
LRO and the ESMD/SMD Partnership
Lessons Learned
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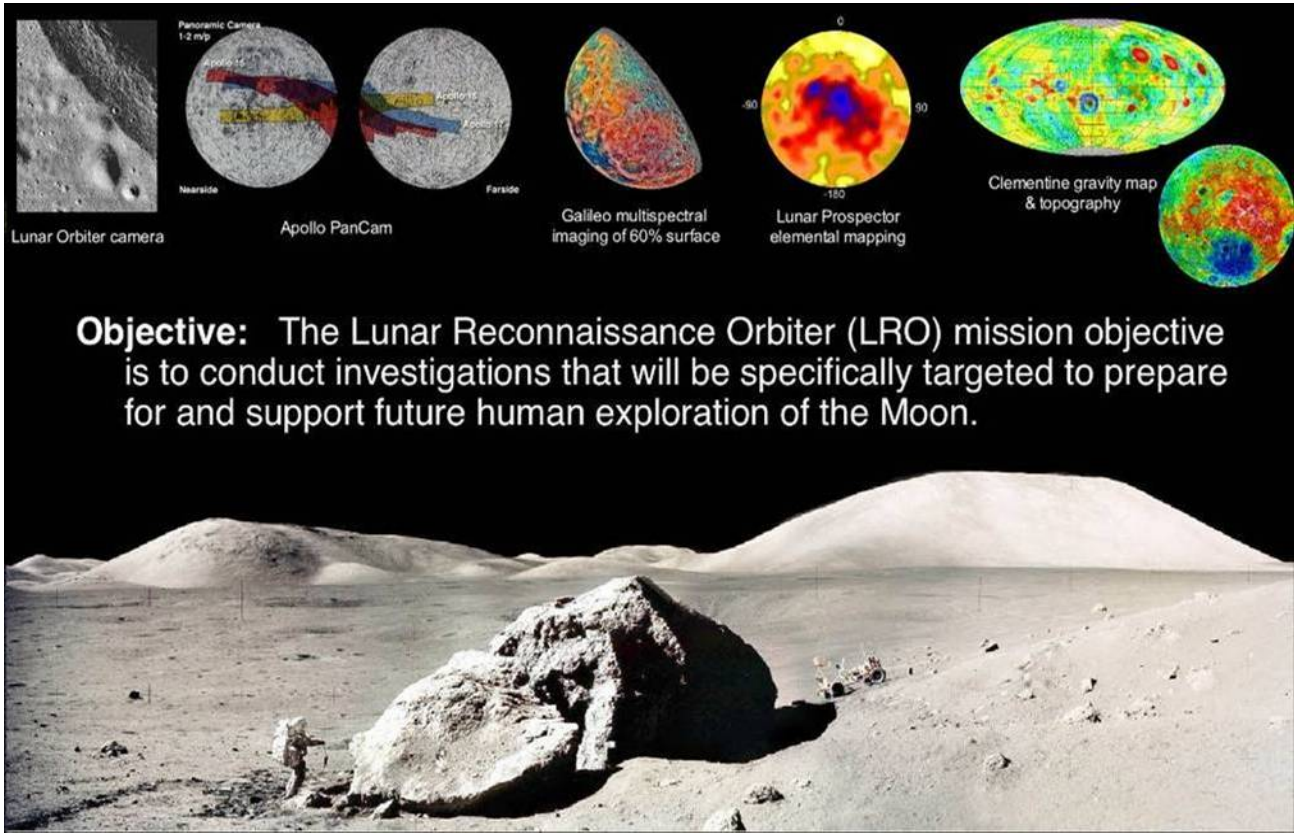
LRO and the ESMD/SMD Partnership

- LRO is a highly successful mission of both exploration and science
- ESMD (Exploration Systems Mission Directorate, now part of HEOMD) and SMD cooperated closely for the mission's success
  - Joint selection of the measurement teams through a joint A.O.
  - SMD added participating scientist
  - LEAG established for community participation, modeled after MEPAG
- LRO Mission benefited from the strong leadership of Mike Wargo, the ESMD Chief Lunar Scientist
  - Advocate in ESMD for science and exploration as co-enablers
  - Ambassador to lunar science and exploration communities.
- Buy-in at the AA and Division Levels was critical.

LRO Mission Objectives



Locate Potential Resources
Hydrogen/water at the lunar poles
Continuous solar energy
Mineralogy

Safe Landing Sites
High resolution imagery
Global geodetic grid
Topography
Rock abundances

Space Environment
Energetic particles
Neutrons

LRO was initiated as a high-priority Discovery-class mission to enable astronaut return to the Moon

HISTORY I

- **Jan. 2004:** President's "Visions for Space Exploration" Speech (mentions "LRO" as 1st step)
- **Late Jan. 2004:** ESMD and SMD agree to charter an ORDT to define LRO (D. Cooke was key official at ESMD with C. Scolese, SMD)
- **March 2004:** ORDT face-to-face with consensus on priorities for LRO measurements
  - *Specified 8 critical measurement sets for LRO to achieve (if possible)*
- **June 2004:** AO release for LRO payload (jointly by SMD and ESMD)
- **Dec. 2004:** Selection of 6 primary measurement investigations by AA's of ESMD and SMD for LRO mission [LOLA, LROC, LEND, DLRE, LAMP, CRaTER]
- **April 2005:** Senior NASA HQ agreement to fly MiniRF *Tech Demo* (SOMD) on LRO to support national goals

LRO: The Exploration Mission

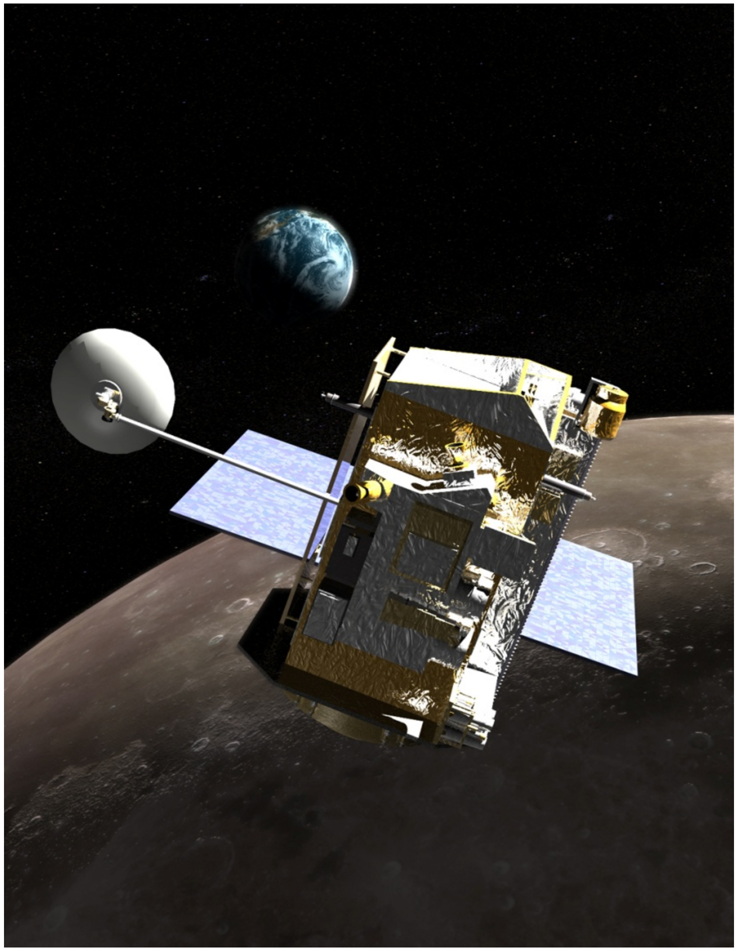
Goals: Locate resources
Identify safe landing sites
Measure the space environment
Demonstrate new technology

Seven instrument payload

Cosmic Ray Telescope for the Effects of Radiation (CRaTER)
Lunar Orbiter Laser Altimeter (LOLA)
LRO Camera (LROC)
Lyman-alpha Mapping Project (LAMP)
Diviner Lunar Radiometer Experiment (DLRE)
Lunar Exploration Neutron Detector (LEND)
Miniature Radio Frequency Technology Demonstration (Mini-RF)

LRO returns

- Global day/night temperature maps (DLRE)
- Global high accuracy geodetic grid (LOLA)
- High resolution black and white imaging (LROC)
- High resolution local topography (LOLA, LROC)
- Global ultraviolet map of the Moon (LAMP)
- Polar observations both in shadowed and illuminated areas (LEND, LROC, LOLA, DLRE, Mini-RF, LAMP)
- Ionizing radiation measurements in the form of energetic charged particles and neutrons (CRaTER, LEND)

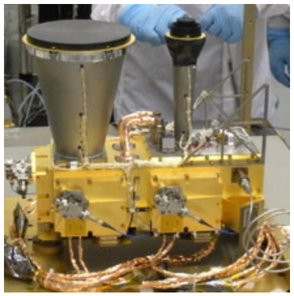


LRO Launched June 18, and entered mapping orbit September 15, 2009

LRO Instruments and Investigations

LOLA: Lunar Orbiter Laser Altimeter

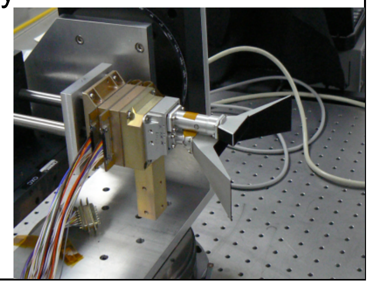
- Topography
- Slopes
- Roughness



5-spot altimeter
10 cm vert.
25 m horz.
resolution

LROC/WAC: Wide-Angle Camera

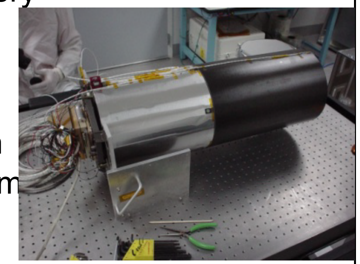
- Global Imagery
- Lighting
- Resources



7-band UV/Vis filters, ~100 m resolution from 50 km altitude

LROC/NACs: Narrow-Angle Cameras

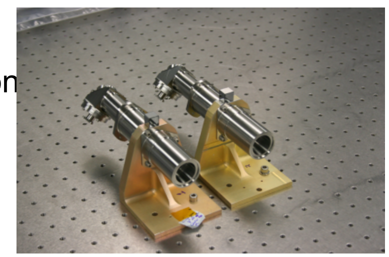
- Targeted Imagery
- Hazards
- Topography



50 cm resolution
2 NACs with 5 km combined swath from 50 km

LR: Laser Ranging

- Precision Orbit Determination



Uses LOLA detector to range from Earth to LRO

Diviner Lunar Radiometer

- Thermal State
- Volatile Stability
- Rocks&Regolith
- Composition

0.35 to 400 μm
in 9 channels
~150-500 m res.

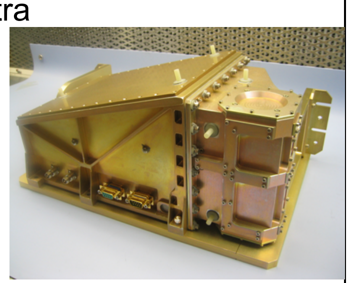
Mini-RF: Synthetic Aperture Radar

- Resources
- Topography
- Hazards

Bistatic radar measurements
30 m S & X
SAR imagery

CRaTER: Cosmic Ray Telescope…

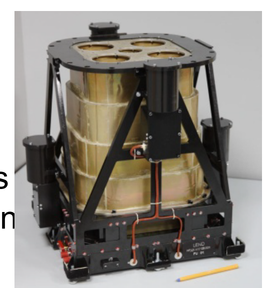
- Radiation Spectra
- Tissue Effects



LET spectra
Behind tissue
Equiv. plastic
0.9 keV/μm to
2.2 MeV/μm

LEND: Lunar Explr. Neutron Detector

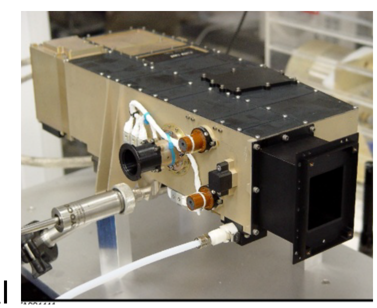
- Neutron Albedo
- Hydrogen Maps



Thermal, epithermal and energetic neutrons
10 km spatial resolution from 50 km

LAMP: Lyman-Alpha Mapping Project

- Water-Frost
- PSR Maps



UV imaging
57 to 196 nm
0.18 nm spec. resolution
~300 m spatial

HISTORY II

- The rapid schedule required fast implementation, so GSFC directed to design and build the spacecraft
  - Goddard team led by Craig Tooley had a strong background in rapid development missions.
- **May 2005 – Fall 2008:** Development of LRO spacecraft together with 7 flight instruments
- **June 2009:** Lauunch of LRO with LCROSS
- **Sept. 2010:** transition of LRO to SMD for "Science Mission"
  - Extended through 2016 by Senior Review Process

LRO Key Dates	
ORDT convened and recommended to NASA LRO objectives	Mar-04
Instruments selected (competitive AO from ESMD & SMD)	Dec-04
Program management moved from NASA SMD to ESMD	Feb-05
Launch	18-Jun-09
Commissioning Orbit (30 x 216 km) established	27-Jun-09
Insert into Mapping Orbit (50 ±15 km)	16-Sep-09
LCROSS Impact	9-Oct-09
First Public Release of LRO Data From Planetary Data System (total at least 545 Tbytes through September 2014)	3/15/2010 and every 3 months
Begin Science Mission	17-Sep-10
Begin First Extended Mission	17-Sep-12
Complete First Extended Science Mission/**Start Second ESM**	15-Sep-14
Complete Second Extended Science Mission	16-Sep-16

ESMD Mission Measurement Requirements

- LRO Mission Objectives defined as a list of measurement objectives
  - e.g. "The LRO shall obtain temperature mapping from 40 - 300K in the Moon's polar regions to better than 500m spatial resolution and 5K precision for a full diurnal cycle." See backup charts for full list.
- LRO instruments had strong planetary science heritage with teams led by planetary scientists
  - Including co-investigators on other SMD missions (MESSENGER, MRO, MGS, etc.)
- Clear requirements for ESMD with resources available for science contributed to LRO's success.
- ESMD mission ended Sep. 2010 – LRO transitioned to SMD
  - ESMD AA review to verify exploration mission success
  - SMD Senior Review to verify new Science Mission objectives
  - SMD AA review to validate new Science Mission requirements

LRO has robust and resilient capabilities

	Objectives	LRO Requirements	Contributing Instruments
1	Find Safe Landing Sites	M30 M40 – Global geodetic grid 10 cm vertical, and at the poles, 50 m horizontal resolution	LOLA, LROC
		M80 – Identify surface features & hazards	LROC, LOLA, DLRE
2	Locate Potential Resources	M50 – Provide lunar temperature map from 40 - 300K, 5 K precision over full diurnal cycle.	DLRE
		M60 – Image the permanently shadowed regions.	LAMP, LOLA
		M70 - Identify putative deposits of water-ice	LAMP,LEND, LOLA
		M90 – Characterize the polar region illumination environment	LROC, LOLA, DLRE
		M100 - Characterize lunar mineralogy	LROC, DLRE
		M110 - Hydrogen mapping	LEND
3	Life in the Space Environment	M10 - Characterize the deep space radiation environment at energies in excess of 10 MeV	CRaTER, LEND
		M20 - measure the deposition of deep space radiation on human equivalent tissue.	CRaTER
4	New Technology	P160 - Technology demo	Mini-RF

LRO Exceeded Exploration Requirements

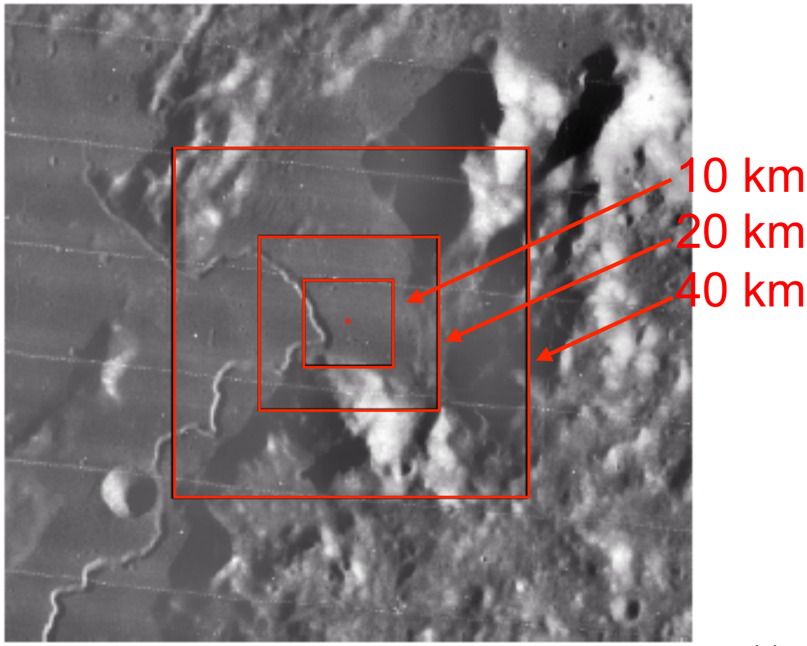
After launch LRO team worked with the Constellation program to identify 100 sites (50 primary) for focused observations*

- Sites are value for both science and value for both human and robotic exploration
- Sites covered a broad variety of geology to help enable future landing near any location on the lunar surface

Approach

- **•10 x 10 – full coverage, photom & geom stereo**
- **•20 x 20 – best effort, photom & geom stereo**
- **•40 x 40 – best effort mosaics at low and high sun**

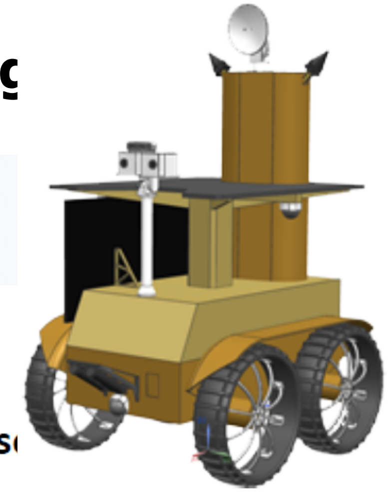
See backup charts for list of sites



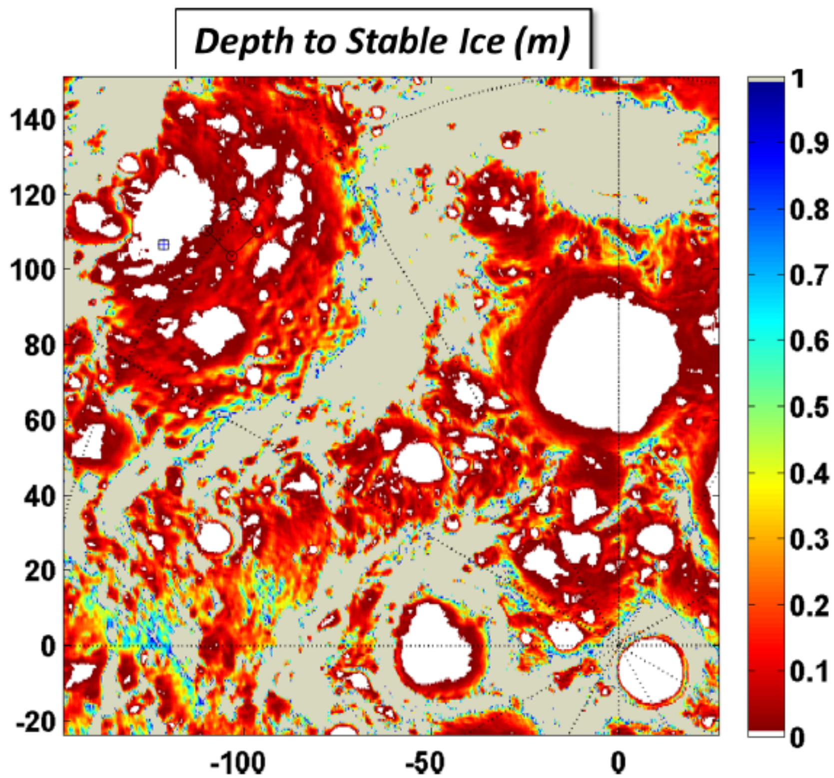
*Gruener, J. E. And B.K. Joosten, NASA Constellation Program Office Regions of Interest on the Moon: A Representative Basis for Scientific Exploration, Resource Potential, and Mission Operations, Lunar Reconnaissance Orbiter Science Targeting Meeting, Tempe, 2009.

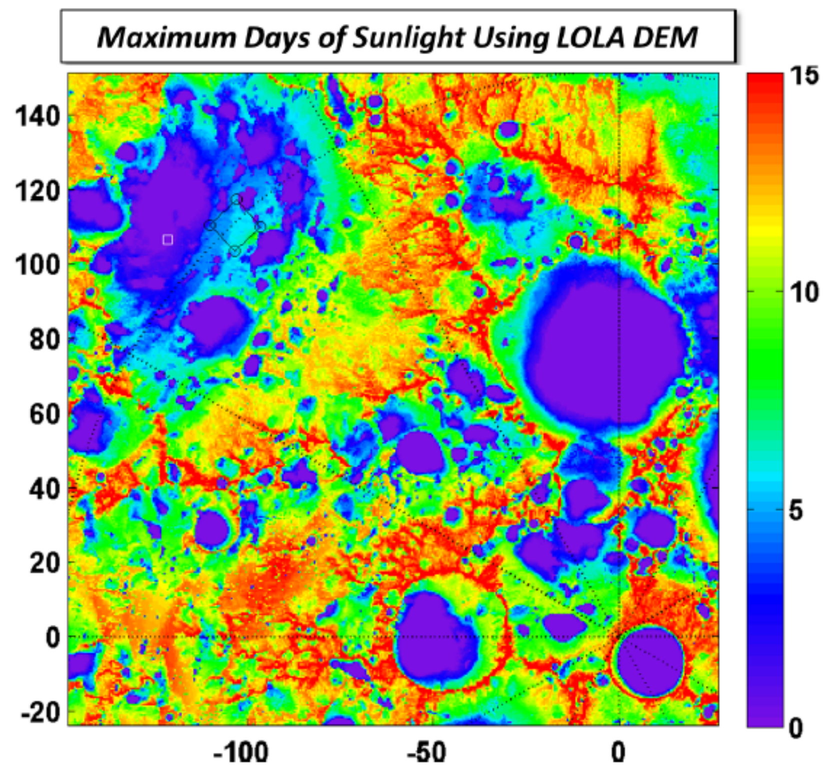
LRO Data Supports Future US Mission Plannin

Resource Prospector – Site Selection



Landing Site analysis looking at near surface temperatures and days of s



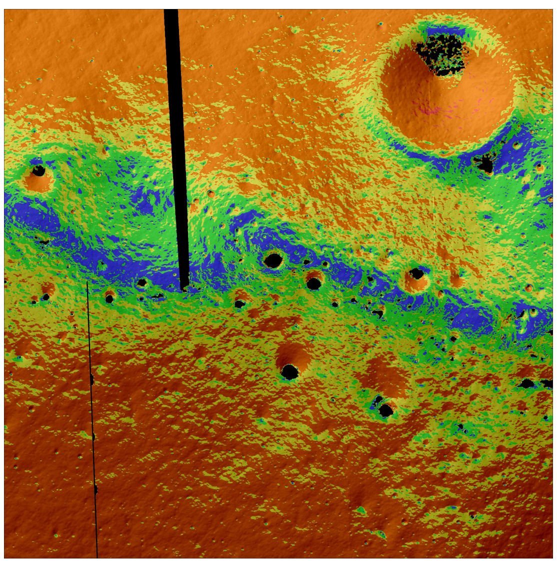


LRO data is also being used by Discovery and New Frontiers proposal teams

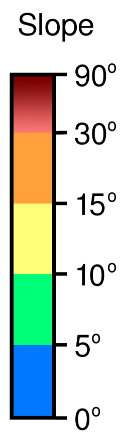
LRO Data Supports International Mission Planning

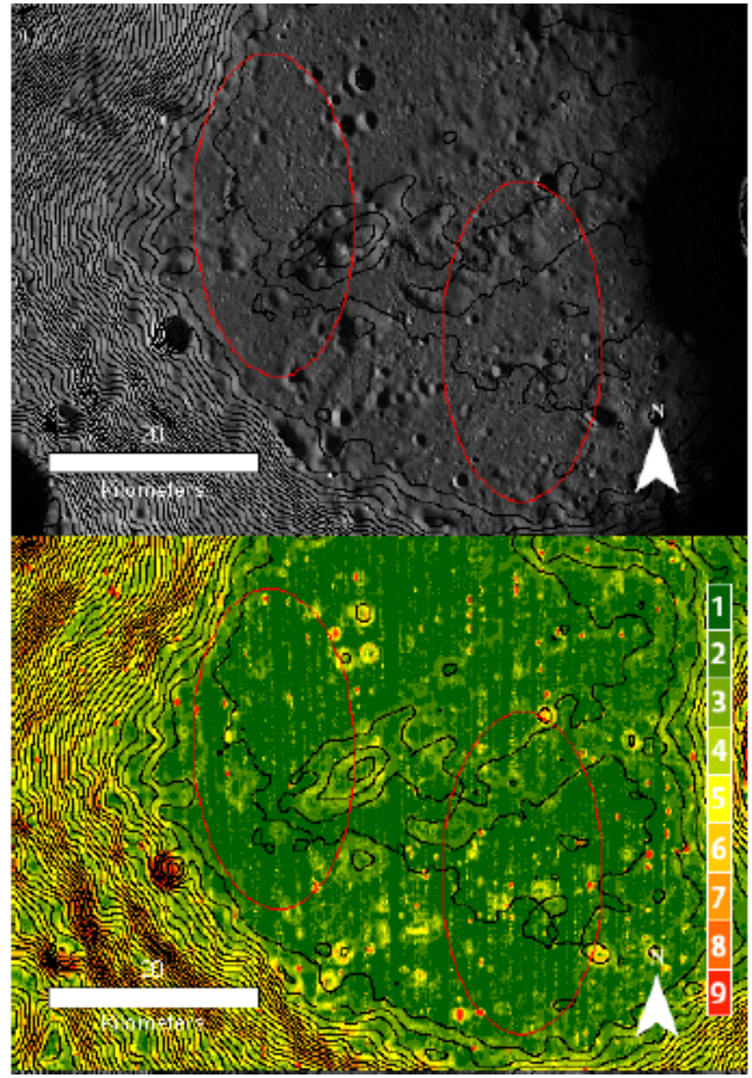
- Data Products uploaded into the Planetary Data System (PDS).
- Participation by LRO Science team (which includes non-U.S. co-investigators) in landing site selection
- Special Data Products put into the PDS through interagency requests.

Malapert Massif Potential Chandrayaan-2 Landing Site



Slope Map of Malapert from NAC DTM



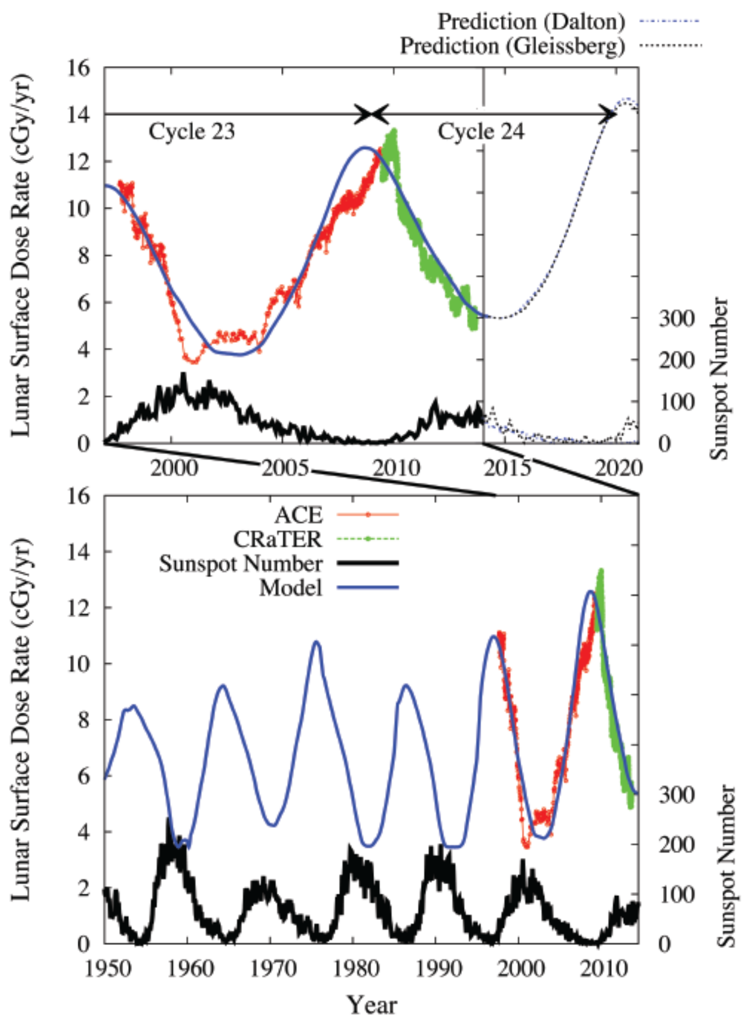


WAC mosaic and slope map of the floor of Boguslawsky crater, potential Luna Glob landing site - H. Hiesinger, M. Ivanov et al., LPSC 2014.

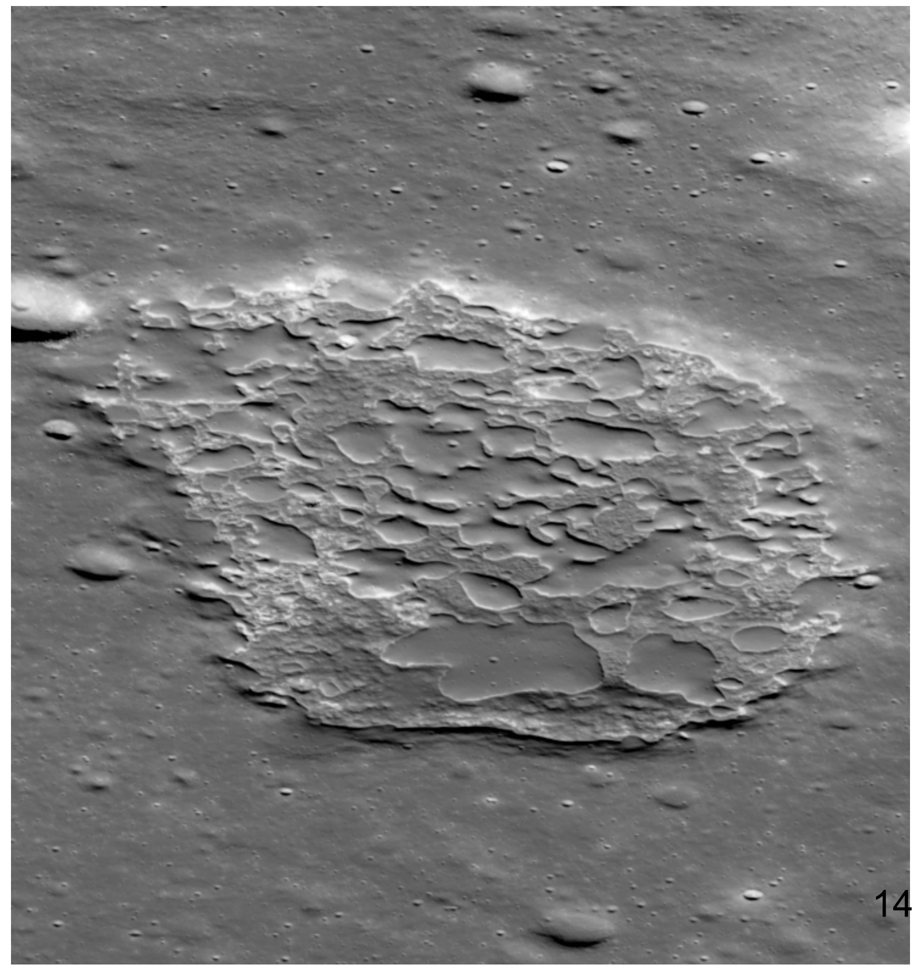
Recent LRO Highlights

Space Weather Special Issue

Results from CRaTER



New Evidence For Young Lunar Volcanism – Nature Geoscience



LRO "proves" cross-directorate partnerships can work

- LRO continues to make valuable science measurements of the Moon
  - Successful transition to SMD followed by two highly rated Senior Reviews
- LRO has added over 525 TB of data and data products to the Planetary Data System
  - Used for both mission planning and the scientific community
- Has developed maps of the Moon that will be used by generations of Explorers to come.
- LRO continues to rewrite the textbooks on the Moon's geologic history and by extension the history of the solar system

LESSONS LEARNED

- The LRO success shows that partnership between SMD and HEOMD can work extremely well
- Need buy-in at the AA and Division level
  - Willingness on both sides to contribute expertise and resources
- A strong advocate for science in ESMD was essential
  - Role as ambassador between the scientific and exploration communities was important
  - Chief scientist role for HEOMD is currently unfilled?
- A counterpart on the SMD side should be identified
  - Open and frequently used lines of communication should be established

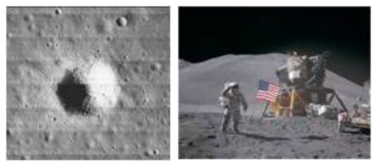
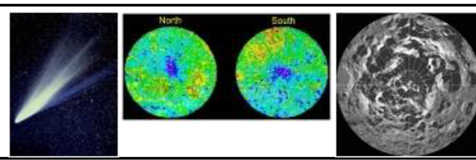
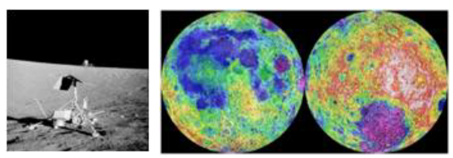
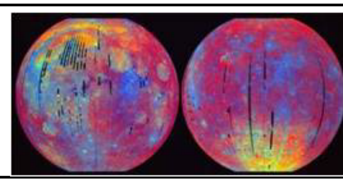
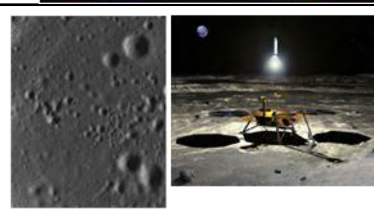
Backups

LRO Addresses Priority Scientific Objectives from NRC Decadal Survey

- National Academy of Sciences NRC Decadal Survey (2003) lists priorities for the Moon (*all mission classes thru* 2013)*:

  - Lunar Geodetic Topography (crustal structure, thermal evolution)
    - *LRO addresses completely (LOLA)*
      - *LOLA measurements enable inversion of topography to infer local gravity and structure*
  - Polar Volatile Inventory (sources and sinks thru time)
    - *LRO addresses as best one can from orbit (LRO targets lander to verify)*
      - *LEND, LROC, LOLA, LAMP, DLRE, MiniRF support volatile inventory goals*
  - Local Geologic Studies in 3D to quantify process interplay
    - *LRO addresses completely (LOLA, LROC stereo)*
      - *Meter scale processes can be quantified for first time on global scale (LROC+LOLA)*
  - Global Mineralogical and Elemental Mapping at fine scales
    - *LRO addresses in part; left to Int'l missions to complete by intention*
      - *Chandrayaan-1 MMM (SMD experiment) achieving this goal; DLRE, LAMP contribute*
  - Targeted Studies to Calibrate the Impact Flux
    - *LRO addresses from orbit; follow-up surface missions needed*
      - *LROC measurements of changes since Apollo provide recent flux data*
  - Geophysical Network (similar to ILN concept)
    - *LRO supports by siting (i.e., thanks to 3D context from LOLA lidar altimetry)*
  - S. Pole Aitken Sample Return
    - *LRO supports via its ability to target safe, compelling landing sites*
      - *LROC can provide data for landing site safety and optimal science context*

NRC Decadal Survey (2003) lists priorities for the Moon
(all mission classes through 2013)

NRC DS Priority Investigation	NRC approach	LRO Measurements
Geodetic Topography (*crustal evolution*) 	**Altimetry from orbit (with precision orbits)**	***Global geodetric topography at ~300 m scales (< 1 m rms)***
Local Geologic Studies In 3D (*geol. Evolution*) 	**Imaging, topography (at m scales)**	***Sub-meter scale imaging with derived local topography***
Polar Volatile Inventory 	**Spectroscopy and mapping from orbit**	***Neutron and IR spectroscopy in 3D context + UV (frosts)***
Geophysical Network (*interior evolution*) 	***In situ* landed stations with seismometers**	***Crustal structure to optimize siting and landing safety***
Global Mineralogical Mapping (*crustal evolution*) 	**Orbital hyperspectral mapping**	***300 m scale multispectral and 20 km scale H mapping***
Targeted Studies to Calibrate Impact Flux *(chronology)* 	**Imaging and in situ geochronology**	***New sub-meter imaging of Apollo panoramic data for impact flux measurements***

ESMD Mission Measurement Requirements

RLEP-LRO-M10	The LRO shall characterize the deep space radiation environment at energies in excess of 10 MeV in lunar orbit, including neutron albedo.
RLEP-LRO-M20	The LRO shall measure the deposition of deep space radiation on human equivalent tissue while in the lunar orbit environment.
RLEP-LRO-M30	The LRO shall measure lunar terrain altitude to a resolution of 10cm and an accuracy of 1m for an average grid density of approximately 0.001 degrees latitude by 0.04 degrees longitude.
RLEP-LRO-M40	The LRO shall determine the horizontal position of altitude measurements to an accuracy of 100m.
RLEP-LRO-M50	The LRO shall obtain temperature mapping from 40 - 300K in the Moon's polar regions to better than 500m spatial resolution and 5K precision for a full diurnal cycle.
RLEP-LRO-M60	The LRO shall obtain landform-scale imaging of lunar surfaces in permanently shadowed regions at better than 100m spatial resolution.
RLEP-LRO-M70	The LRO shall identify putative deposits of water-ice in the Moon's polar cold traps at a spatial resolution of better than 500m on the surface and 10km subsurface (up to 2m deep).
RLEP-LRO-M80	The LRO shall assess meter-scale features of the lunar surface to enable safety analysis for potential lunar landing sites over targeted areas of $100km^2$.
RLEP-LRO-M90	The LRO shall characterize the Moon's polar region illumination environment to a 100m spatial resolution and 5 Earth hour average temporal resolution.
RLEP-LRO-M100	The LRO shall characterize lunar mineralogy by mapping the thermal properties of regolith and characterizing UV, visible, and infrared spectral differences and variations at km scales globally.
RLEP-LRO-M110	The LRO shall perform hydrogen mapping of the Moon's surface with a sensitivity of 100 ppm or better, a SNR of 3, and 10 km resolution in the polar regions.

Constellation Sites, Northern

Near Side, Northern Hemisphere

Site	Latitude	Longitude
North Pole	89.60	76.19
Peary Crater	89.00	76.00
Anaxagoras Crater	73.48	-9.30
Mare Frigoris	59.80	26.10
Humboldtianum	54.54	77.14
Plato Ejecta	53.37	-5.21
Gruithuisen Domes	36.03	-40.14
Lichtenberg Crater	31.65	-67.23
Aristarchus 2	27.70	-52.40
Rimae Prinz	27.41	-41.72
Apollo 15	26.08	3.66
Aristarchus 1	24.56	-48.95
Sulpicius Gallus	19.87	10.37
Ina (D-caldera)	18.65	5.29
Marius Hills	13.58	-55.80
Rima Bode	12.90	-3.80
Mare Crisium	10.68	58.84
Copernicus Crater	9.85	-20.01
Reiner Gamma	7.53	-58.56
Hortensius Domes	7.48	-27.67
Mare Tranquillitatis	6.93	22.06
Murchison Crater	4.74	-0.42

Far Side, Northern Hemisphere

Site	Latitude	Longitude
Compton/Belkovich Th Anomaly	61.11	99.45
Mare Moscoviense	26.19	150.47
Dante Crater	26.14	177.70
King Crater	6.39	119.91
Mare Smythii	2.15	85.33
Hertzsprung	0.09	-125.56

Constellation Sites, Southern

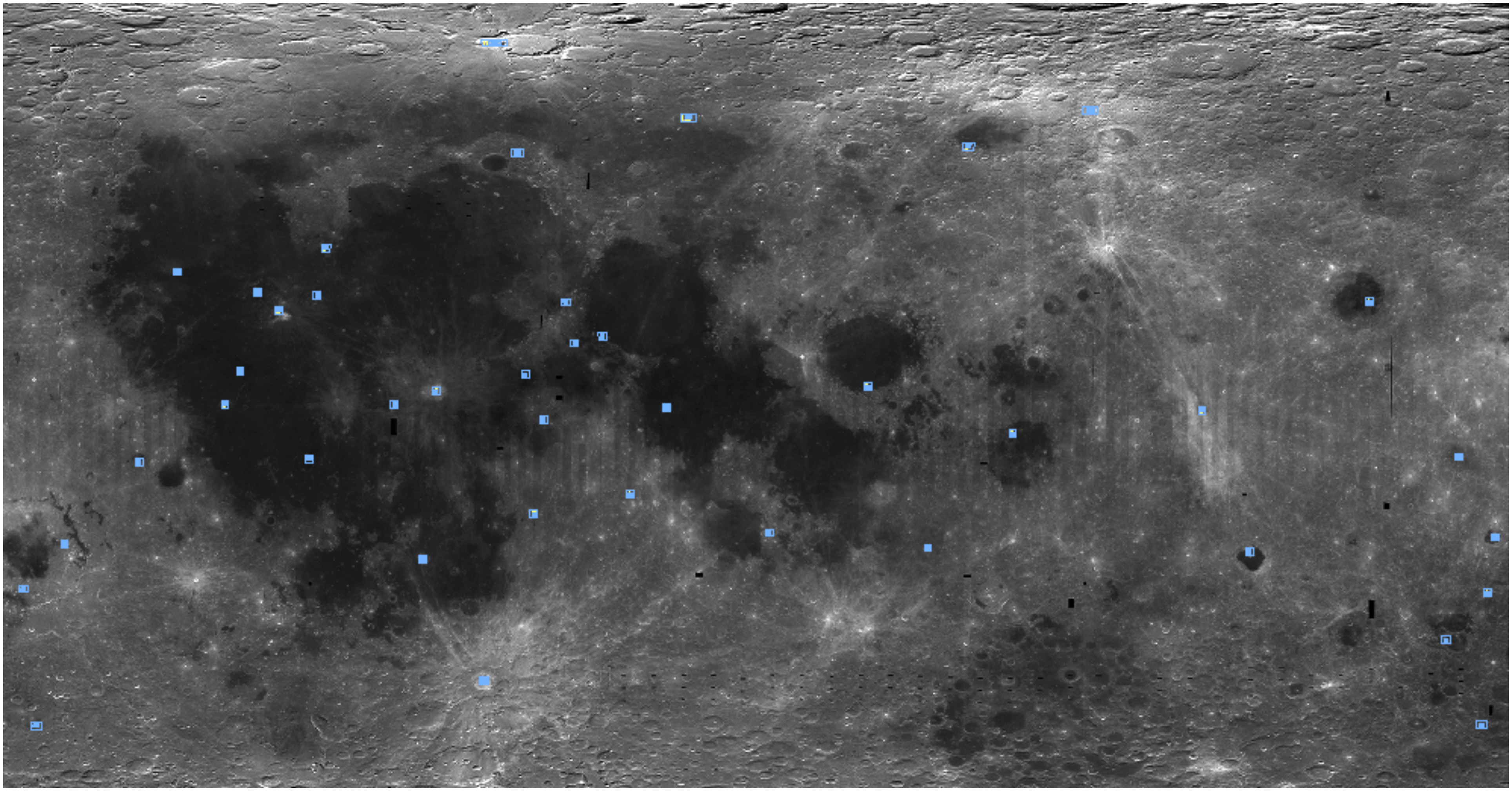
Near Side, Southern Hemisphere

Site	Latitude	Longitude
Flamsteed Crater	-2.45	-43.22
Riccioli Crater	-3.04	-74.28
Apollo 16	-9.00	16.47
Alphonsus Crater	-12.56	-2.16
Montes Pyrenaeus	-15.91	40.81
Orientale 2	-18.04	-87.91
Balmer Basin	-18.69	69.82
Bullialdus Crater	-20.70	-22.50
Tycho Crater	-42.99	-11.20
Malapert Massif	-85.99	-2.93

Far Side, Southern Hemisphere

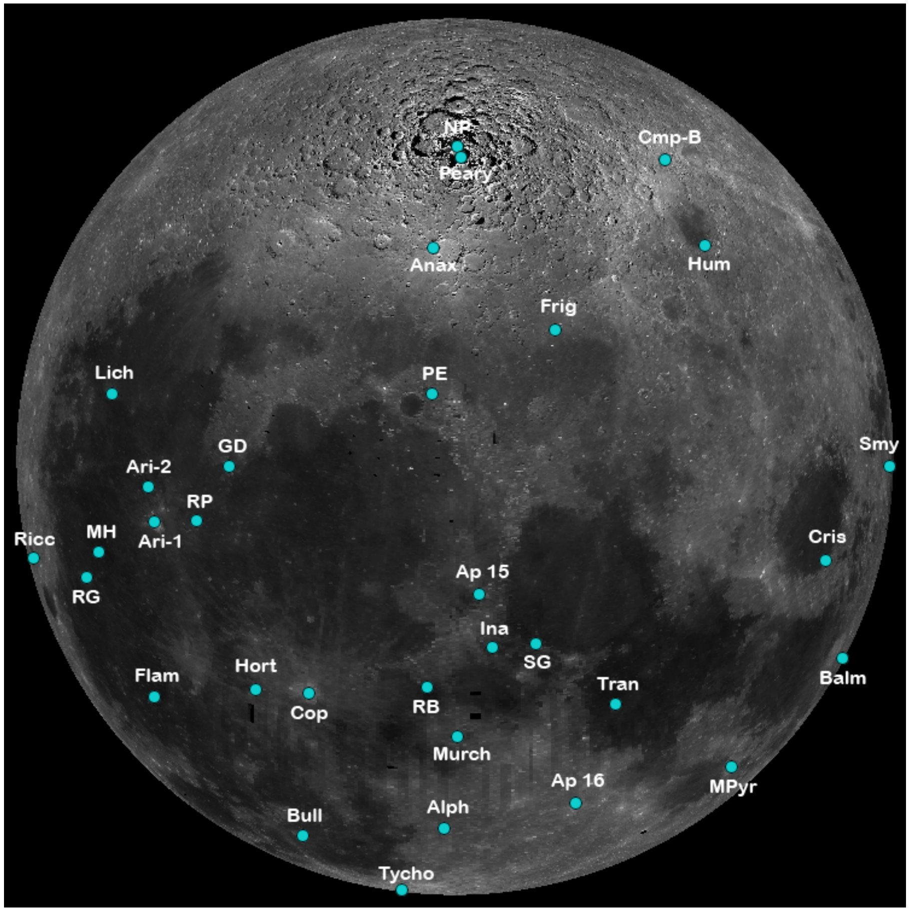
Site	Latitude	Longitude
Dewar (Stratton)	-2.08	166.88
South Pole-Aitken Rim	-5.00	-170.00
Aitken Crater	-16.76	173.48
Tsiolkovsky Crater	-19.35	128.51
Orientale 1	-26.20	-95.38
Van De Graaff Crater	-26.92	172.08
Mare Ingenii	-35.48	164.42
Apollo Basin	-37.05	-153.72
Mendel-Rydberg Cryptomare	-51.14	-93.07
SPA Basin Interior	-60.00	-159.94
Schrödinger	-75.40	138.77
South Pole	-89.30	-130.00

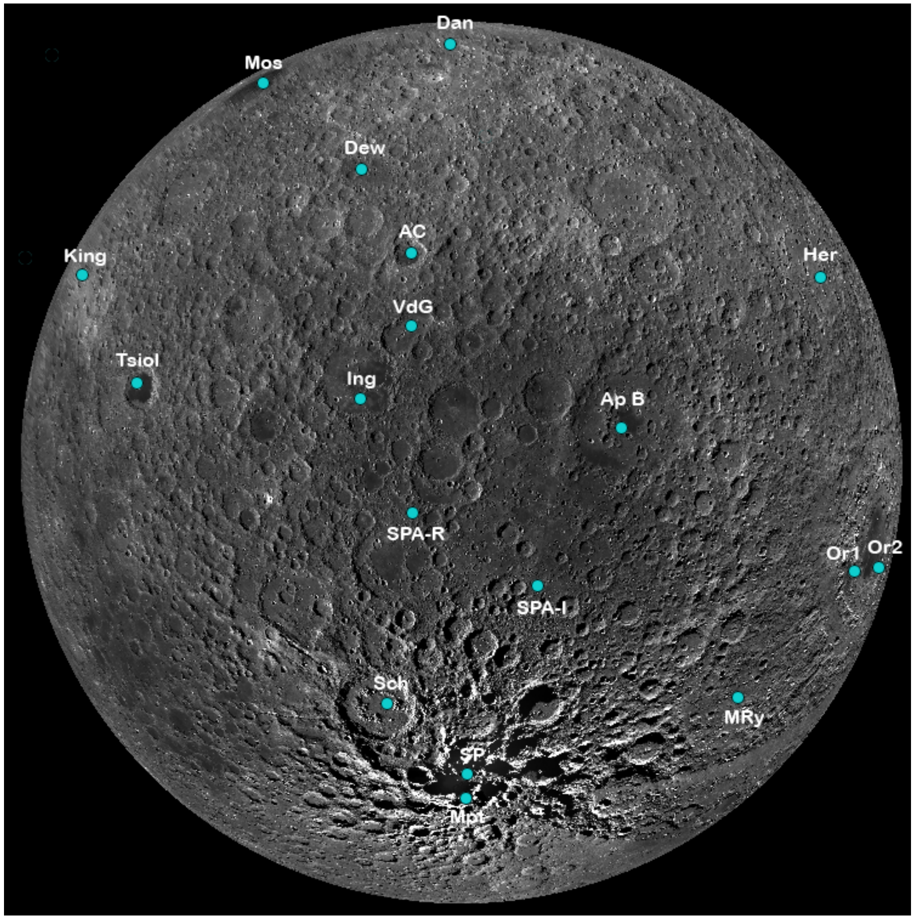
Cx Target Locations



Non-Polar Sites

Constellation Sites





Near Side and North Polar

Far Side and South Polar