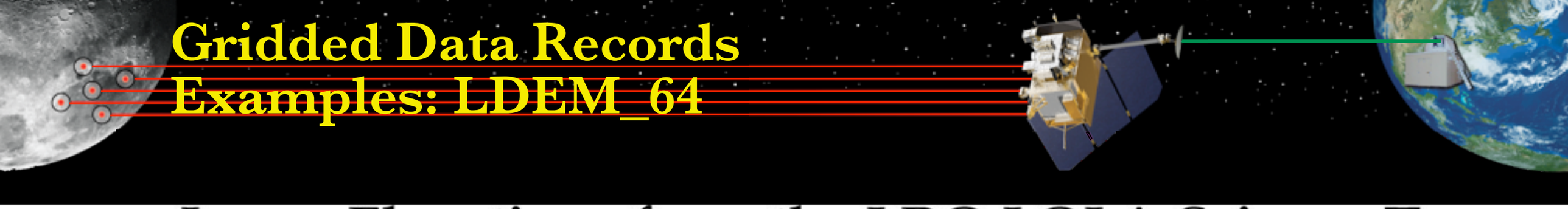
- Lunar Digital Elevation Count (**LDECs**) in the same 16-bit IMG format
  - identical products as DEMs except they present the number of LOLA measurements averaged to obtain each pixel value
  - a value of zero (no LOLA coverage, gap) indicates interpolated value (typically with GMT 'surface')
  - also stored in JPEG2000 lossless
- Additional GDRs: slope (**LDSM**), roughness (**LDRM**)
  - those products are due for an update in the next release
- in EXTRAS (e.g. not reviewed by PDS, use more caution)
  - geoid height (older fields, would advise to use GRAIL, on GRAILS PDS)
  - Hurst exponent (Rosenburg et al. 2011)
  - polar illumination and sky visibility (Mazarico et al. 2011)

Gridded Data Records (GDRs)

- GDRs are typically pixel-registered
- Polar stereographic projection has true scale at the pole and uses a projection radius of 1737.4km

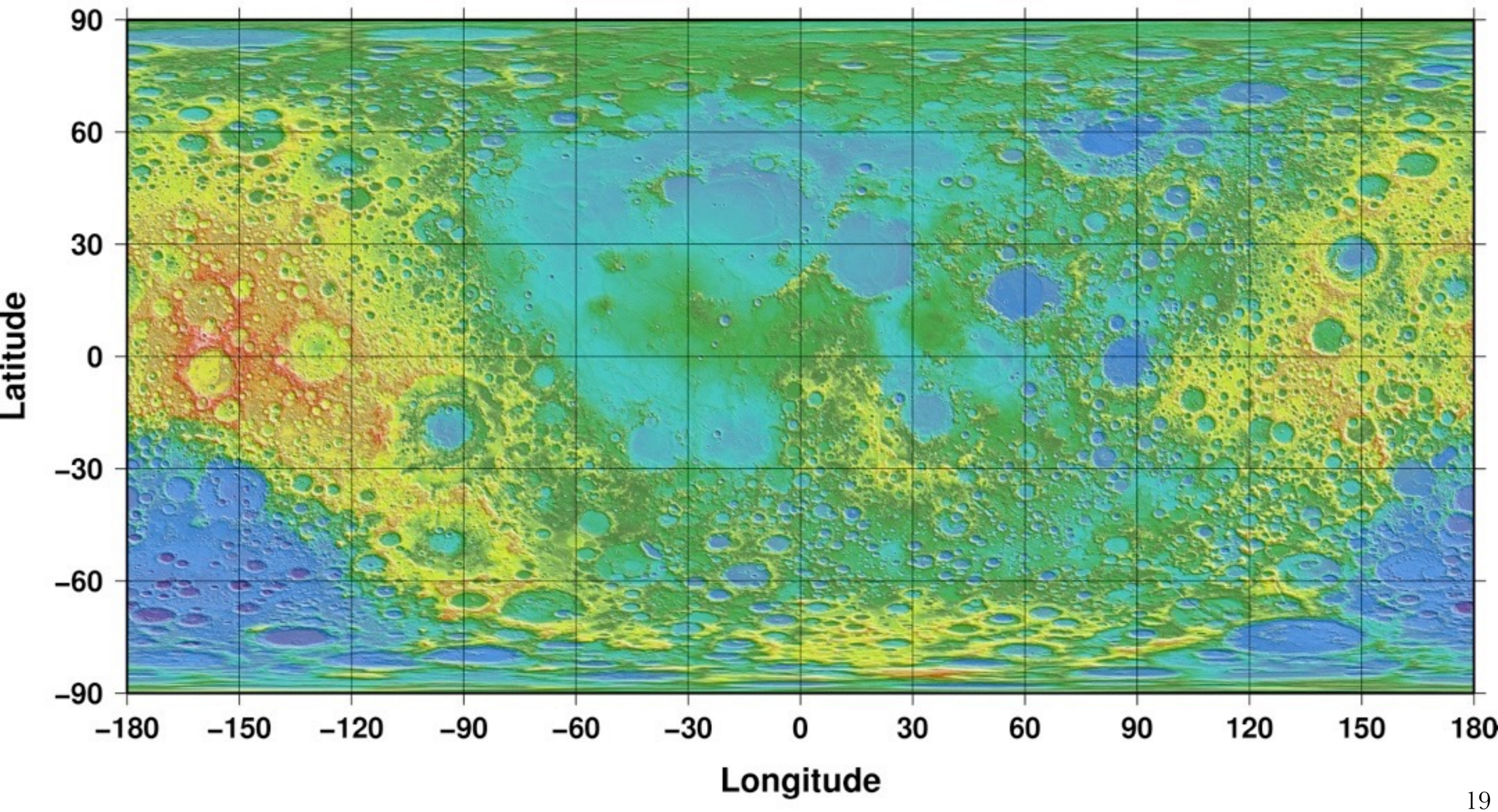
- A note on the JPEG2000 products:
  - you really just need the "`.JP2`" file to import in ArcGIS, etc.
  - BUT:
    - LBL indicates the scaling to be applied (always check)
    - an XML file also contains the scaling/offset, but previous (current?) versions of ArcMap do not read/use it !
    - the XML file contains pre-computed statistics, which can save you time when importing large maps
    - due to PDS filename conventions, you will need to rename the XML file to be recognized: "**`???_JP2_AUX.XML`**" to "`???.jp2.aux.xml`"

Gridded Data Records
Examples: LDEM_64



Lunar Elevations from the LRO LOLA Science Team

LDEM_64, 0.015625° resolution



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Examples: LDEM_64

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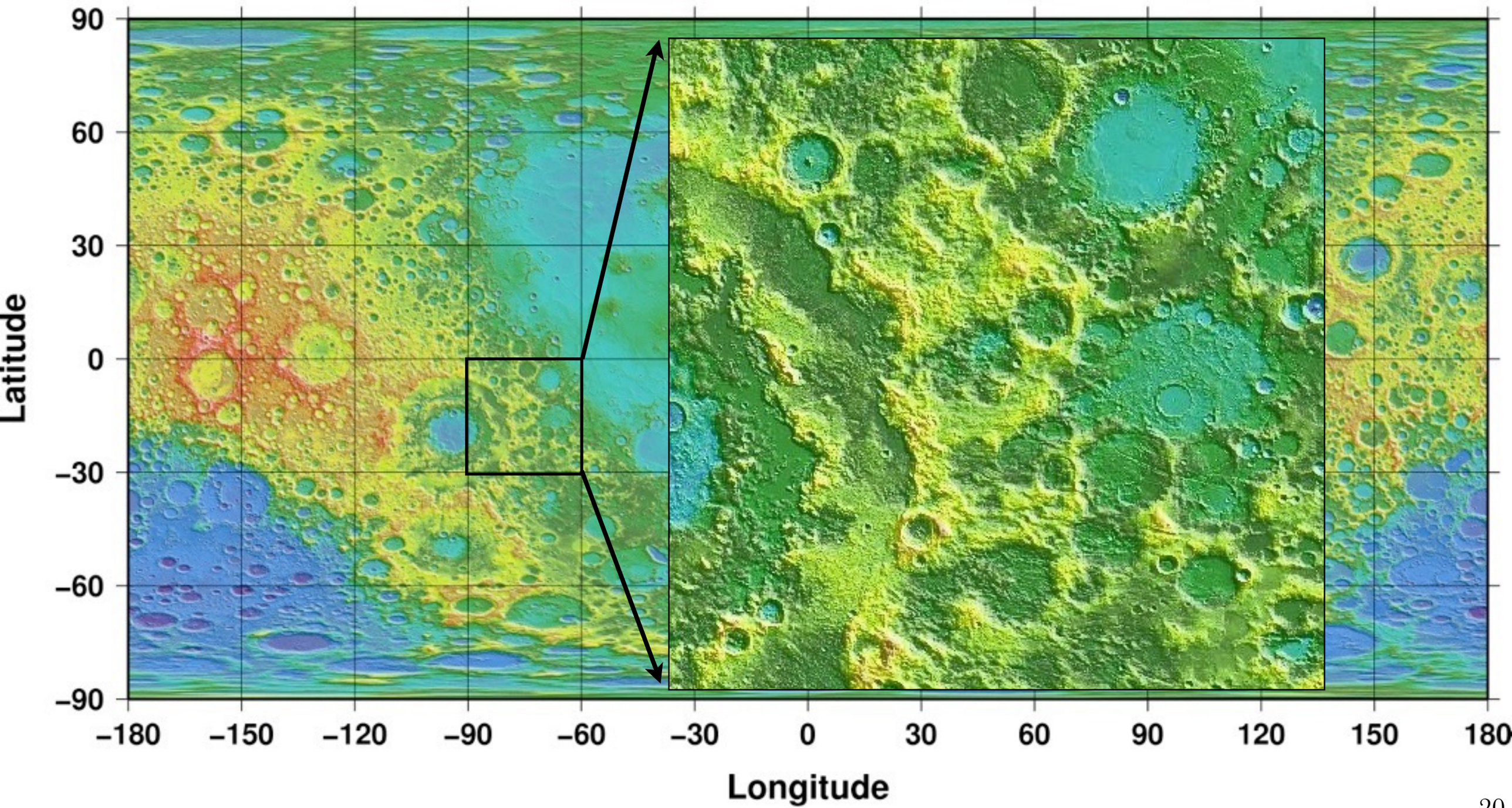
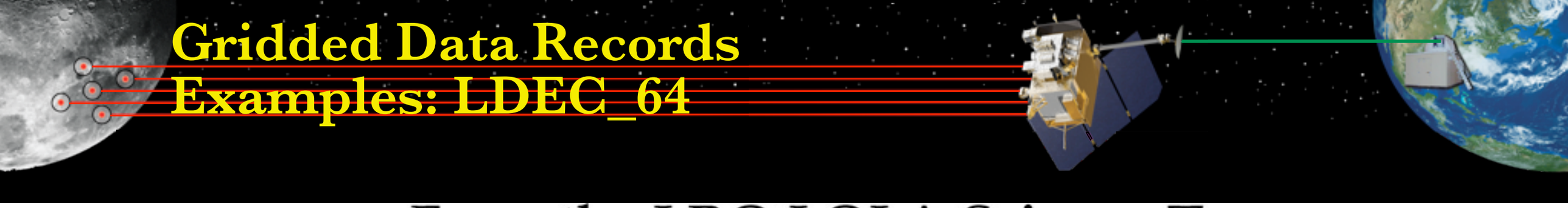


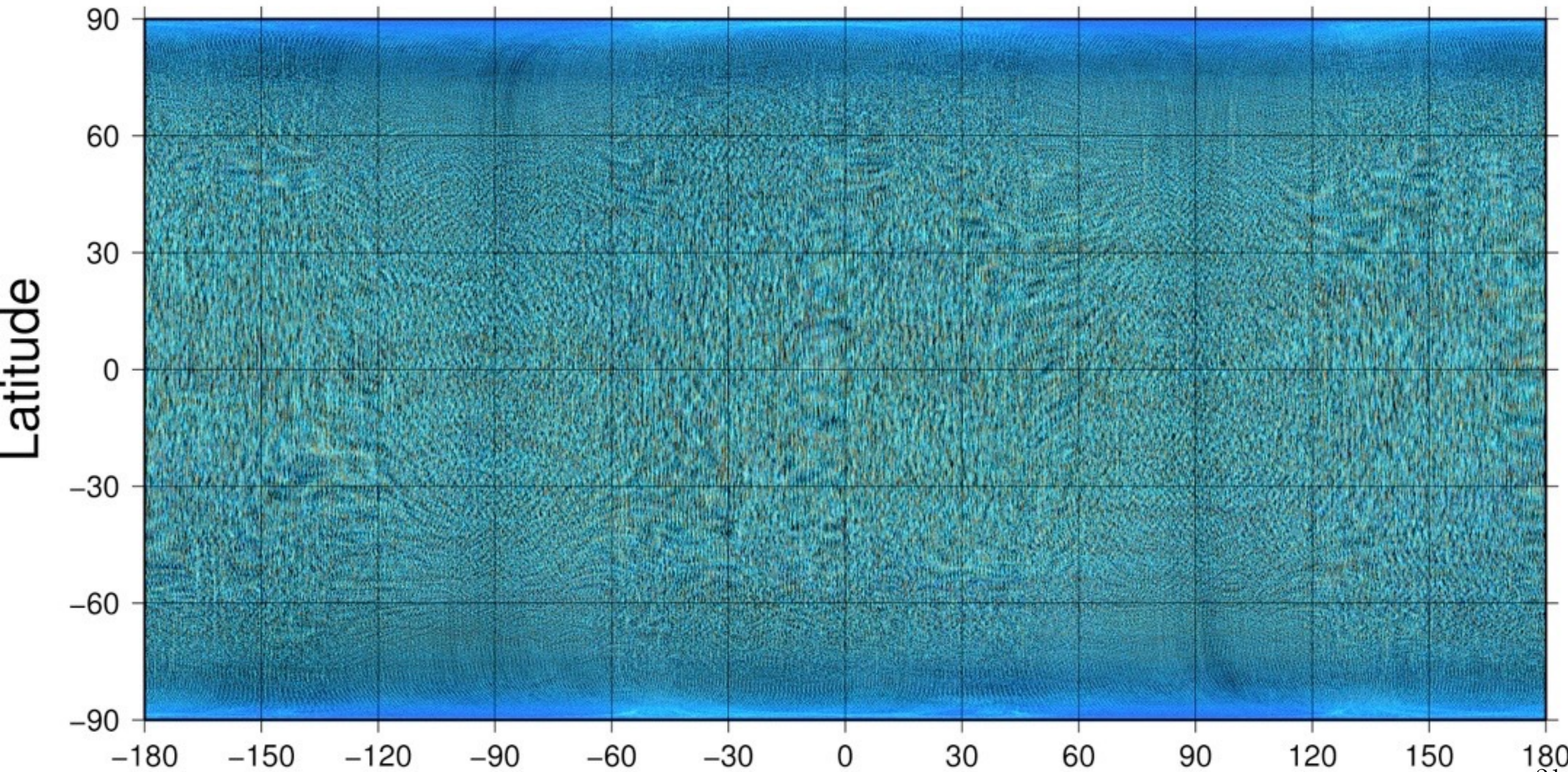
Gridded Data Records
Examples: LDEC_64



From the LRO LOLA Science Team

LDEC_64.GRD: counts in each 0.015625° pixel

min 0 max 367



Gridded Data Records
Examples: LDEC_64

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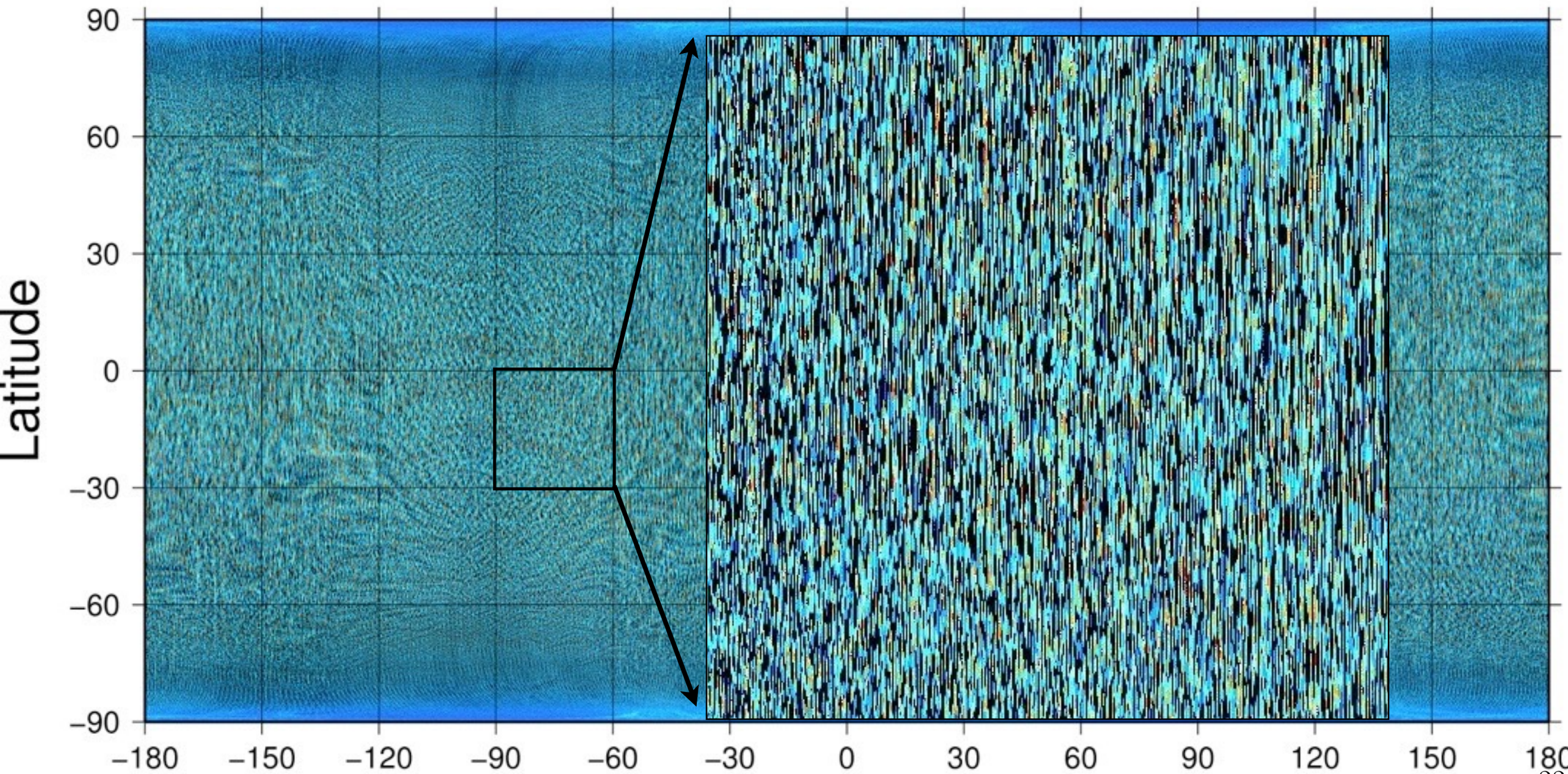
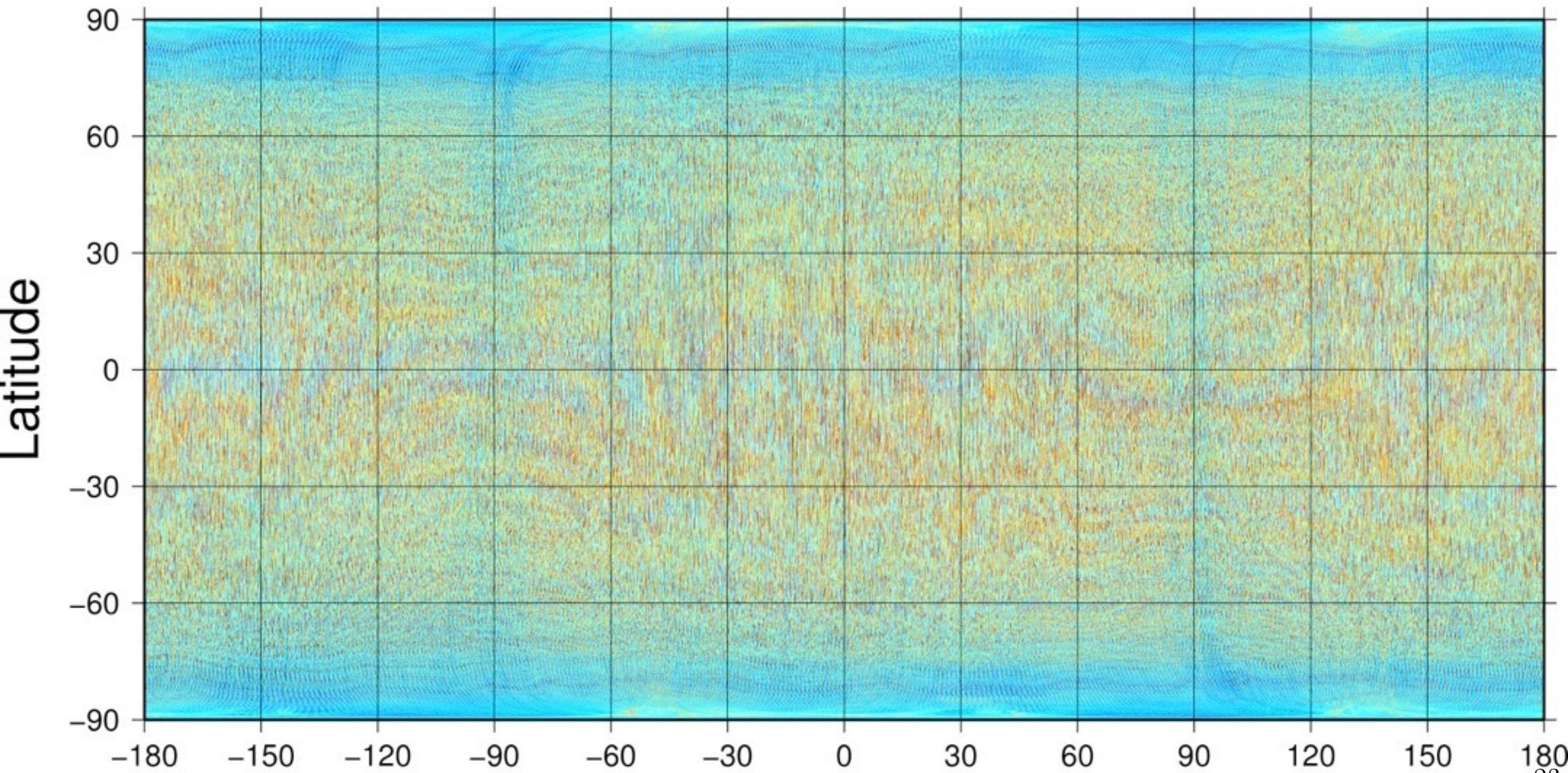


Gridded Data Records
Examples: LDEC_64

From the LRO LOLA Science Team

LDEC_16.GRD: counts in each 0.0625º pixel

min 0 max 2439 mean 294.0 rms 200.2

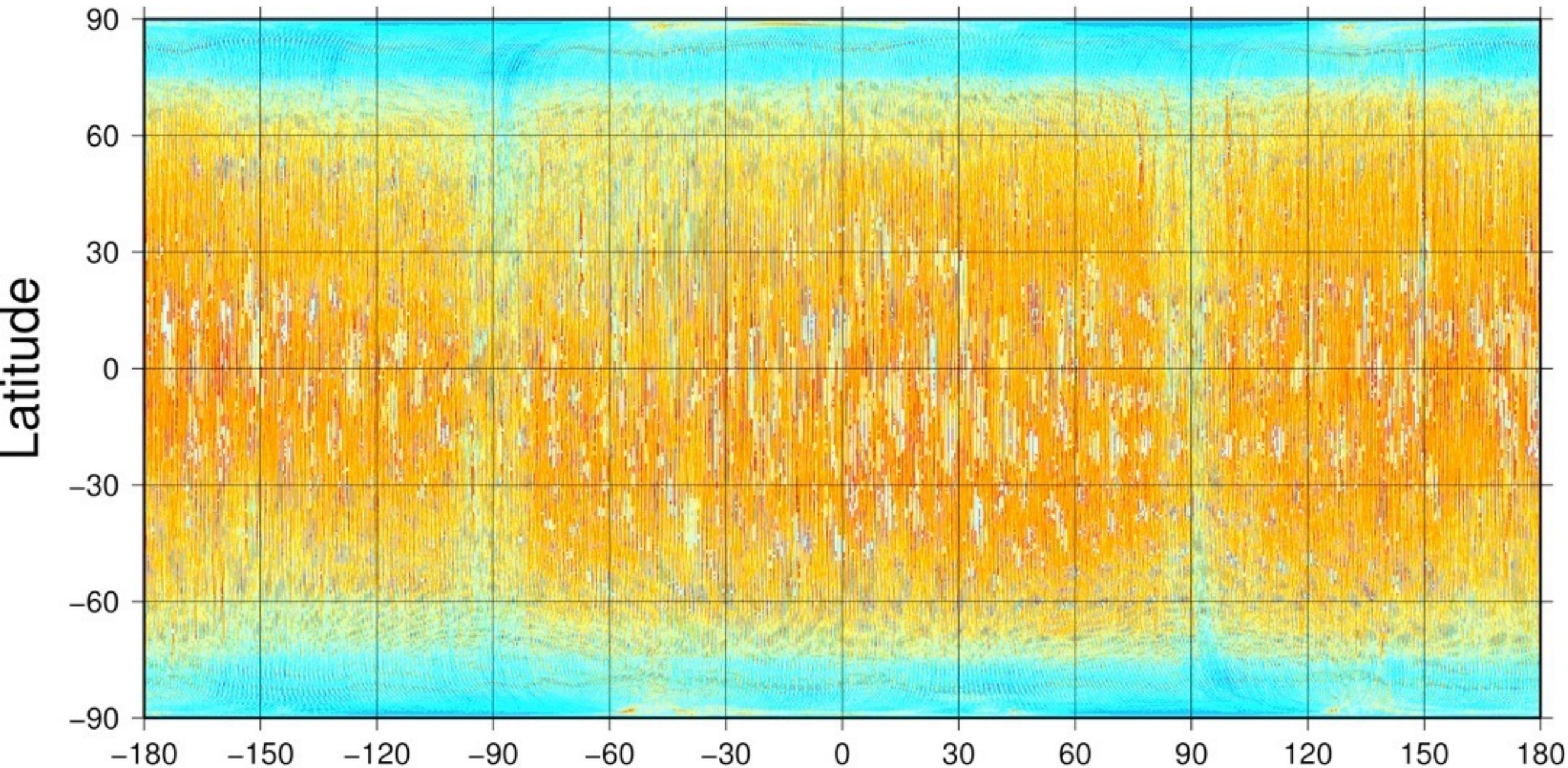


Gridded Data Records
Examples: LDEC_64

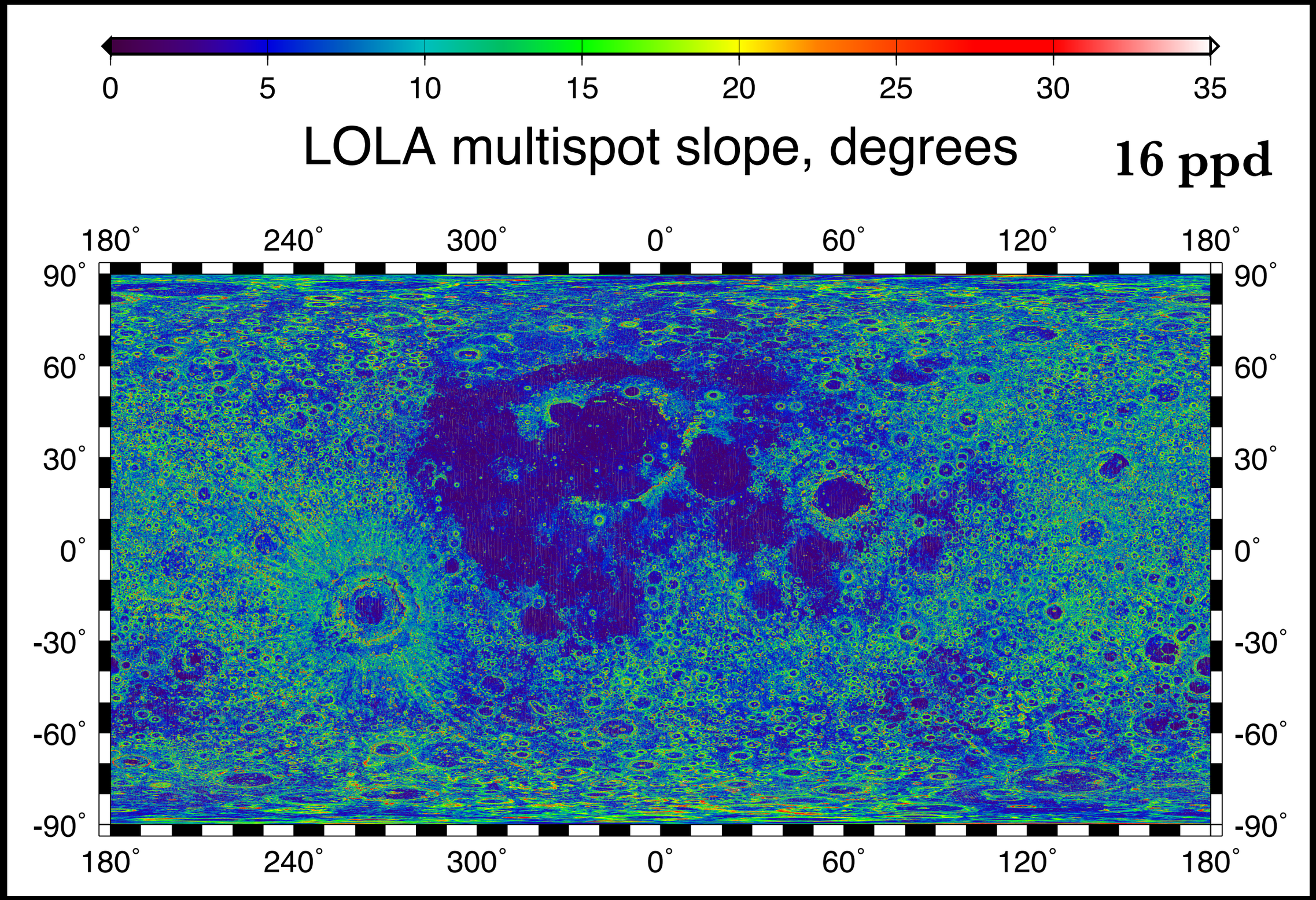
From the LRO LOLA Science Team

LDEC_4.GRD: counts in each 0.25° pixel

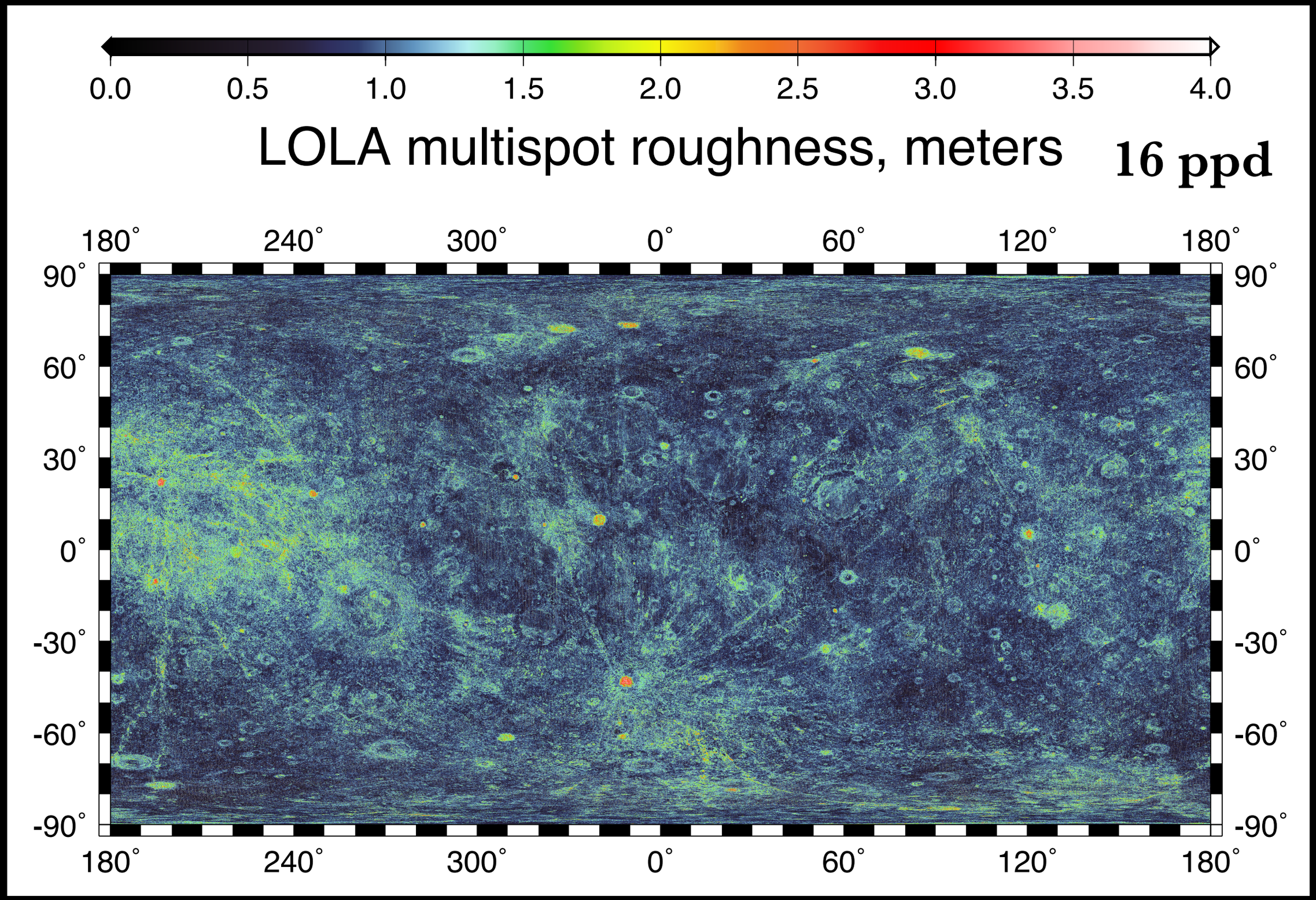
min 35 max 18119 mean 5215.0 rms 1798.4



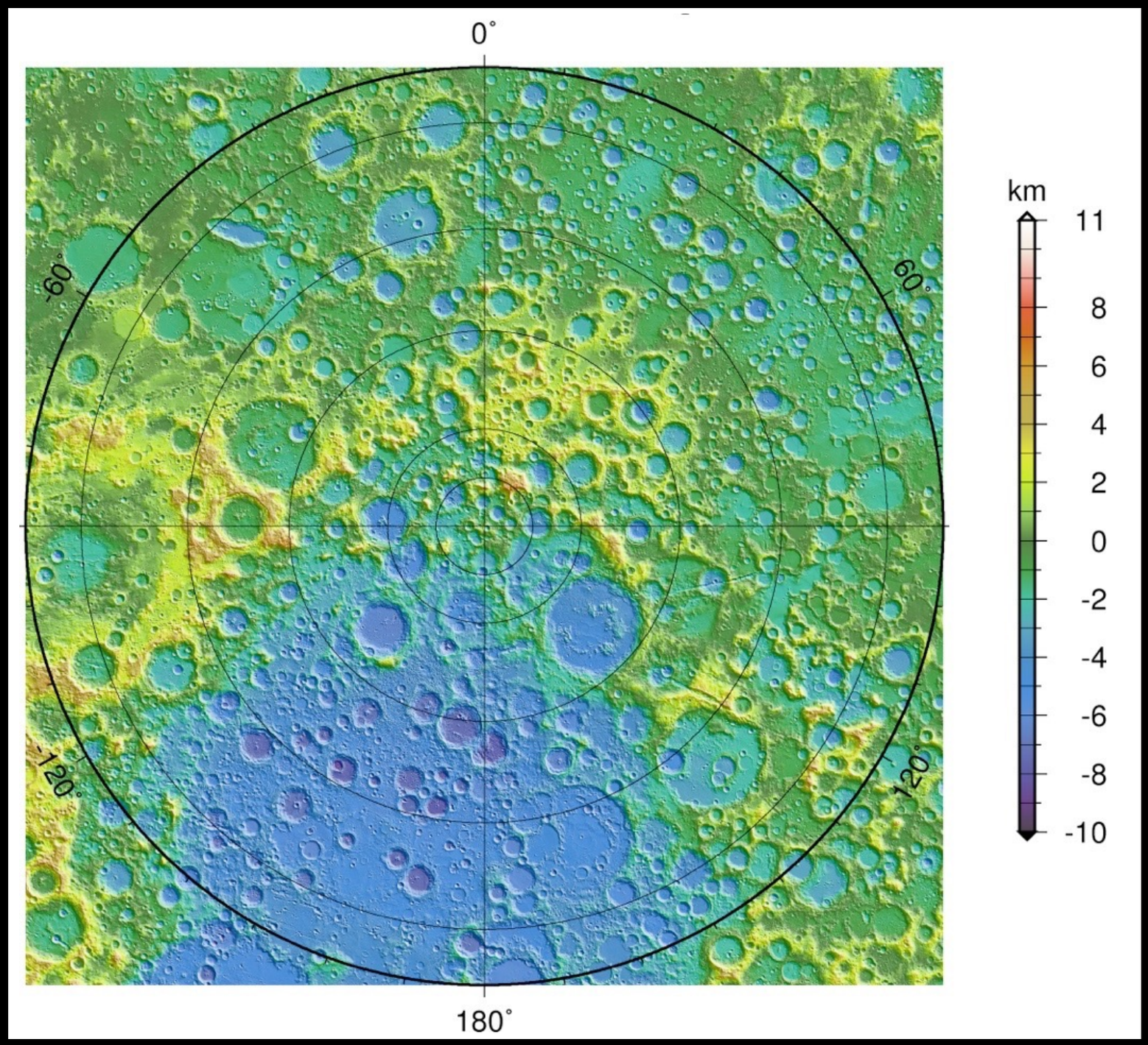
Gridded Data Records
Examples: LDSM_16



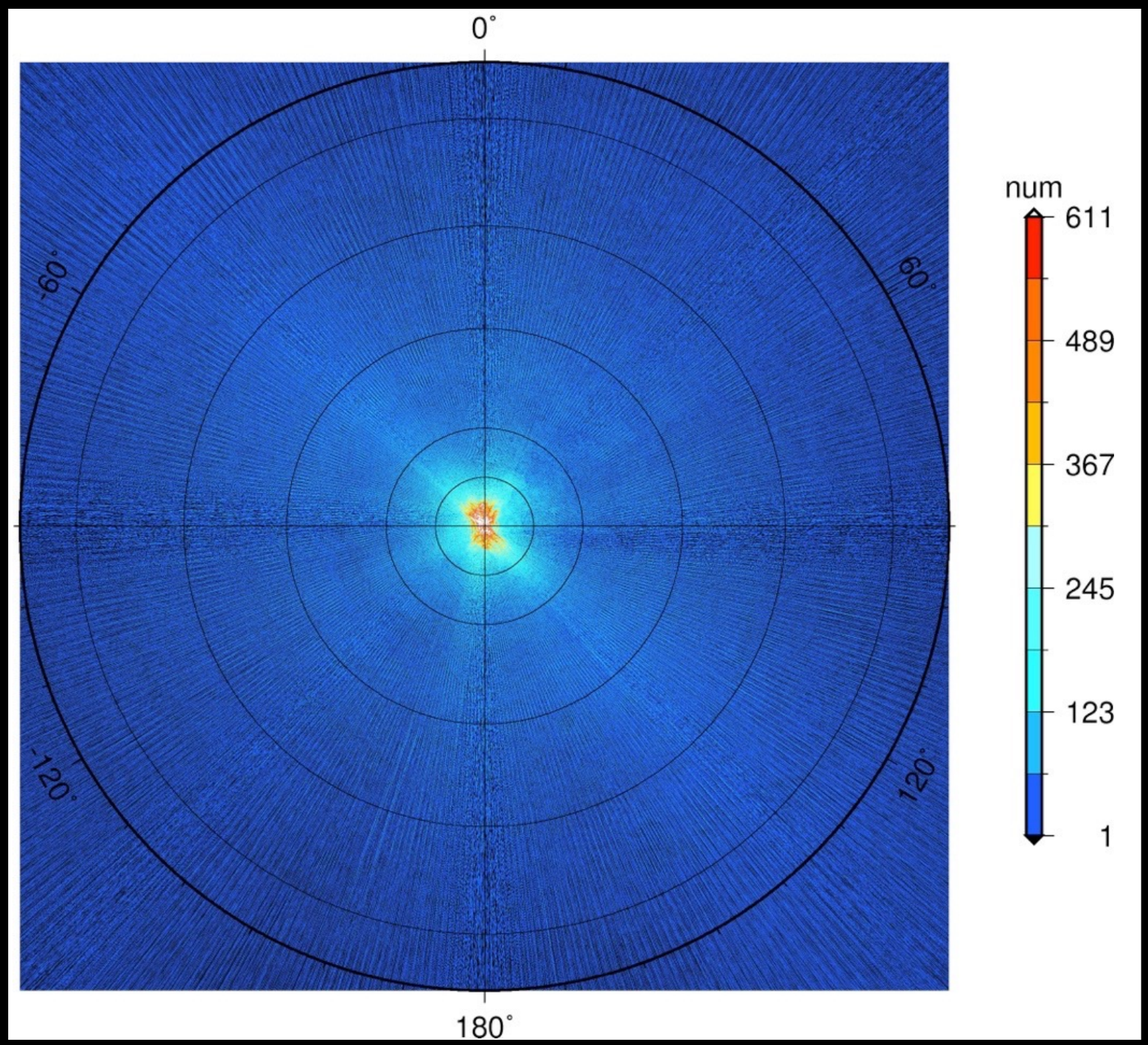
Gridded Data Records
Examples: LDRM_16



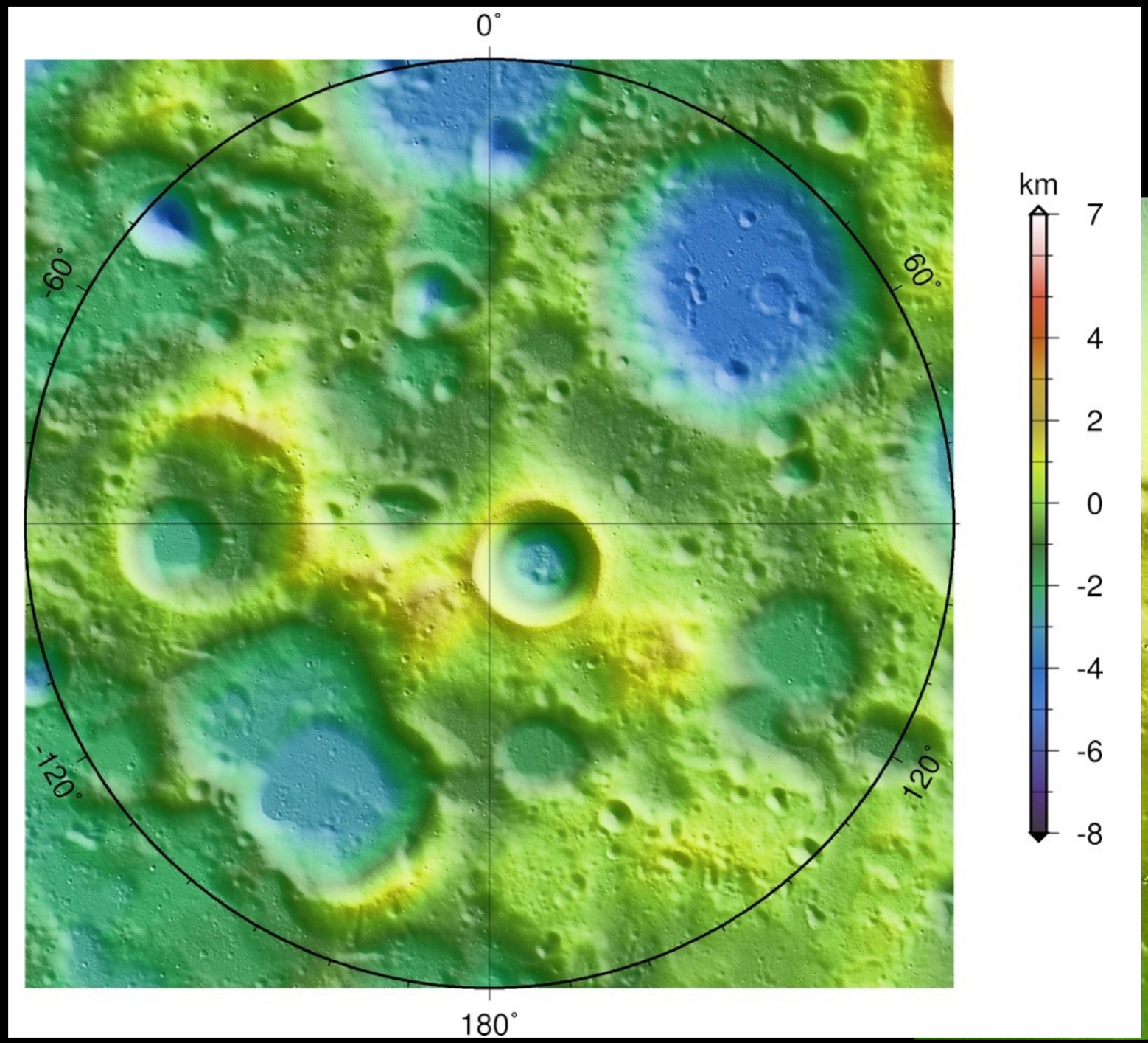
Gridded Data Records
Examples: LDEM_45S_400M



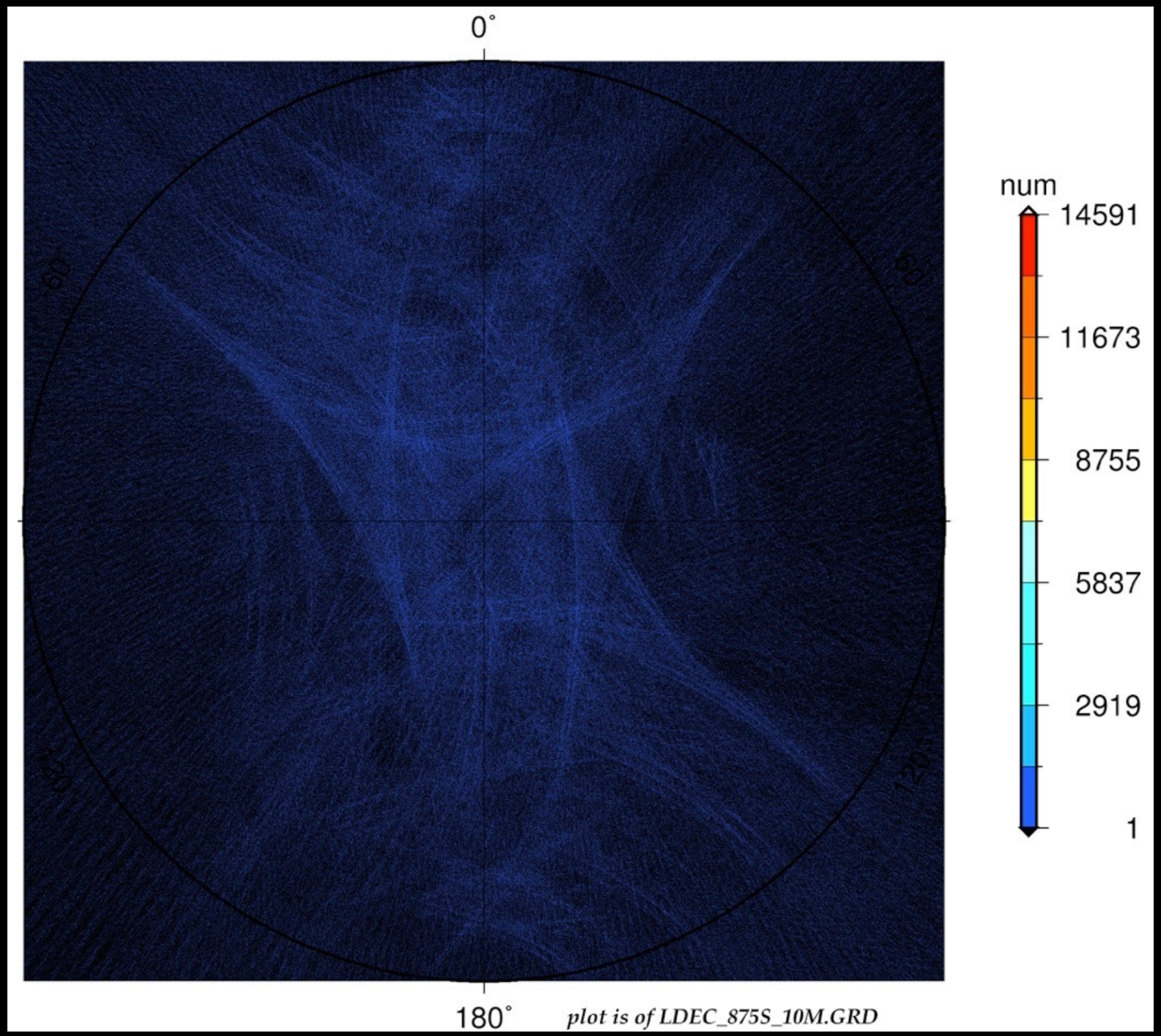
Gridded Data Records
Examples: LDEC_45S_400M



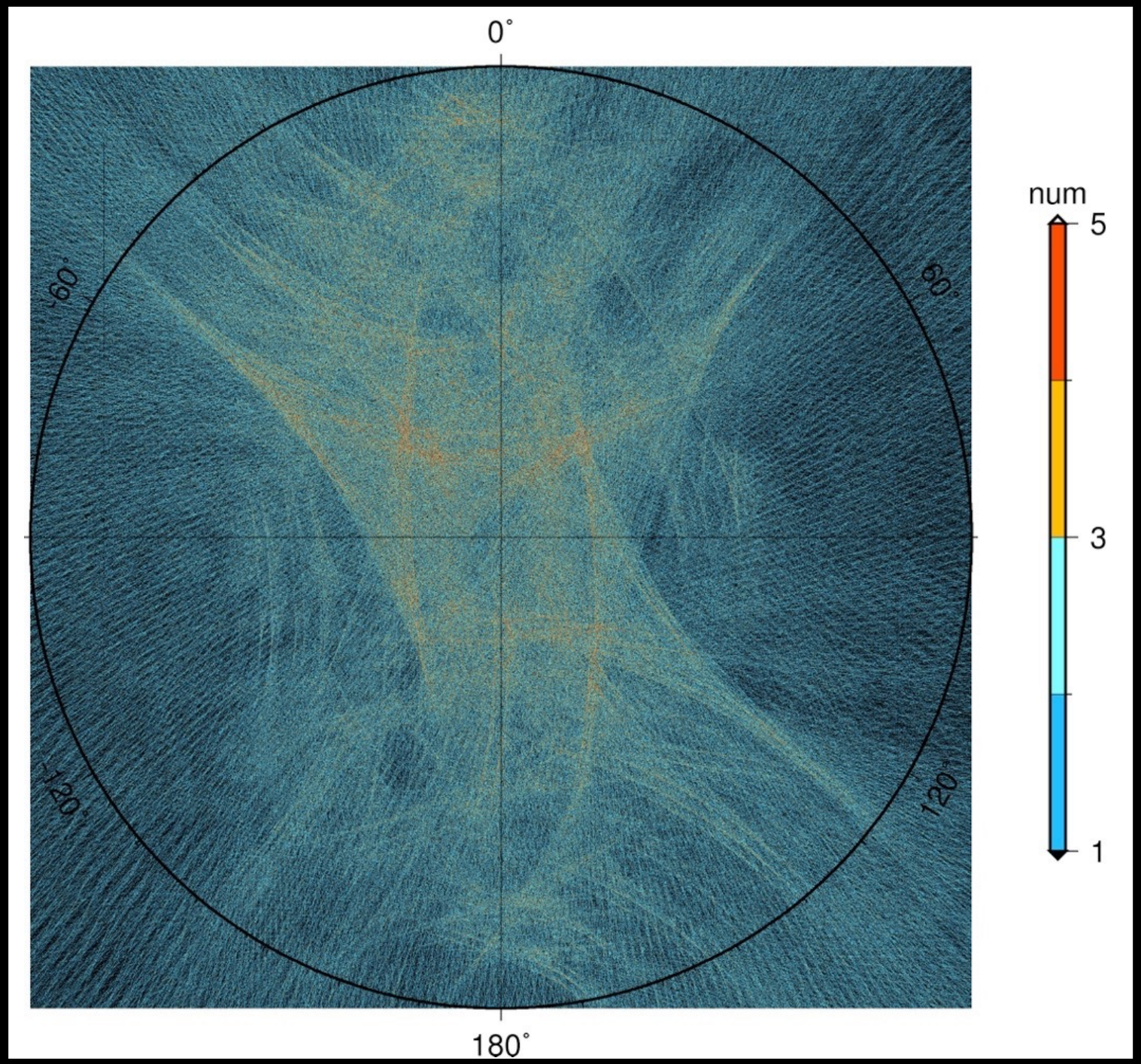
Gridded Data Records
Examples: LDEM_875S_5M



Gridded Data Records
Examples: LDEC_875S_5M



Gridded Data Records
Examples: LDEC_875S_20M



Spherical Harmonic Data Rec. (SHADRs)

- Spherical harmonic expansions of lunar shape derived from 16 and 64 ppd GDRs
  - ASCII tables with: degree (l), order (m), and C_{lm}/S_{lm} Stokes coefficients
- Detached PDS labels describe table contents
- The latest version is LRO_LTM05, to L=2050

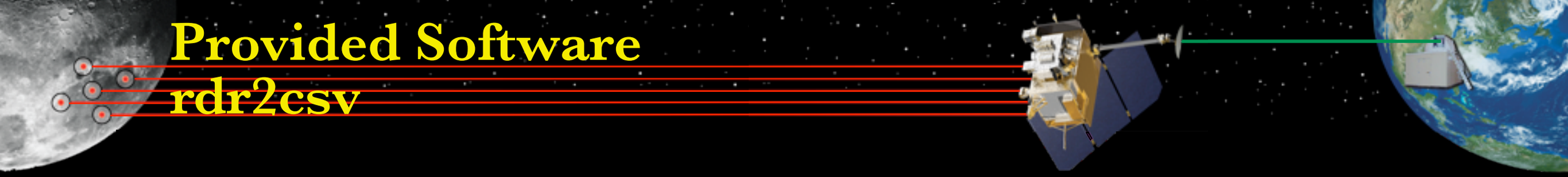
- Useful for spectral studies, and comparison of topography and gravity to study the crust and sub-surface

Provided Software

- Command-line executable tools for outputting LOLA RDR files:
  - rdr2csv - ASCII comma delimited output format
  - rdr2table - Space delimited output
  - rdr2tab - like rdr2table, but more options
  - rdr2xyz - 3-column binary output (good for large jobs)

- Includes FORTRAN source and executables for several architectures

Provided Software
rdr2csv



- rdr2csv writes the RDRs to lengthy Comma-Separated Value tables that can be imported to spreadsheets
- To get a usage message, run the executable 'rdr2csv' with no argument
- To execute, you must place the leap second kernel file, naif0010.tls, in the working directory
- The CSV table is written to standard output in engineering and scientific units
- Each table record has 68 columns and exceeds 720 characters, so it is advisable to pipe the output to a unix filter such as 'more', or redirect the output to a file

```
%  rdr2csv LOLARDR_100392325.DAT H > OUTPUTFILE.CSV
```

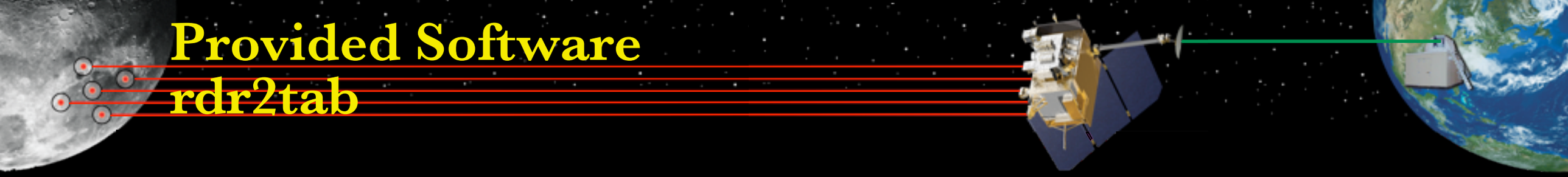
- Leave out the “H” if you don’t want a header
- Each table row corresponds to all 5 spots in a single shot (e.g. minor frame)
- Column descriptions in LABEL/LOLARDR.FMT file

Provided Software
rdr2csv: example output

```
Coordinated_Universal_Time,Frame,Mission_ET,Subseconds,Terrestrial_Dyn_Time
, TX_Energy_mJ,TX_PulseW,SC_Longitude, SC_Latitude,SC_radius,
Geoid,D1_Longitude, D1_Latitude,D1_Radius,D1_Range, D1_PulseW,
D1_Energy,D1_noi,D1_Thr, D1_Gn,Flg1,D2_Longitude, D2_Latitude,   D2_Radius,
D2_Range, D2_PulseW, D2_Energy,D2_noi,D2_Thr, D2_Gn,Flg2,D3_Longitude,
D3_Latitude,   D3_Radius,    D3_Range, D3_PulseW, D3_Energy,D3_noi,D3_Thr,
D3_Gn,Flg3,D4_Longitude, D4_Latitude,   D4_Radius,    D4_Range, D4_PulseW,
D4_Energy,D4_noi,D4_Thr, D4_Gn,Flg4,D5_Longitude, D5_Latitude,   D5_Radius,
D5_Range, D5_PulseW, D5_Energy,D5_noi,D5_Thr, D5_Gn,Flg5,Offnadir,Emission,
Sol_INC, Sol_Phs, Earth_Centr.,Earth_PW,Earth_E.

2010-02-08T23:25:41.19902676,  0,  20334315, 0.0096541403,
318943607.383026838,    2.661147,     8.927, 289.9432895,   0.2324604,
1779.811229,1737.21461, 289.9369335,   0.2338465, 1737.201828,   42.609866,
21.598,    0.1918,     4, 58.81, 50.21,   0, 289.9372340,   0.2332029,
1737.204538,   42.607101,    24.799,    0.3699,     3, 31.64, 49.87,   0,
289.9362832,   0.2335533, 1737.201984,   42.609799,    23.757,    0.4560,
5, 31.94, 49.97,   0, 289.9366190,   0.2344836, 1737.197877,   42.613887,
23.440,    0.4042,     7, 27.93, 49.23,   0, 289.9375633,   0.2341331,
1737.202284,   42.609337,    20.451,    0.4350,     5, 32.92, 50.16,   0,
0.266,   0.275,  48.412,  48.684, 0.0000000000,  39.865,   0.000
```

Provided Software
rdr2tab



rdr2tab writes the RDR file to a space-delimited ASCII table with many options

Usage:

% rdr2tab <rdrfile> [A 0 1 2 3 4 5] [F|flag] [G|geoid] [H|header] [L|limitfile] [O|origin] [C|ckernel] [D|dateline] [M|manual] [N|n] [O|origin] [Q|quarrel] [U|utc] [[S|swap_bytes] [V|verbose] [W|weird]

0 Spacecraft position, altitude, attitude, and laser pulse information.
1-5 Any combination of number(s) between 1 and 5 to select detector spots.
A,a Include all detector spots, equivalent to '1 2 3 4 5'
C,c Check for missing C-kernel attitude data
F,f Ground return flag is checked → noise is excluded
G,g Geoid (selenoid) reference instead of IAU radius (1737.4 km) datum (LLGM-2 geoid !)
H,h Include a header row
L,l Filename - use Limits in r2x.prm or filename containing lonmin, lonmax, latmin, latmax, tmin, tmax, offndr, zmax
M,m Manual flag bit only test. Default is test M and N
N,n Noise editor flag bit only test - a density, slope test
O,o Origin is time in seconds from first shot in RDR file, else SC_MET
Q,q Quarrels between manual and automatic noise editor output
S,s Swap bytes from big endian to little endian, and vice versa (legacy)
U,u UTC DOY and time output
V,v Diagnostic output to unit 0
W,w Points flagged as 'weird' are output regardless of other flags

Provided Software
rdr2tab: example

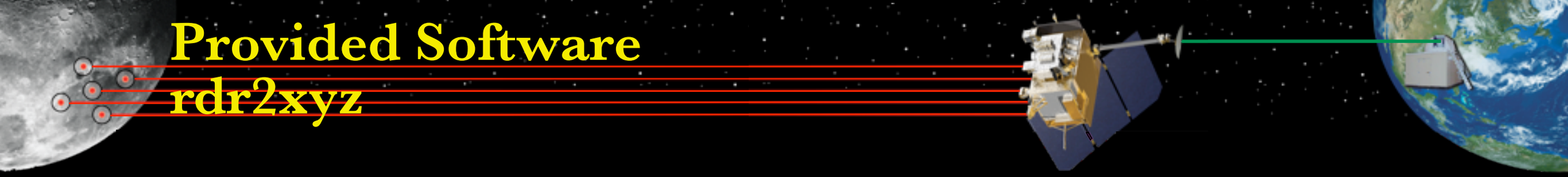
Example: Output all spots; set t = 0 s at beginning of file; include header

% rdr2tab LOLARDR_093271248.DAT A O H > output.txt

SCLK_LOLA	alt_km	id	longitudeE	latitudeN	range_km	energy	noise	thrs	gain		flg	reflect	pulsewd
0.000000	0.0000	1	231.066382	0.240696	53.014	0.0000		1	22.616	50.211	89	-0.17503	-0.00
0.000000	0.1881	3	231.065497	0.240324	52.826	0.2992		10	23.083	49.972	0	0.33656	23.25
0.000000	0.1869	4	231.065907	0.241479	52.827	0.3068		6	19.712	49.227	0	0.24360	21.27
0.035715	0.1848	1	231.066301	0.242583	52.829	0.1482		2	22.616	50.211	0	0.01698	9.37
0.035715	0.1854	3	231.065497	0.242214	52.829	0.2751		6	23.083	49.972	0	0.28851	18.72
0.035715	0.1850	4	231.065908	0.243370	52.829	0.3068		6	19.712	49.227	0	0.24362	19.19
0.071428	0.0000	1	231.066384	0.244477	53.013	0.0000		2	22.616	50.211	89	-0.17072	-0.00
0.071428	0.1846	3	231.065499	0.244105	52.829	0.2871		6	23.083	49.972	0	0.30487	19.79
0.071428	0.1852	4	231.065909	0.245260	52.828	0.2960		5	19.712	49.227	0	0.21775	17.81
0.107143	0.0000	1	231.066386	0.246367	53.013	0.0000		2	22.616	50.211	89	-0.17356	-0.00

- Each row corresponds to a single detector.
- If a particular detector didn't record any return pulse, then its entry is skipped **EXCEPT** detector 1 whose boresight is geolocated onto the reference sphere to give an approximate ground track (e.g. exercise caution).
- 1st column = time
- 2nd column = elevation (or topograhy if G).
- 3rd column = detector number.
- 3rd to last column = Flag. **0** means valid ground according to slope and density test.
- Best to use the "M" command-line option.

Provided Software
rdr2xyz



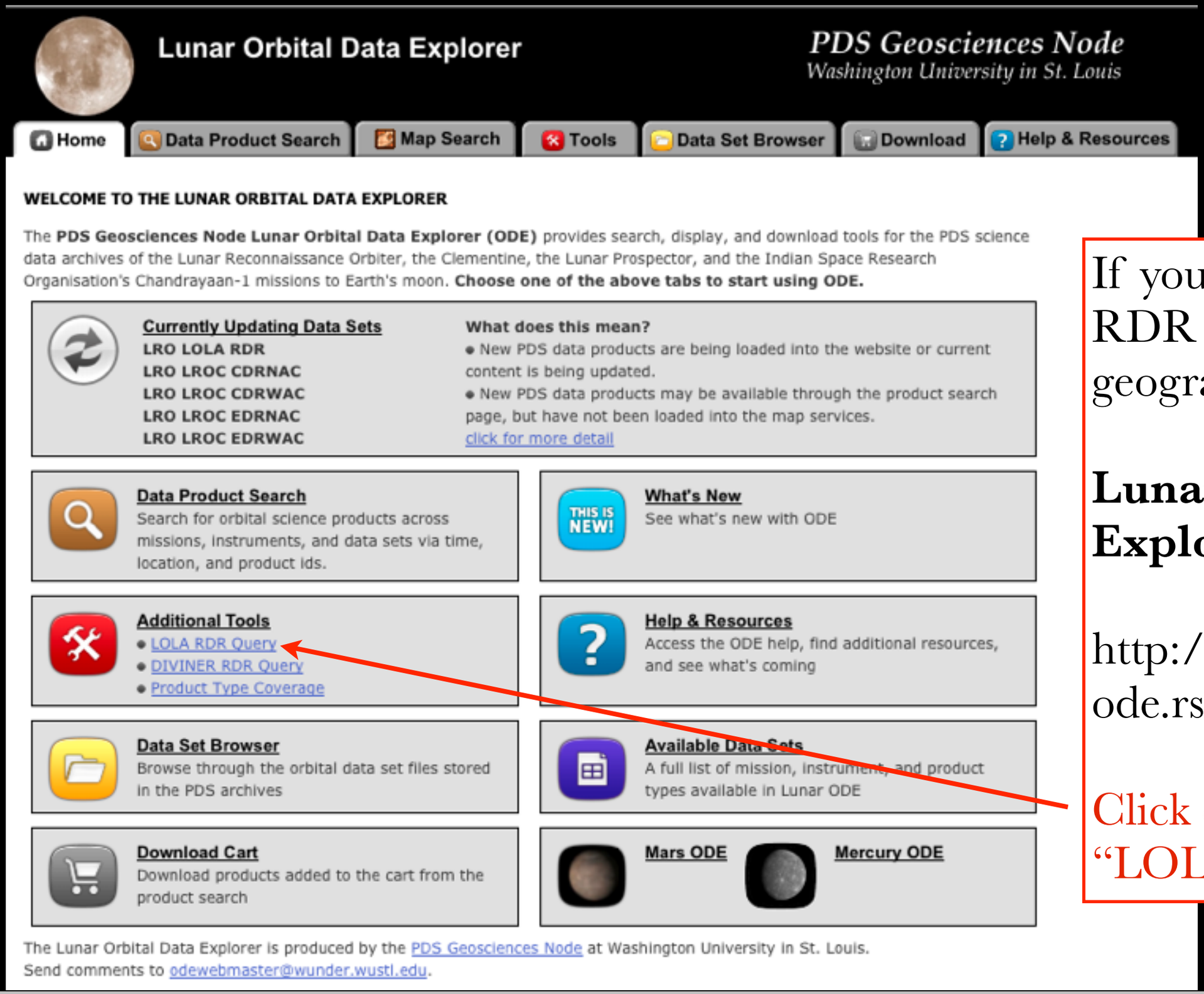
- If running rdr2tab on many RDRs, consider using rdr2xyz to save disk space and time.

- Example:

```
% rdr2xyz LOLARDR_093271248.DAT A M
 spot        1  rec=     86766
 spot        2  rec=     86242
 spot        3  rec=    162337
 spot        4  rec=    161253
 spot        5  rec=     83419
```

- Create 5 separate binary xyz (lon, lat, z) files, one for each detector.
- Here, used "A" to output all spots and "M" to output points that passed manual editing.

A practical example
How to create a custom DEM?



If you want to get all RDR data in a small geographic patch:

Lunar Orbital Data Explorer

http://ode.rsl.wustl.edu/moon

Click on "LOLA RDR Query"

Lunar Orbital Data Explorer

PDS Geosciences Node
Washington University in St. Louis

Home | Data Product Search | Map Search | Tools | Data Set Browser | Download | Help & Resources

LOLA offers two key altimetry products - the RDR and GDR products. LOLA RDR products are sets of individual altimetry readings organized along the spacecraft orbit track. The GDR products are RDR products assembled into global grids referenced to the Moon's center-of-mass, with resolutions up to 1/128 degree per pixel. LOLA GDR products will meet many user needs and should be reviewed prior to using the LOLA RDR Query. Click here to view the results list of GDR products.

The LOLA RDR Query provides a searchable database of individual RDR measurements.

STEP 1. SELECT DATA POINT LATITUDE / LONGITUDE RANGE TO SEARCH (A SELECTION IS REQUIRED)

Select a Specific Feature

A selected feature's Latitude and Longtude bounding box will be used for search criteria.

Feature Type: Crater — Feature Type Descriptions

Feature Name: Trumpler — Full Feature Name List

or

Directly specify a Latitude and Longitude coverage area

ODE uses planetocentric coordinates that are based on the frame center latitude and longitude. Please see the frame vs. point comparison in the ODE help.

Max Latitude (-90 to 90): 30.5437

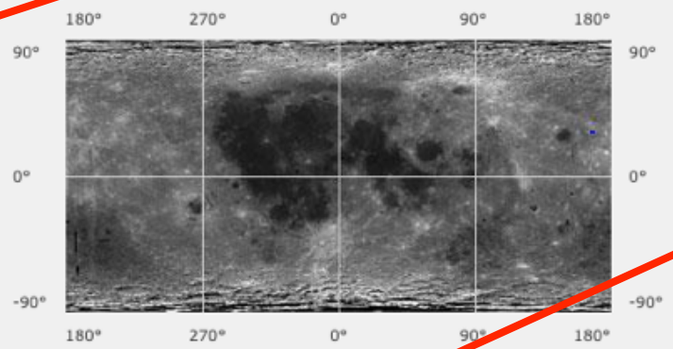
Western most Longitude (0 to 360): 165.5662

Eastern most Longitude (0 to 360): 168.4461

Min Latitude (-90 to 90): 28.0318

Show Area On Map

Selected Search Area



STEP 2. SET ADDITIONAL FILTERING PARAMETERS (OPTIONAL)

Select a Product ID or filter by a partial Product ID	(Show Options - 0 Parameters Set)
Filter by Altitude	(Show Options - 0 Parameters Set)
Filter by Orbit Number	(Show Options - 0 Parameters Set)
Filter by UTC Time	(Show Options - 0 Parameters Set)
Filter by Channels	(Show Options - 5 Parameters Set)

STEP 3. PREVIEW RESULTS COUNT

Click the button below to see how many LOLA RDR points match your selected criteria.

Query Count — Points found: 712,345

Proceed to download results if you are satisfied with the point count.

STEP 4. REQUEST RESULTS

Note: Any change to the search criteria will clear the results and require a requery. Please acquire generated files before changing criteria.

CSV Format — Generate Files

Files

RDR_165E168E_28N30NPointPerRow_csv_table.csv (231 MB)
RDR_165E168E_28N30NPointPerRow_csv_table.lbl (13 KB)
RDR_165E168E_28N30NFramePerRow_csv_table.csv (154 MB)
RDR_165E168E_28N30NFramePerRow_csv_table.lbl (27 KB)
RDR_165E168E_28N30NTopoFull_csv_table.csv (50 MB)
RDR_165E168E_28N30NTopoFull_csv_table.lbl (4 KB)

Grouped Files - Download Format

zip | tar | tar.gz

1) Enter lon, lat limits or choose specific feature for example: crater - Trumpler)

2) Click on "Query Count"

3) Click on "Generate Files"

4) Download CSV files

A practical example
How to create a custom DEM?

- **Example:** Trumpler crater, 100 ppd

- Convert CSV file from Orbital Data Explorer to 3-column format:

```
% awk '{FS=",";if(FNR>1)print $1,$2,$3}' csv_table.csv > trumpler.xyz
```

- Using Generic Mapping Tools (GMT):

  - Bin the data and compute median:

```
% blockmedian -R165.57/168.44/28.04/30.54      -I0.01 -bo trumpler.xyz -V -C
> trumpler_100.xyz
```

  - Interpolate:

```
% surface trumpler_100.xyz -R165.565/168.445/28.035/30.545 -V -bi3 -I0.01 -
T0.5 -Gtrumpler_100.grd
```

A practical example
How to create a custom DEM?

- Plot it with GMT now:

  - Calculate gradient for shading:

```
% grdgradient -A45 -Nt -Gtrumpler_100.grad trumpler_100.grd
```

  - Make color table:

```
% makecpt -Z -T-1600/4000/1 > colors.hsv
```

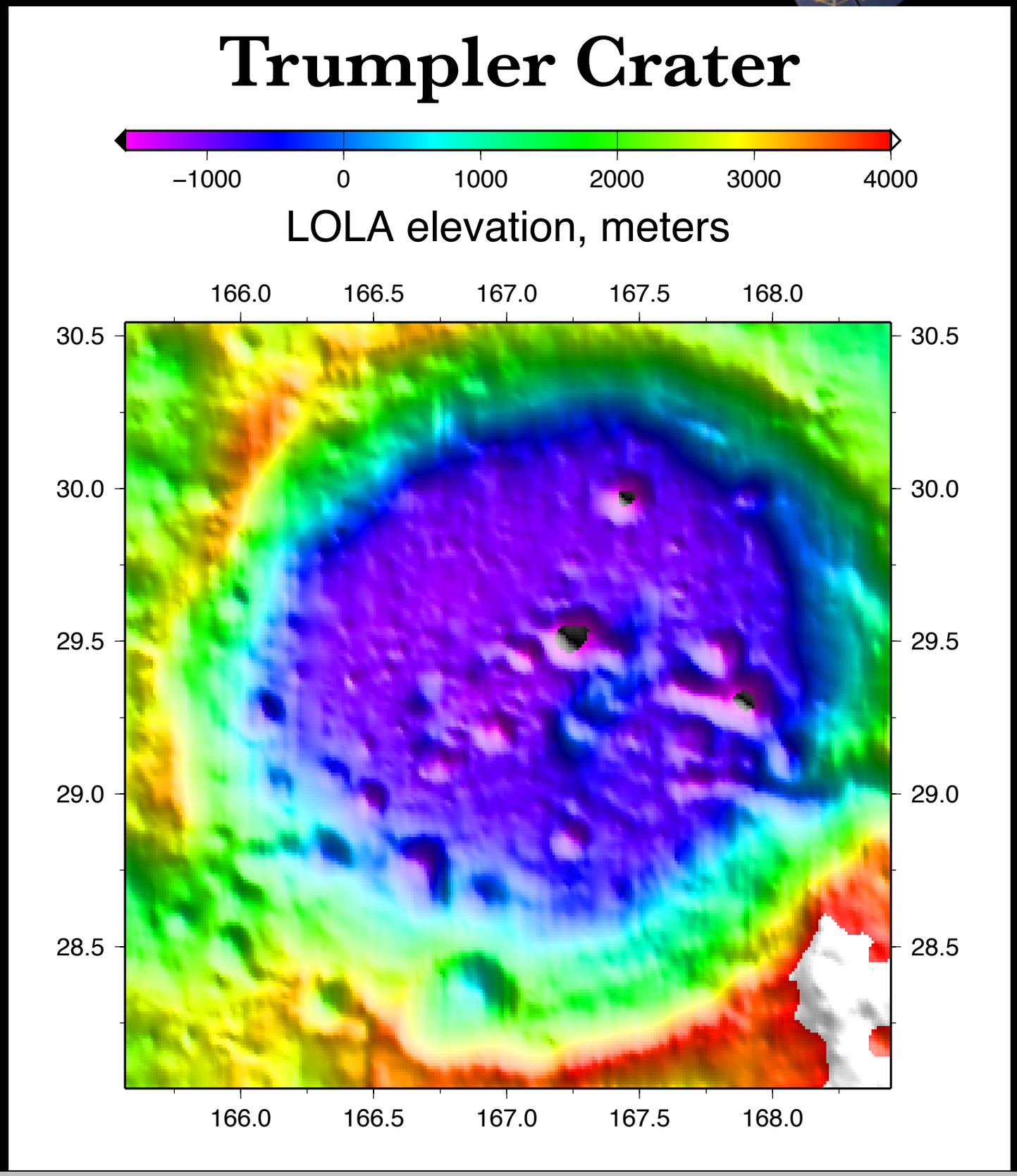
  - Make postscript image:

```
% grdimage -JX6i/6i trumpler_100.grd -P -Xc -Yc -Ccolors.hsv ...
-Itrumpler_100.grad -K -Bf0.25a0.5/f0.25a0.5 > trumpler_100.ps
```

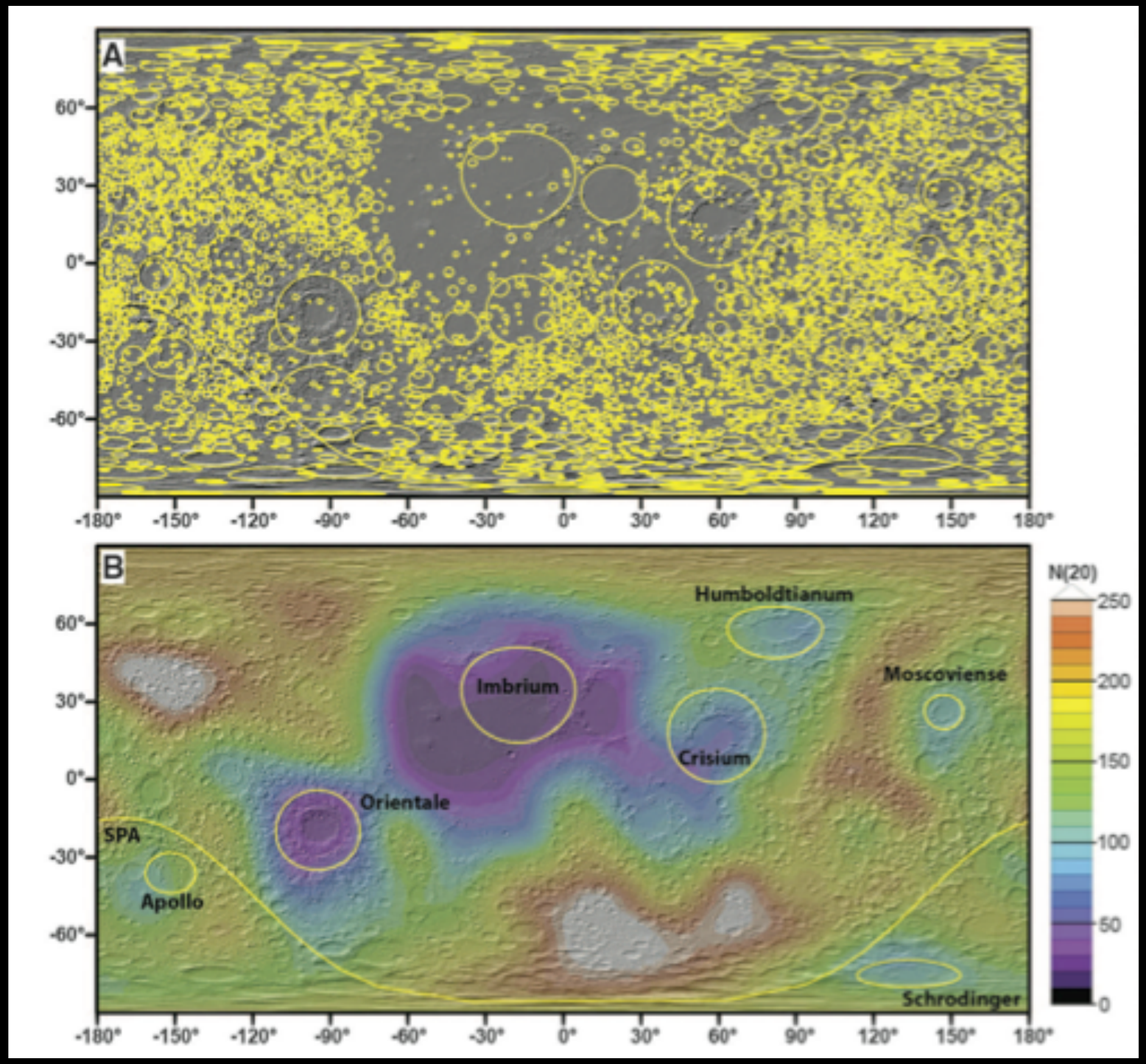
  - Add colorbar:

```
% psscale -D3i/7.5i/6i/0.15ih -Ccolorscale.hsv -E -B1000g2000:“LOLA\ ...
elevation,\ meters”: -O >> trumpler_100.ps
```

A practical example
How to create a custom DEM?



Examples of what you can do
Global Distribution of Craters



Head et al. (2010)

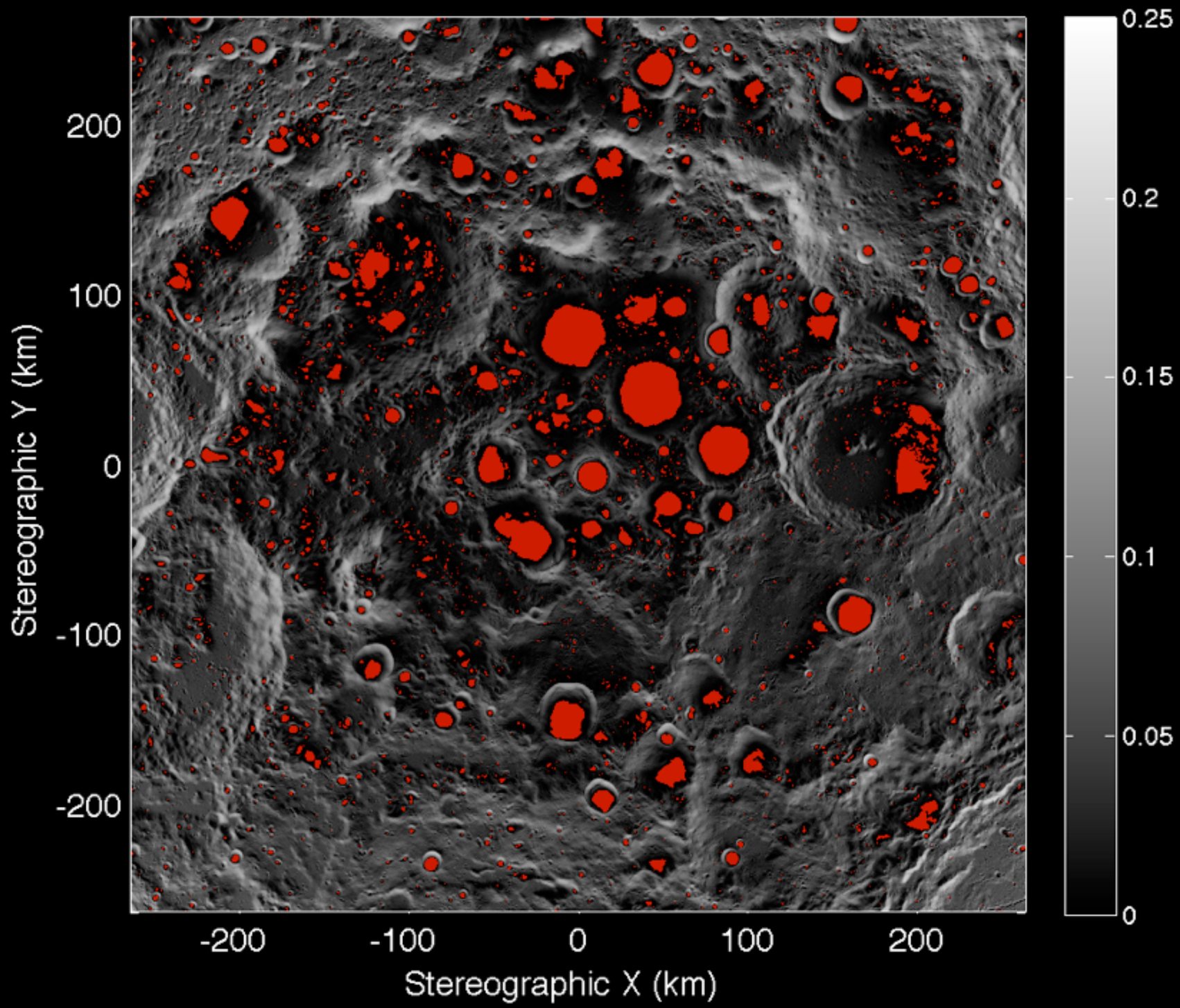
Used 64 ppd LOLA DEM with CraterTools extension to ArcGIS.

Catalogued 5185 craters > 20 km in diameter and analyzed distribution and population characteristics.

2x increase in N(20) over previous work, which suffered from heterogeneous illumination conditions and uneven coverage and quality.

Examples of what you can do
Polar illumination conditions

Average incident flux (%, normalized to F_{inc})

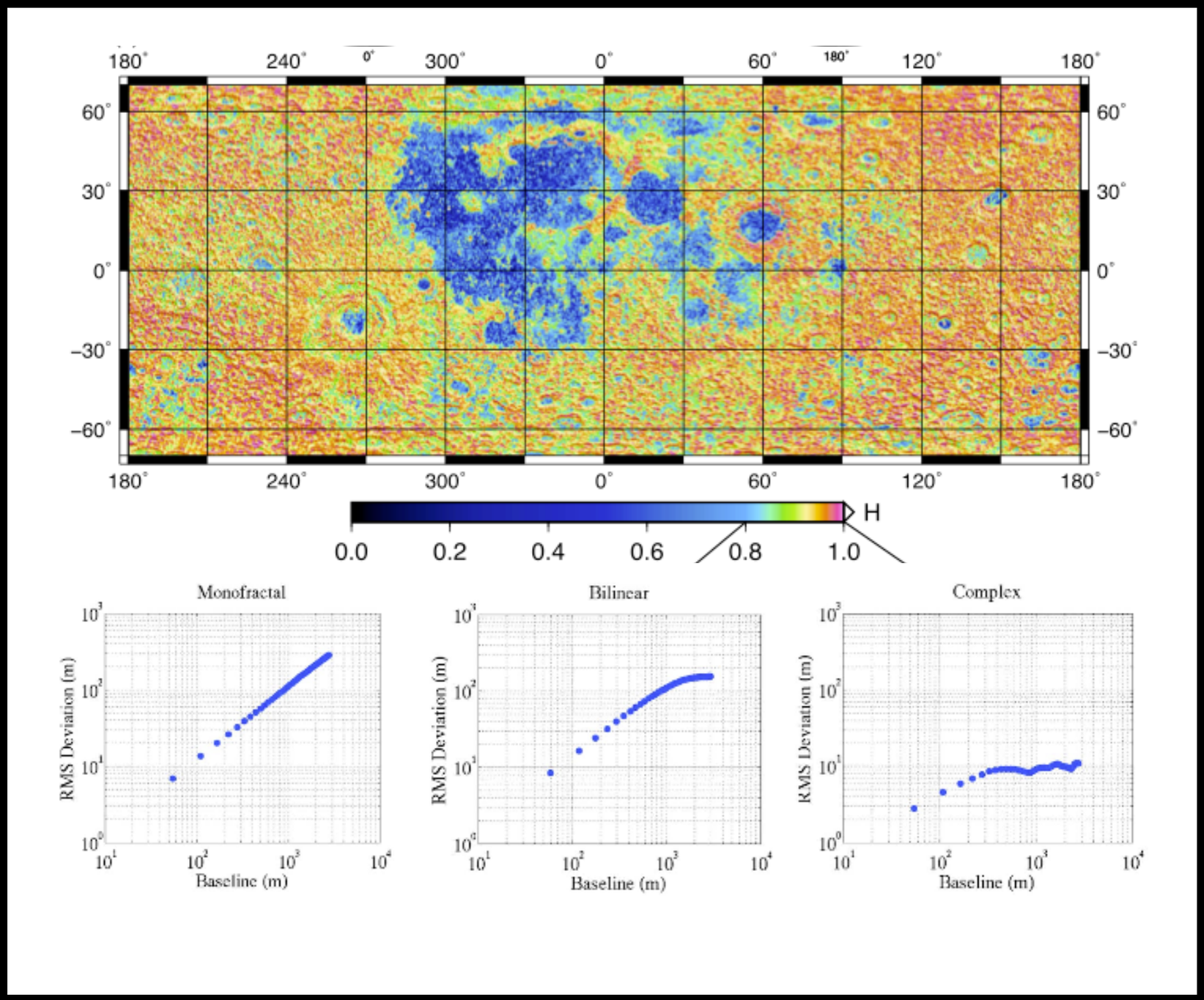


Mazarico et al. (2011)

Mapped permanently shadowed regions using 240 m/pix LOLA polar DEMs

Compared to previous studies, this work incorporates a more accurate & complete DEM, increases computational precision, and greatly extends spatial & temporal coverage.

Examples of what you can do
Spectral nature of surface slope



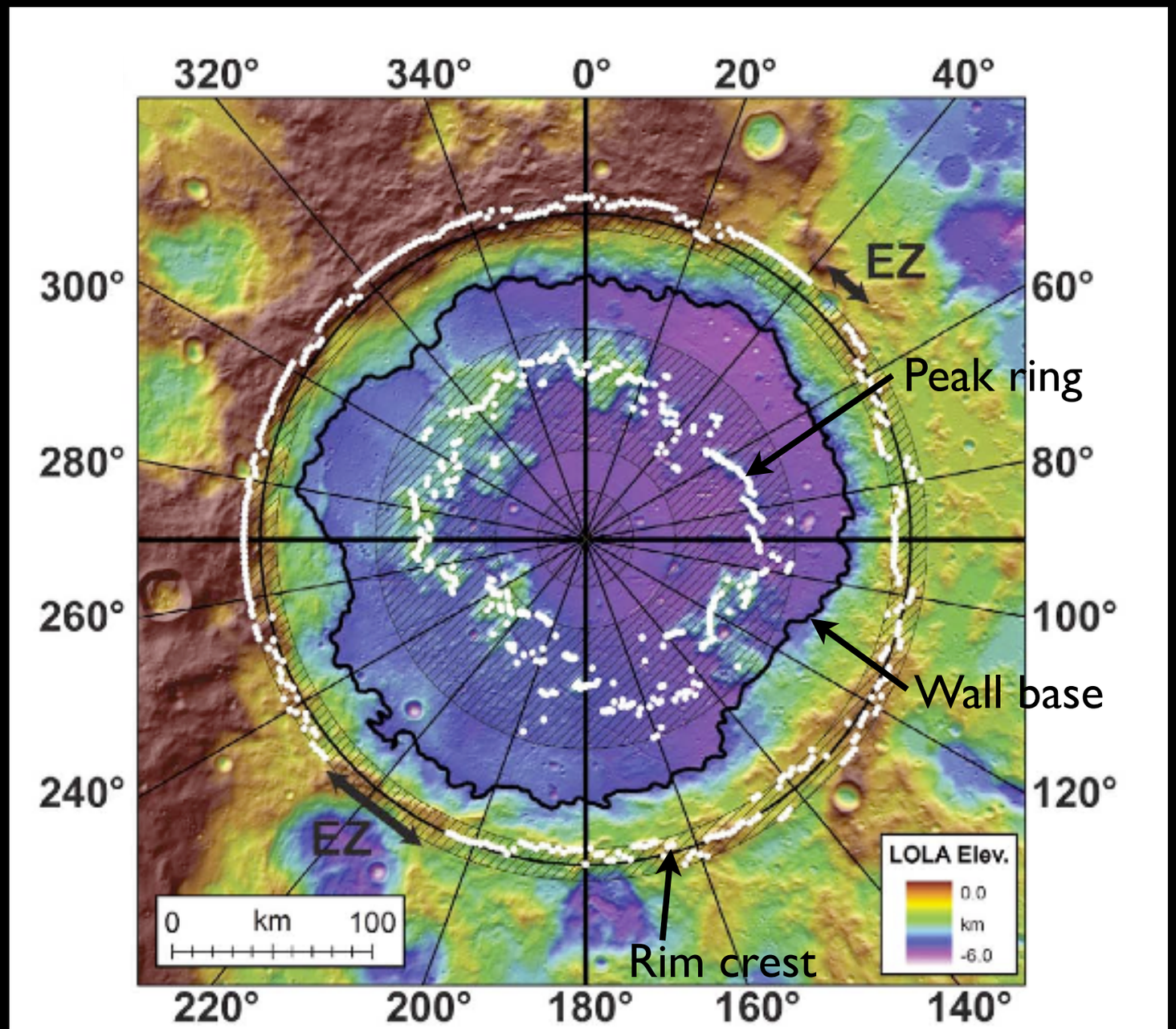
Rosenburg et al. (2011)

Global map of Hurst exponent - available at LOLA Data Node

Deviograms of 1-D slopes at baselines from ~57 m to ~2.7 km

Maria tend to have complex deviograms; highlands - mono and bi

Examples of what you can do
Geometric Properties of Basins



Schrödinger Basin

Baker et al. (2011)

Used 128 ppd LOLA DEM with MATLAB and ArcGIS.

Developed new, semi-automated method for extracting topographic information in a systematic, reproducible way that accounts for complete azimuthal variations.

The LOLA dataset
What you need to know

- What is it?
  - A high-resolution, geodetically precise topography dataset that includes the highest resolution grids of polar topography to date.
  - The current topographic reference for the Moon.

- Where to get it:
  - LOLA Data Node - http://imbrium.mit.edu
  - Lunar Orbital Data Explorer - http://ode.rsl.wustl.edu/moon

- Primary data products:
  - EDR - Experimental Data Record, i.e., raw data
  - RDR - Reduced Data Record, i.e., calibrated, geolocated data at full resolution
  - GDR - Gridded Data Record, i.e., maps
  - SHADR - Spherical Harmonic Data Record, i.e., topography models

The LOLA dataset
What you need to know

- What you can do with the data:
  - Plot & analyze individual tracks (RDR data) or DEMs (GDR data) using standard software like GMT, ArcGIS, MATLAB
  - Make maps of topographical characteristics like one- or two-dimensional slope, roughness
  - Compile catalogs of features like craters & basins
  - Study polar illumination conditions, crustal structure, etc. etc.

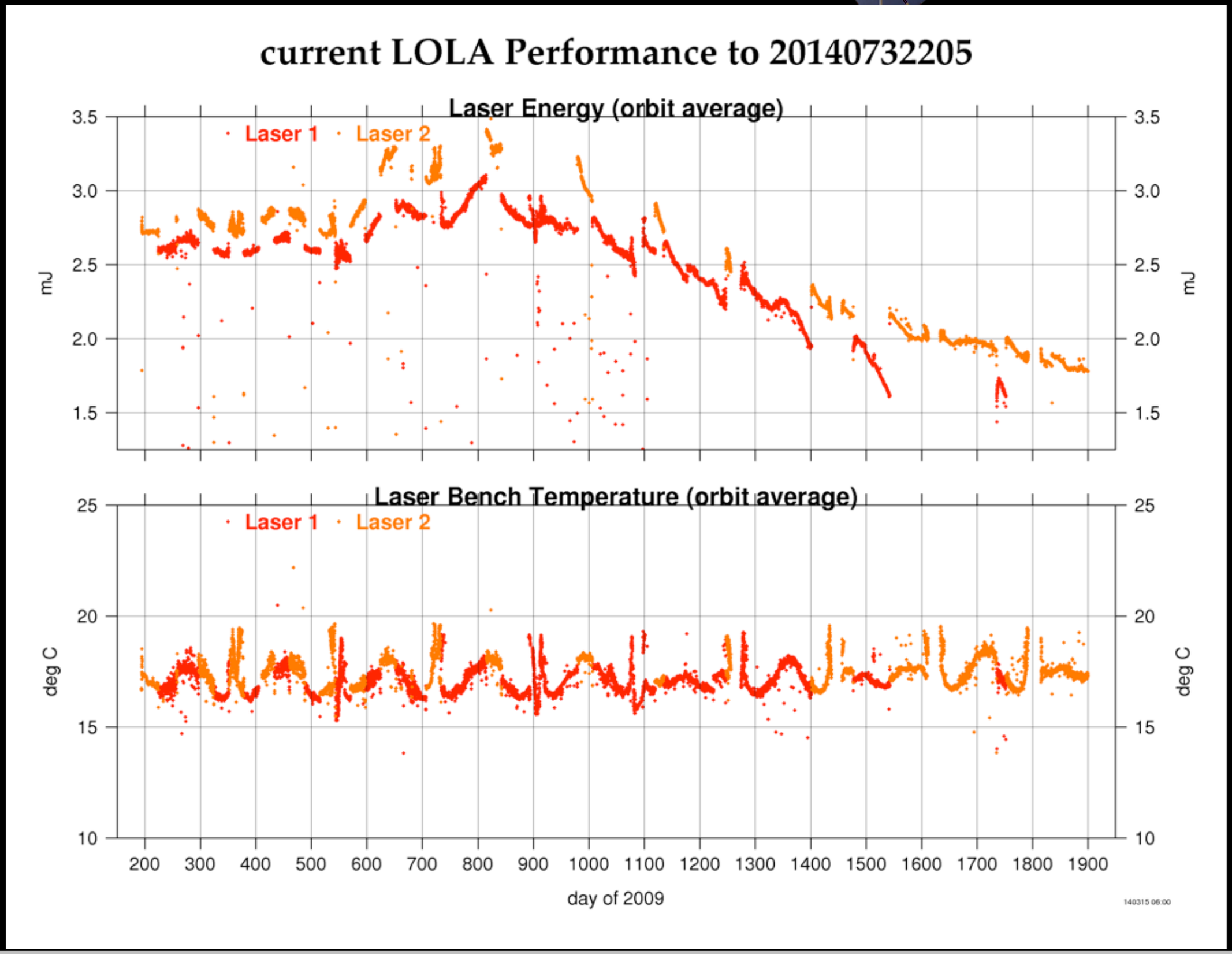
- Things to keep in mind before interpreting the data:
  - LOLA geolocation in Mean Earth-Polar frame and elevation relative to reference sphere of radius 1737.4 km
  - Genuine ground returns sorted from noise with auto-editor and manual editing
  - Signal anomaly - genuine ground returns primarily from det. 3 & 4 on nightside
  - As of Dec. 11, 2011, most data in southern hemisphere

The LOLA dataset
Want to know more?

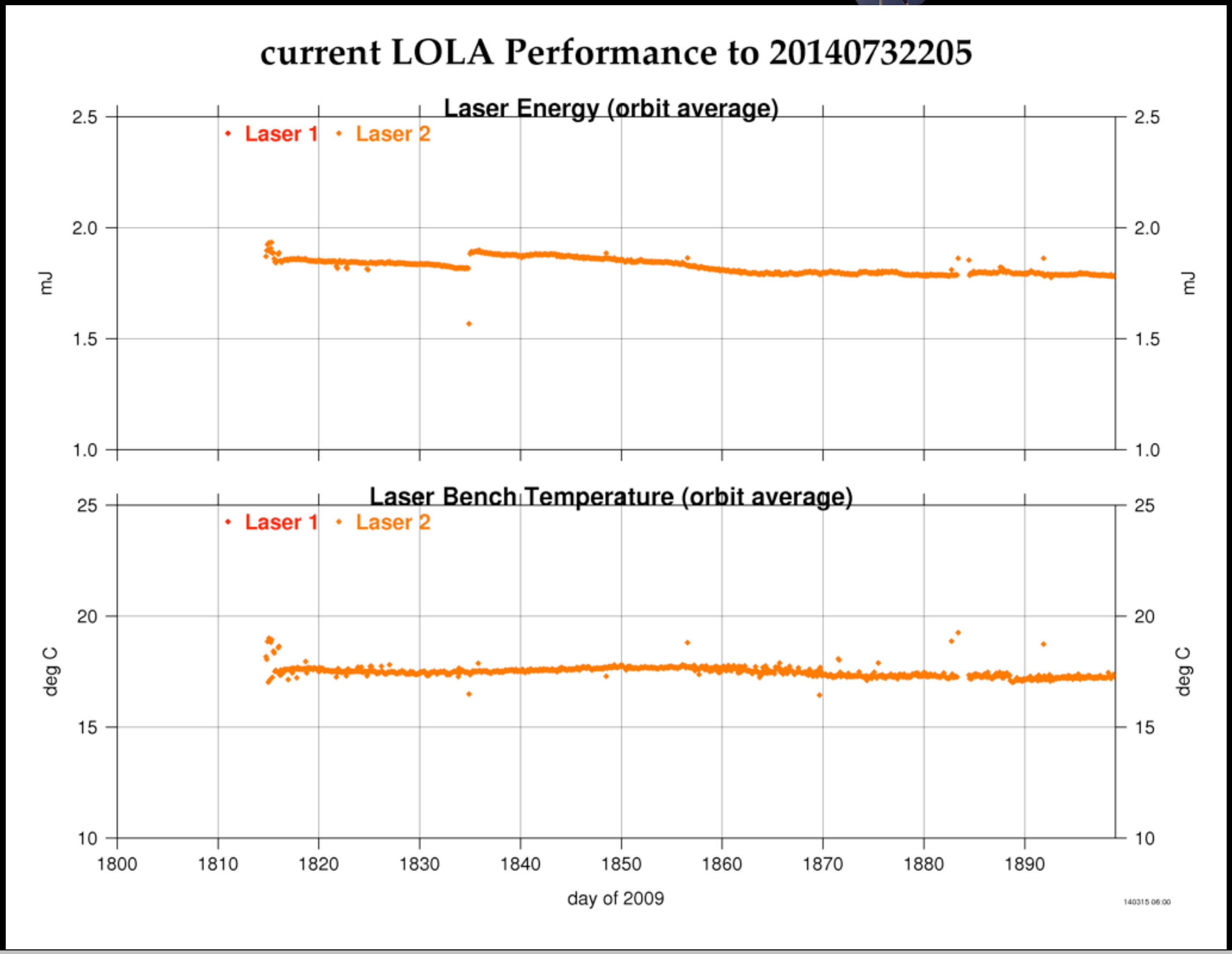
More details on LOLA dataset
Mission Phases

- The LOLA team divides the LRO mission in short periods of about one month, that we call 'mission phase'
  - the EDR and RDR directories are organized according to those
  - naming convention:
    - CO
    - NO_01 to NO_13
    - SM_01 to SM_26
    - ES_01 to ... (currently ES_29)

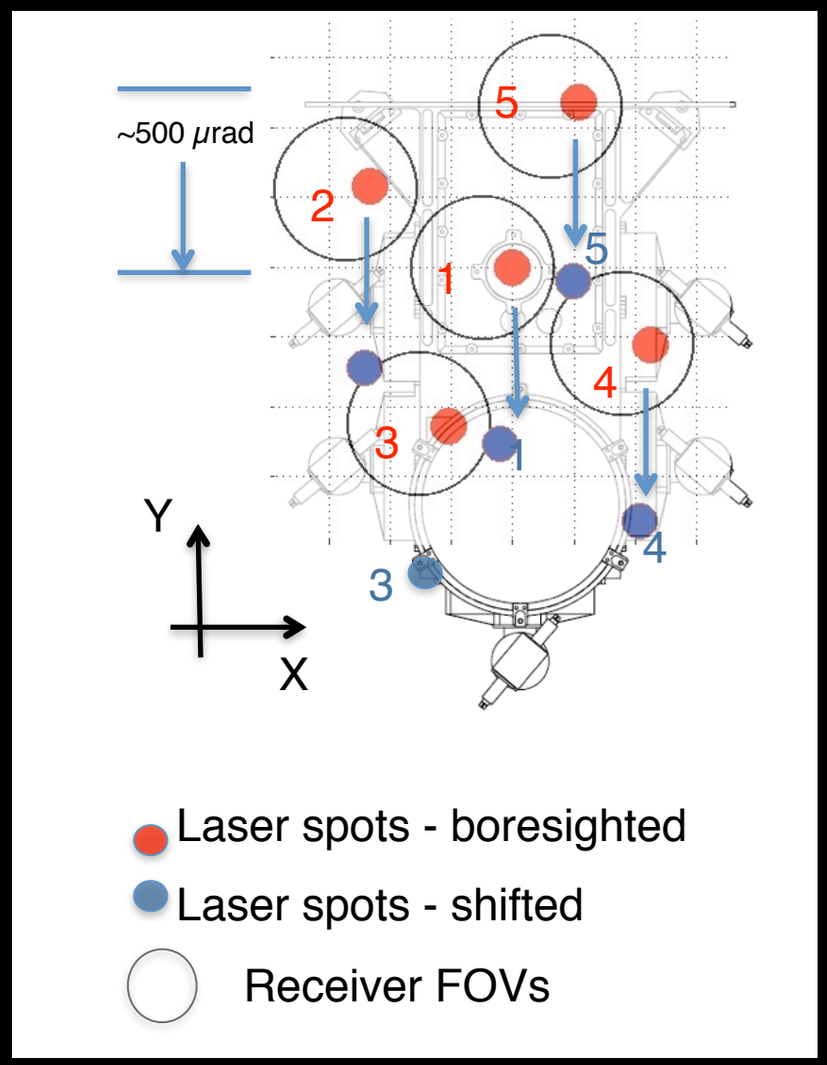
More details on LOLA dataset
Laser Energy trend

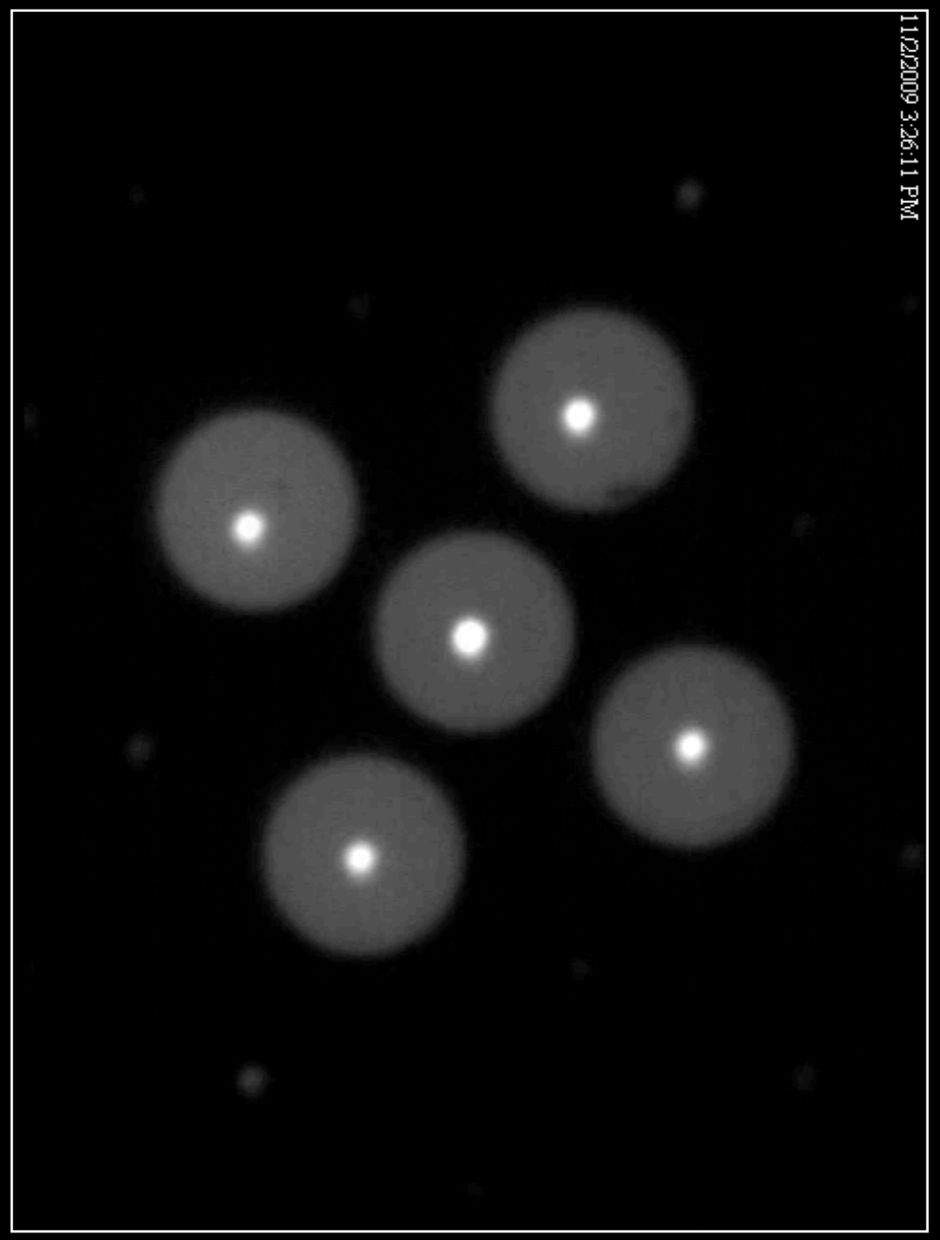


More details on LOLA dataset
Laser Energy trend



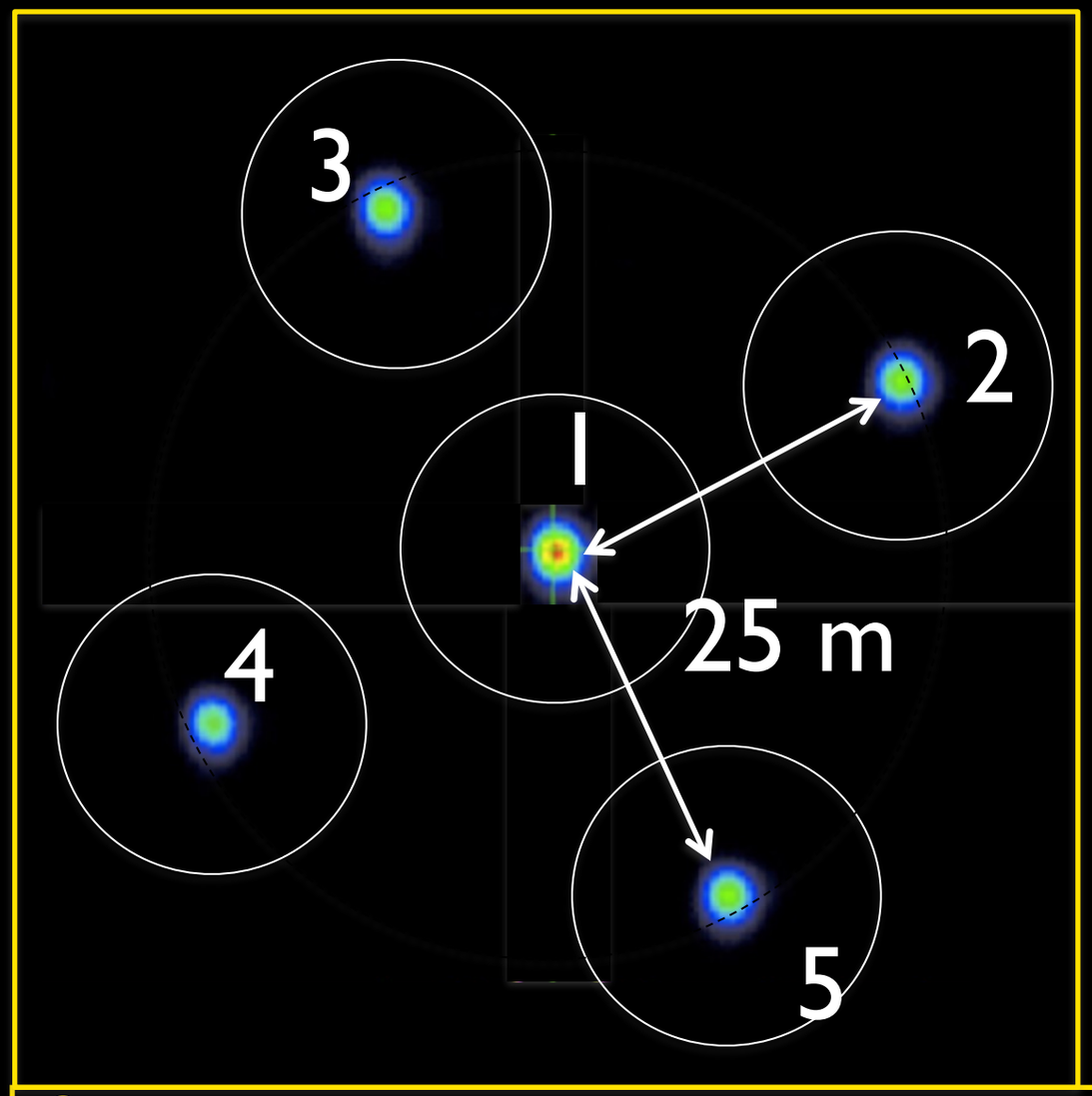
More details on LOLA dataset
Blanket anomaly



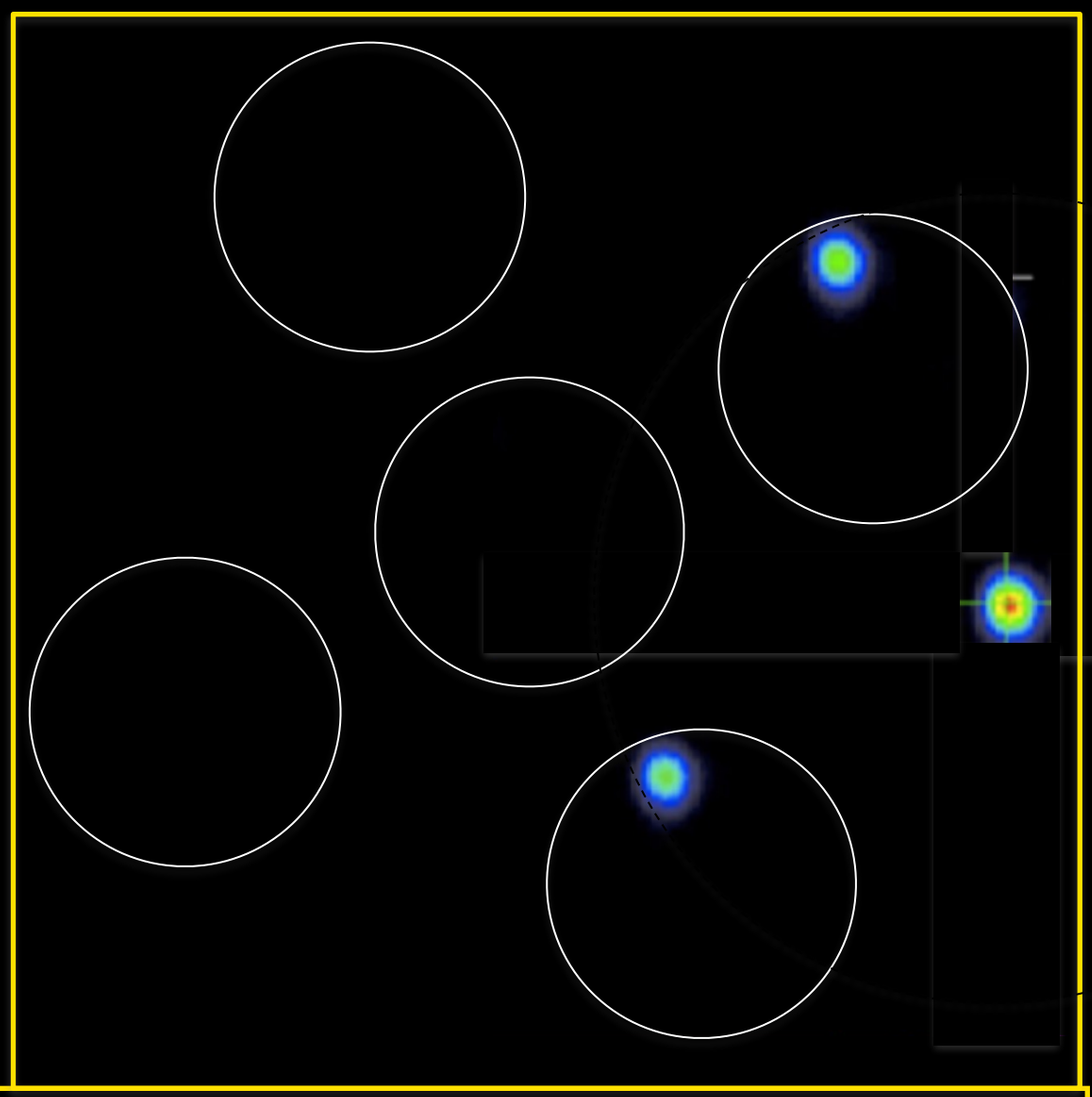


More details on LOLA dataset
Blanket anomaly

Instrument in Sunlight –
THERMAL BLANKETS WARM

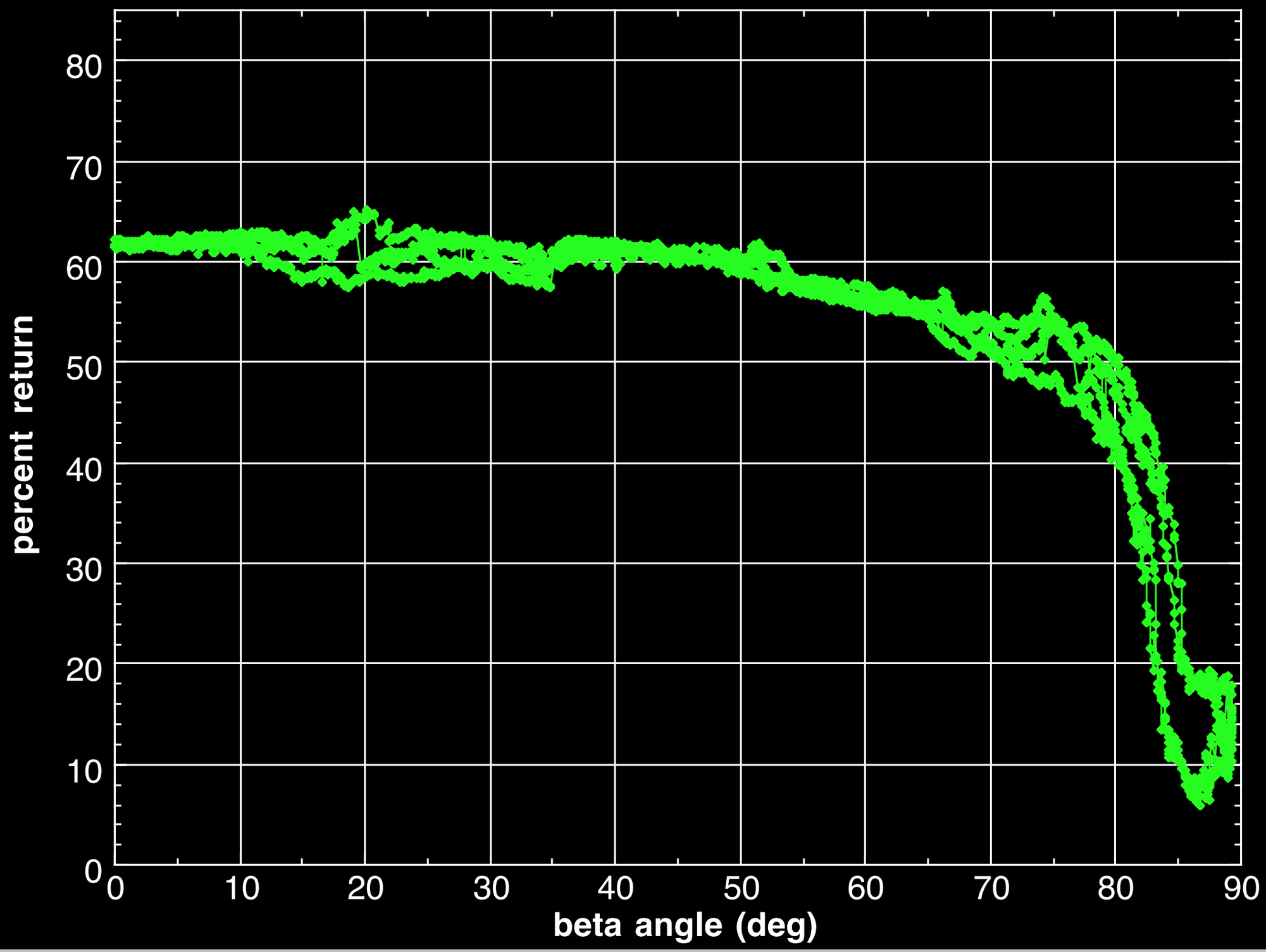


Instrument in Darkness –
THERMAL BLANKETS COLD



- Thermal blankets surrounding LOLA are exposed to thermal radiation from Moon.
- When LOLA is over sunlit side, instrument performance is nominal.
- When LOLA is over dark side, thermal blankets "freeze" at about 220K, contract and pull laser beam expander, causing laser spots to move outside detector fields of view.

More details on LOLA dataset
Blanket anomaly



More details on LOLA dataset
Principal Axes frame

- for analysis in conjunction with GRAIL data, it is recommended to use the LOLA data in the Principal Axes (PA) frame
  - this is <u>not the standard</u> of the LRO project !
  - all the RDR/GDR/SHADR products are in ME, <u>not PA</u> !

- Except for:
  - a 64ppd GDR produced from PA-geolocated LOLA points
    http://imbrium.mit.edu/DATA/LOLA_GDR/CYLINDRICAL/PA/
  - a SHADR in PA (to L=1080)
    http://imbrium.mit.edu/DATA/LOLA_SHADR/PA/

LRO Radio Science PDS archive
Radio Tracking data

- The LRO tracking data are acquired primarily by the NASA White Sands station, and supported by the (commercial) USN network
  - near-continuous tracking
  - support by DSN around maneuvers
  - White Sands/USN data are in UTDF format
  - ancillary weather data

  - see: Mazarico et al. (2012) in *Journal of Geodesy* for details on LRO orbit determination, and Mazarico et al. (2013) in *AIAA/AAS Astrodynamics Specialist Conference* for details on improvements due to the GRAIL gravity field

LRO Radio Science PDS archive
Improved LRO ephemeris

- LRO trajectory reconstructed by LOLA team are available in the SPK folder (SPICE format)
  - http://imbrium.mit.edu/LRORS/DATA/SPK/
  - current version uses GRGM900C, based on the GRAIL primary and extended mission data (Lemoine et al., 2014)
  - the orbit quality is assessed by orbit overlap analysis
    - 12 h of overlap between consecutive ~2.5-day arcs
    - typical consistency: ~10m total position, <1m radially

LRO Radio Science PDS archive
Laser Ranging data

- The Laser Ranging data are archived in the same archive
  - http://imbrium.mit.edu/LRORS/DATA/RANGE/
  - uses the ILRS-standard CRD format
  - this is the 'raw' data:
    - ground station firetimes (UTC)
    - LOLA receive times, in the Earth window (MET)
  - BUT a lot of the work has already been done for you:
    - pair-wise matching of the two time series
    - removal of noise and unmatched fire/receive times
  - you will need to consider relativistic corrections and model the behavior of the LRO clock to make good use the data
    - challenging !
  - two flavors : full-rate data (every shot) and 5-second normal points