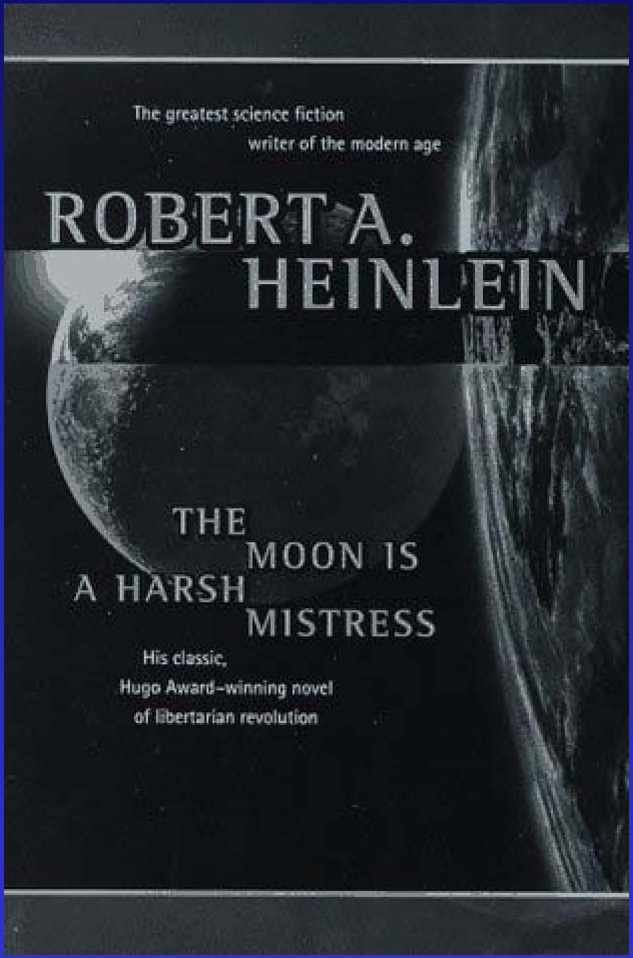
The Lunar Reconnaissance Orbiter – Instrument Suite and Measurements

Presented for the LRO team by John Keller, Deputy Project Scientist

Vision For Space Exploration

Jan. 14 2004 – The President announced a new vision for space exploration that included among its goals "… to return to the moon by 2020, as the launching point for missions beyond. Beginning no later than 2008, we will send a series of robotic missions to the lunar surface to research and prepare for future human exploration."

Vision implies extended periods in space



The greatest science fiction
writer of the modern age

ROBERT A.
HEINLEIN

THE
MOON IS
A HARSH
MISTRESS

His classic,
Hugo Award-winning novel
of libertarian revolution

- Unknown terrain, poor maps
- Radiation Environment
- Long Cold Nights and Warm Days
  - Daytime 400 K (266 F)
  - Nighttime 100 K (-280 F)
- Long Way From Home
- Exploitable Resources?
  - Water
  - Shelter
  - Energy

LRO Objectives

Apollo 15 - Commander Dave Scott returns from the Rover with camera in hand. From left to right is Hadley Rille, Mount Hadley, the Swann Hills, Silver Spur, Mount Hadley Delta and St George Crater

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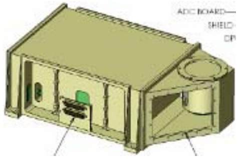
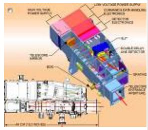
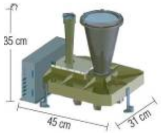
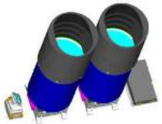
- Safe Landing Sites
  - High resolution imagery
  - Global geodetic grid
    - Topography
    - Rock abundances

- Locate potential resources
  - Water at the lunar poles?
  - Continuous source of solar energy
  - Mineralogy

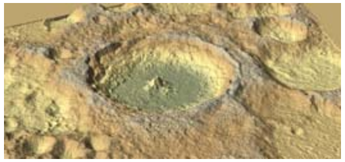
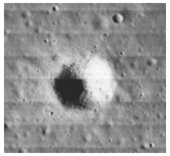
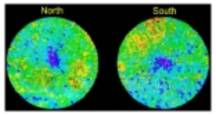
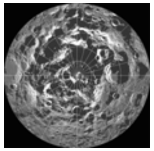
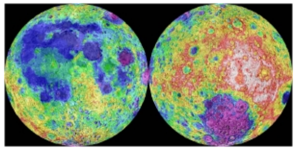
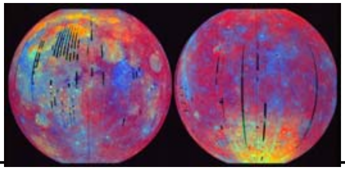
- Space Environment
  - Energetic particles
  - Neutrons

- New Technology
  - Advanced Radar

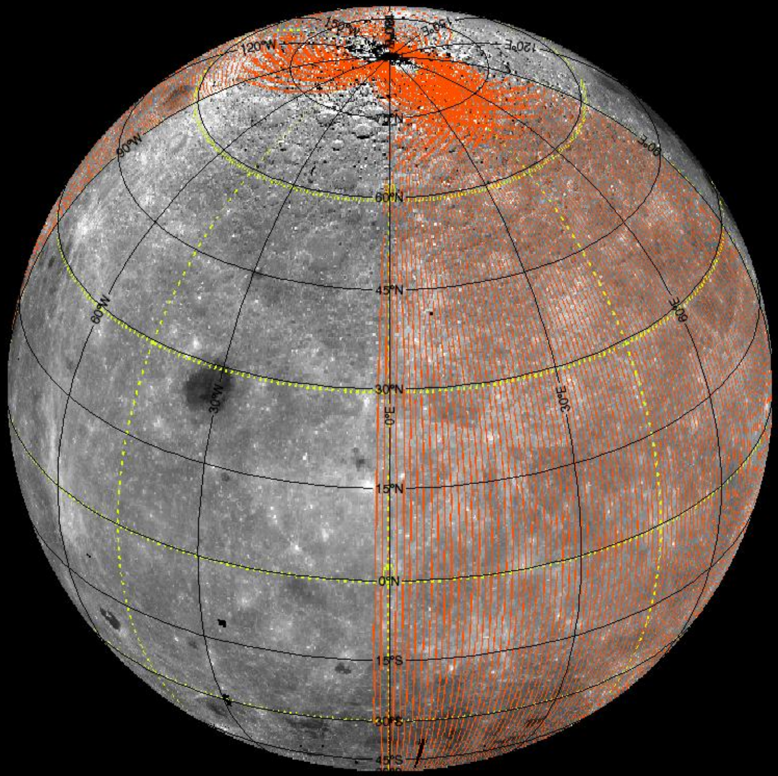
Instrument Suite has Detailed Traceability to Exploration Requirements

Instrument	Navigation/ Landing Site Safety	Locate Resources	Life in Space Environment	New Technology
CRaTER Cosmic Ray Telescope for the Effects of Radiation 			• High Energy Radiation • Radiation effects on human tissue	
DLRE Diviner Lunar Radiometer Experiment 	• Rock abundance	• Temperature • Mineralogy		
LAMP Lyman Alpha Mapping Project 		• Surface Ice • Image Dark Craters		
LEND Lunar Exploration Neutron Detector 		• Subsurface Hydrogen Enhancement • Localization of Hydrogen Enhancement	• Neutron Radiation Environment	
LOLA Lunar Orbiter Laser Altimeter 	• Slopes • Topography/Rock Abundance • Geodesy	• Simulation of Lighting Conditions • Crater Topography • Surface Ice Reflectivity		
LROC Lunar Reconnaissance Orbiter Camera 	• Rock hazards • Small craters	• Polar Illumination Movies • Mineralogy		
Mini-RF *Technology Demonstration* 				• S-band and X-band SAR demonstration

NRC Decadal (2002) lists priorities for the MOON *(all mission classes thru 2013)* :

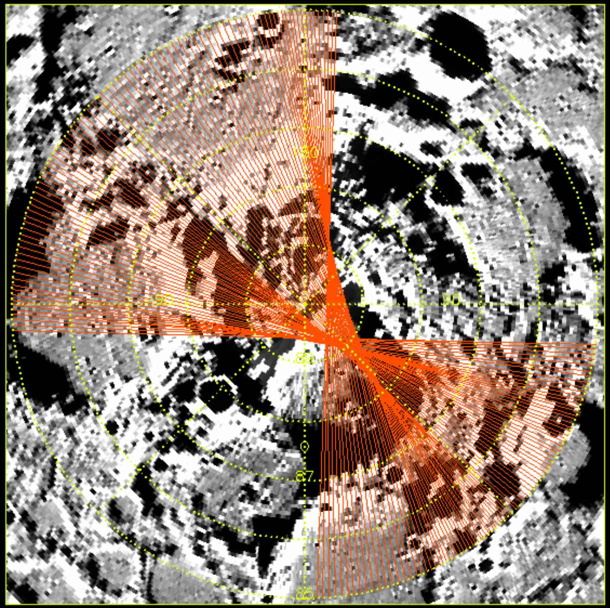
NRC Priority Investigation	***NRC approach***	LRO measurements
Geodetic Topography (*crustal evolution*) 	Altimetry from orbit (with precision orbits)	*Global geodetic topography at ~100m scales (< 1 m rms)*
Local Geologic Studies In 3D (*geol. Evolution*)  	Imaging, topography (at m scales)	*Sub-meter 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	*100m scale multispectral and 5km scale H mapping*
Targeted Studies to Calibrate Impact Flux (*chronology*)  	Imaging and in situ geochronology	*Sub-meter imaging of Apollo sites for flux validation and siting*

LRO Emphasizes the Lunar Poles

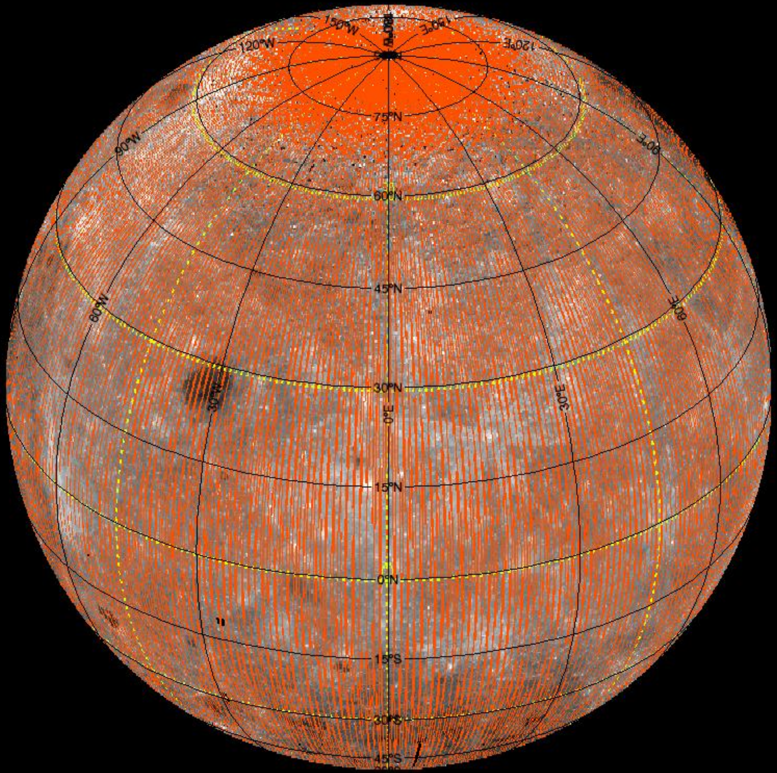


7 day orbital ground track prediction

North Pole.

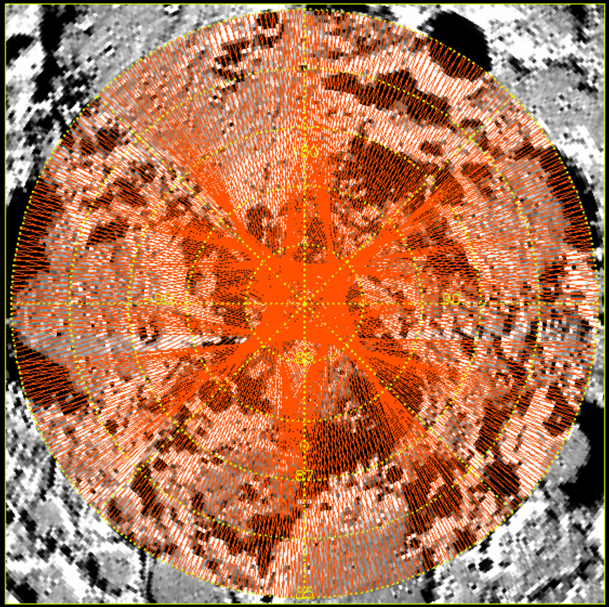


LRO Emphasizes the Lunar Poles



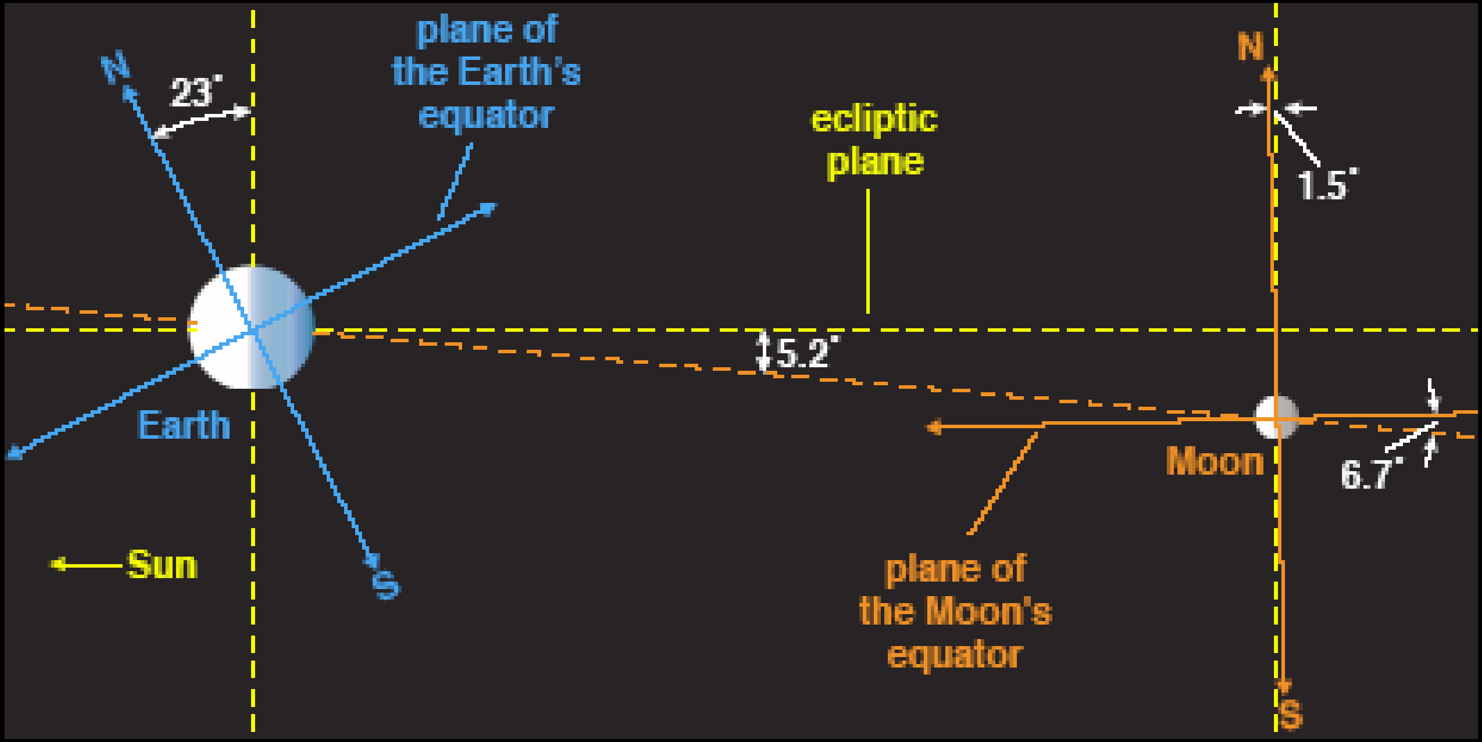
27 day orbital ground track prediction

North Pole.



Why the Poles and Where?

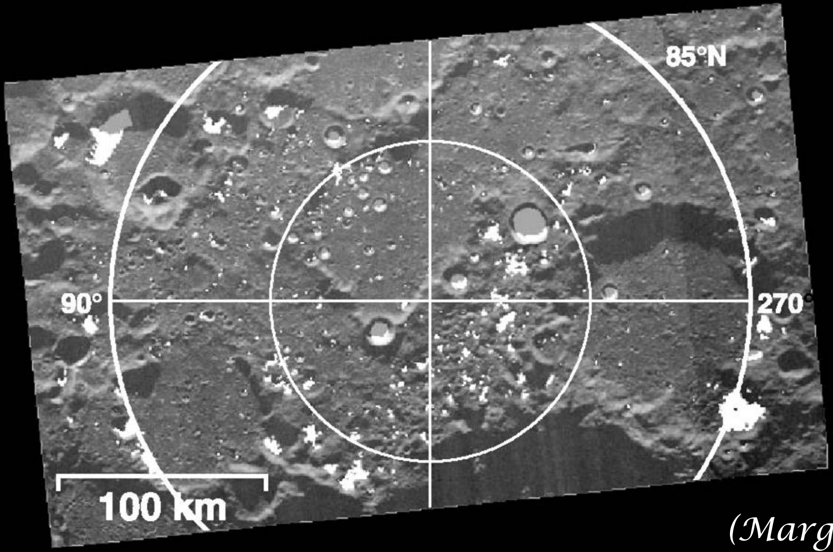
- Cold traps exist near the lunar poles (Watson et al., 1961)
  - Low obliquity of Moon affords permanent shadow in depressions at high latitude.
  - Temperatures are low enough to retain volatiles for t > τ_{Moon}.



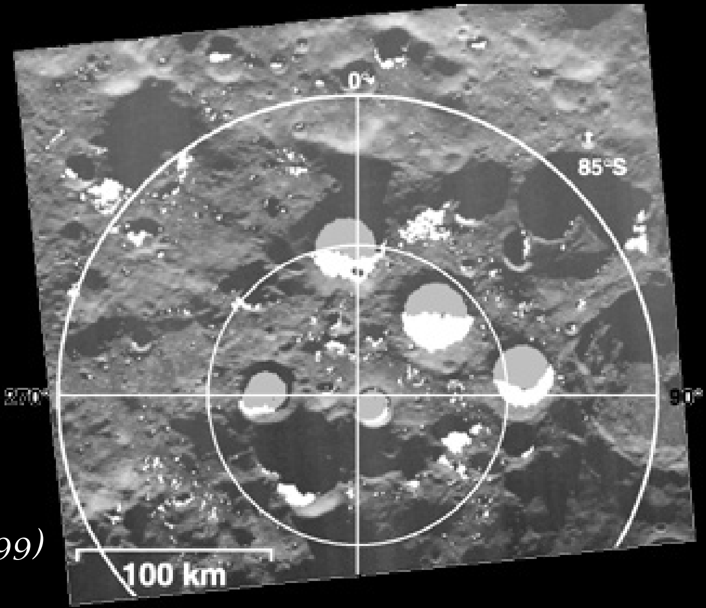
Lunar Ice: Current State of Knowledge

1. There are abundant permanently shadowed regions at both poles

North Pole



South Pole

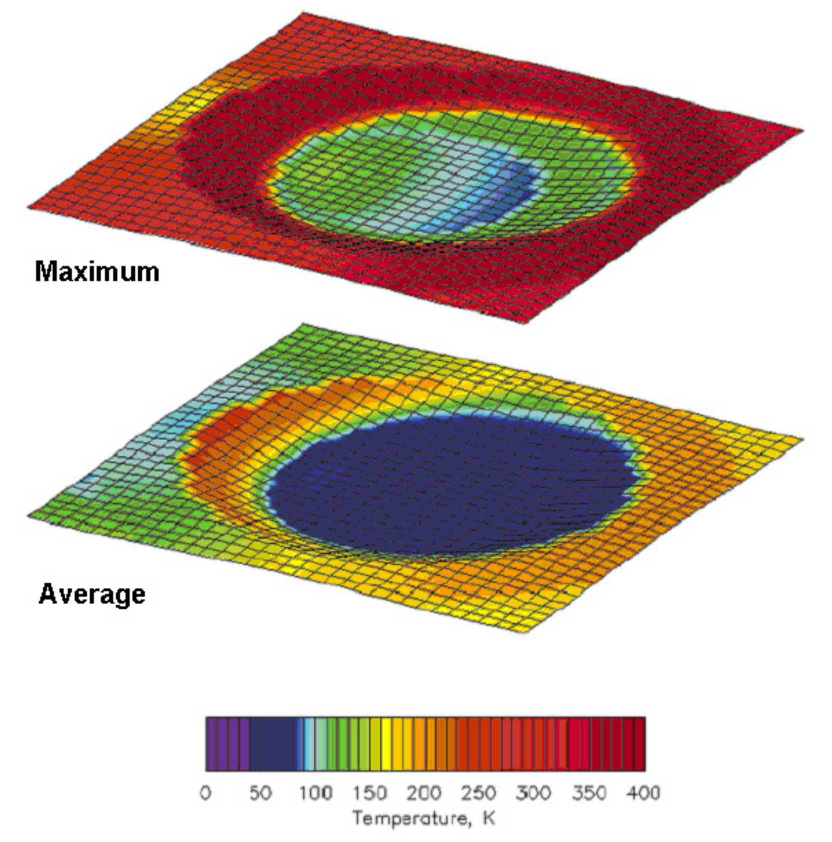


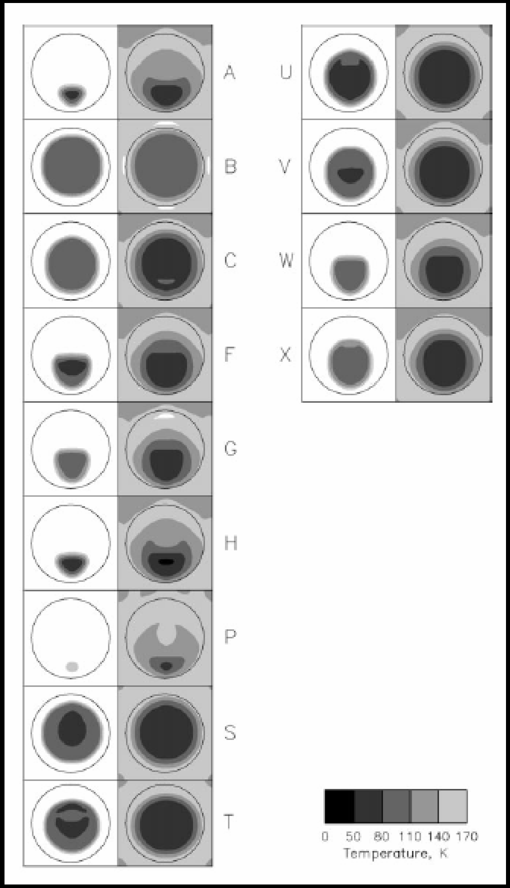
(Margot et al., 1999)

- *Earth-Based RADAR topography maps of the lunar polar regions (150 meters spatial resolution 100 m vertical resolution) White areas are permanent shadows observable from Earth, Grey areas are an inferred subset of permanent shadows that are not observable from Earth.*
- *Polar illumination varies diurnally, seasonally and over 18-year lunar precessional cycle*

Lunar Ice: Current State of Knowledge

2. Thermal models predict widespread ice stability in lunar polar craters





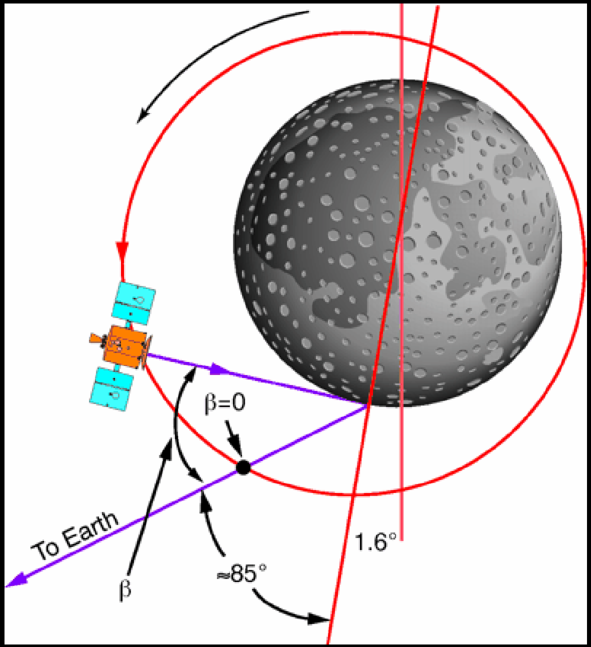
(Vasavada et al., 1999)

- *Annual maximum surface and subsurface temperatures in the floors of high-latitude lunar craters are typically colder than those on Mercury*

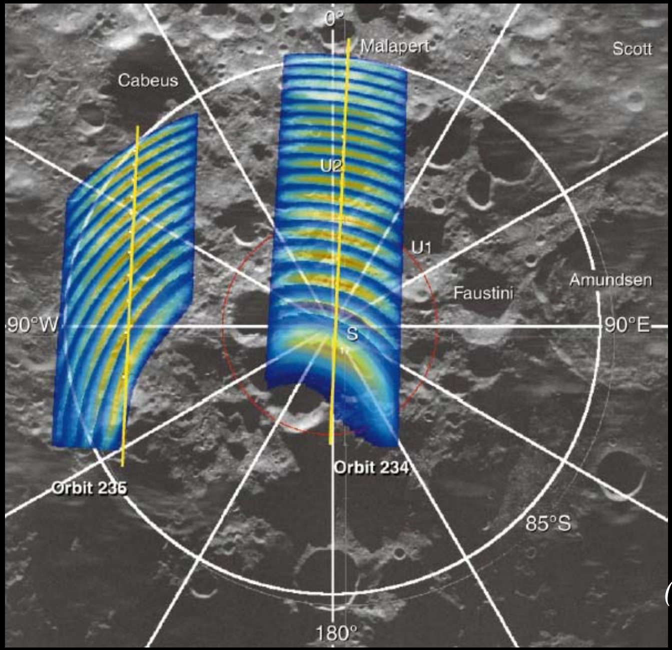
Lunar Ice: Current State of Knowledge

3. No strong RADAR signatures have been observed

Clementine Bistatic RADAR Geometry



Arecibo and Clementine South Polar Coverage

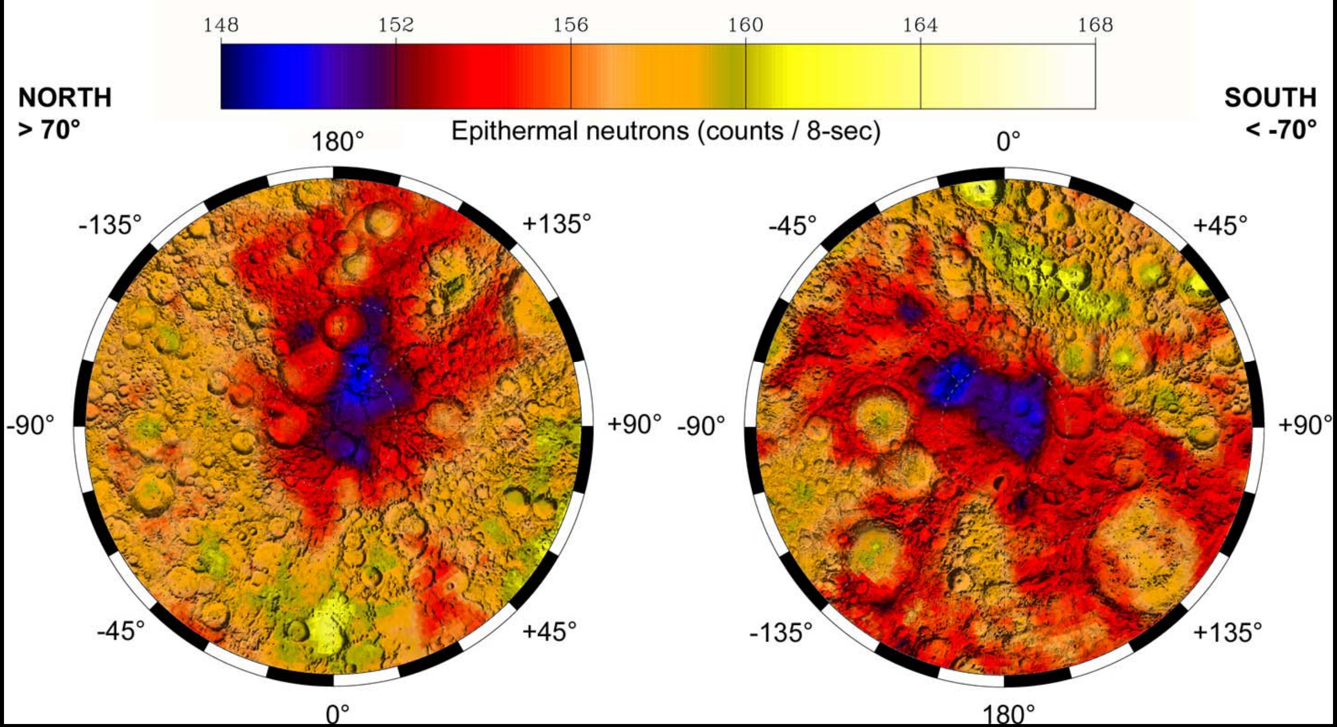


(Nozette et al., 2003)
(Stacy et al., 1997)

- *No experiment (from Earth or space) has yet observed a convincing RADAR ice signature on the moon*
- *Similar RADAR observations of Mercury (under comparable observing geometries) yield strong ice signatures*

Lunar Ice: Current State of Knowledge

4. Lunar Prospector Neutron Spectrometer maps show small enhancements in hydrogen abundance in both polar regions



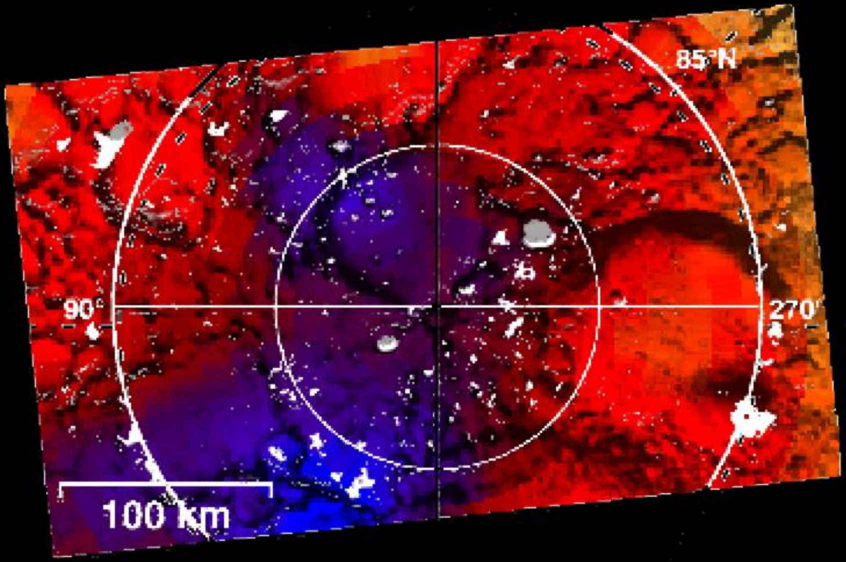
(Maurice et al, 2004

- NS results have ~ 100 km spatial resolution, and are most sensitive to hydrogen in the uppermost meter of soil
- The weak neutron signal implies a the presence of small quantities of near-surface hydrogen mixed with soil, or the presence of abundant deep hydrogen at > 1 meter depths

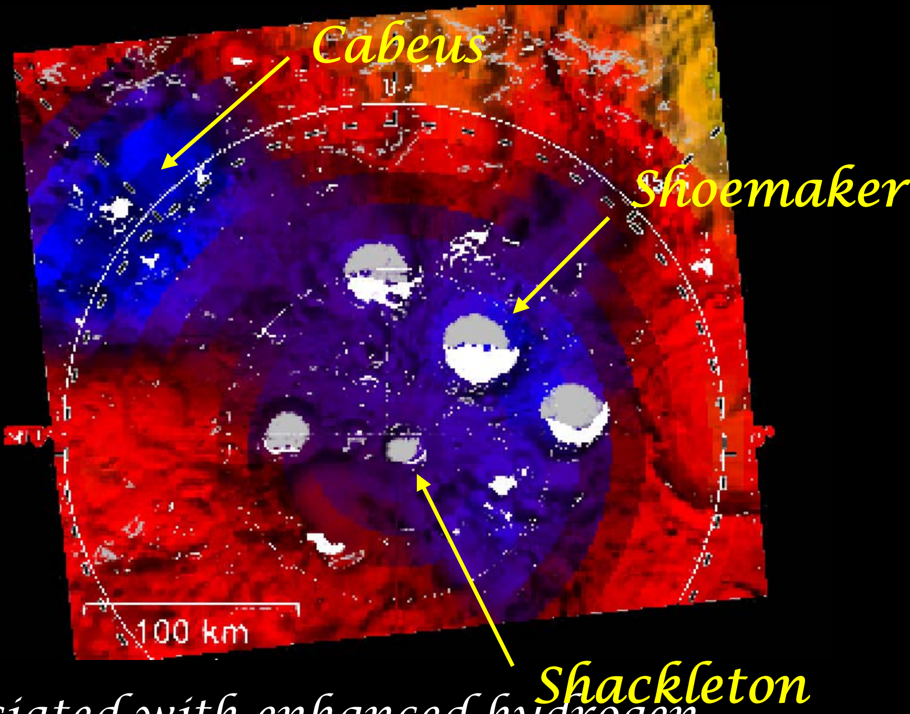
Lunar Ice: Current State of Knowledge

5. The locations of polar hydrogen enhancements are associated with the locations of suspected cold traps

North Pole



South Pole



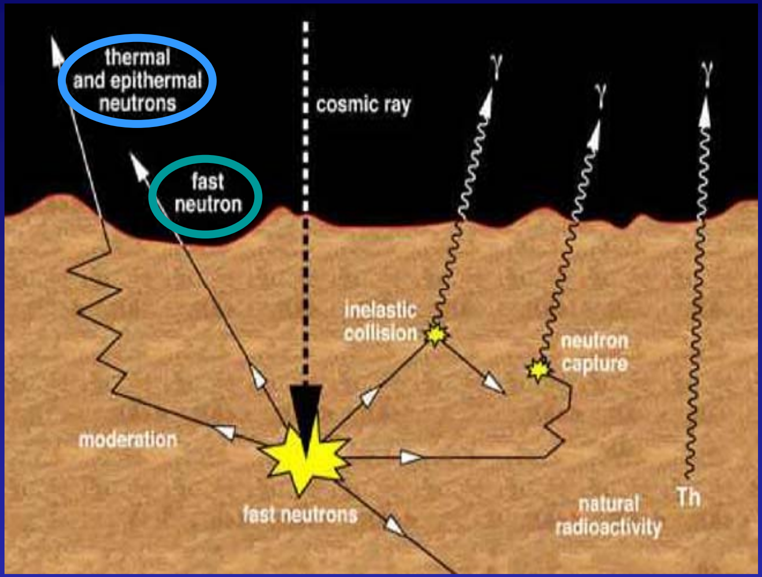
- *Not all suspected cold traps are associated with enhanced hydrogen*
- *This can't be explained purely as an artifact of the low spatial resolution of the LP NS data*
- *Thermal models show that the the effectiveness of cold-trapping and the depth of ice burial is extremely sensitive to topography*
- *Aside from permanent shade, the most important parameter for lunar ice stability is the flux of indirect solar radiation and direct thermal radiation*

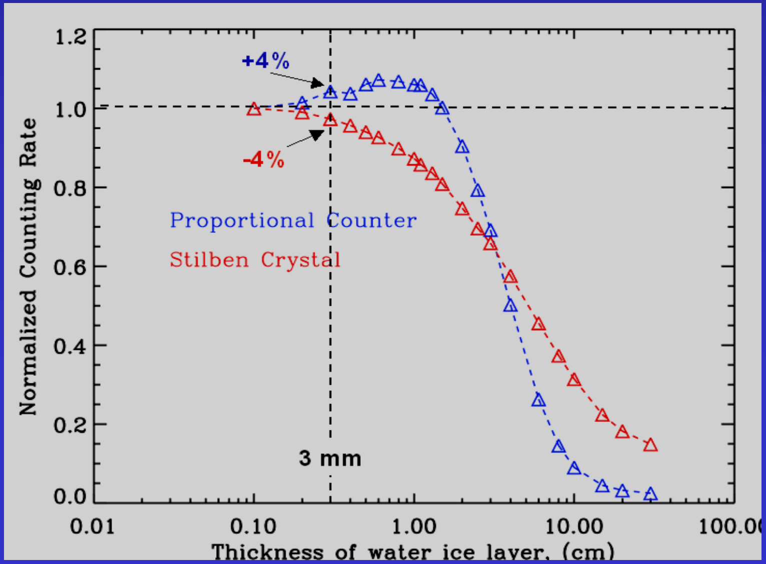
Lunar Exploration Neutron Detector (LEND)

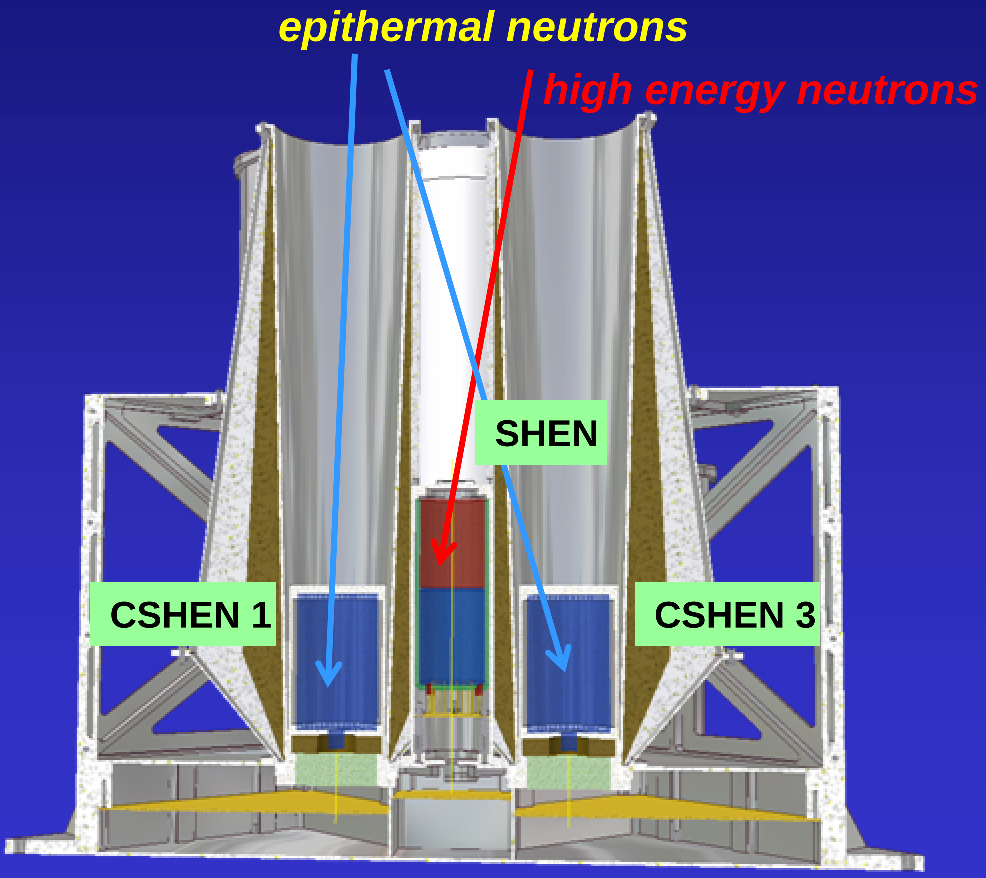
Igor Mitrofanov	PI	Russian Institute for Space Research
William Boynton	CoI	University of Arizona
Larry Evans	CoI	Computer Science Corporation
Alexandr Kozyrev	CoI	Russian Institute for Space Research
Maxim Litvak	CoI	Russian Institute for Space Research
Roald Sagdeev	CoI	University of Maryland
Anton Sanin	CoI	Russian Institute for Space Research
Vladislav Shevchenko	CoI	Sternberg Astronomical Institute
Valery Shvetsov	CoI	Joint Institute for Nuclear Research
Richard Starr	CpI	Catholic University
Vlad Tret’yakov	CoI	Russian Institute for Space Research
Jakob Trombka	CoI	NASA Goddard Space Flight center

LEND Science Overview and Theory of Operations

LEND collimated sensors CSETN1-4 and SHEN detect epithermal neutrons and high energy neutrons with high angular resolution to test water ice deposit on the surface

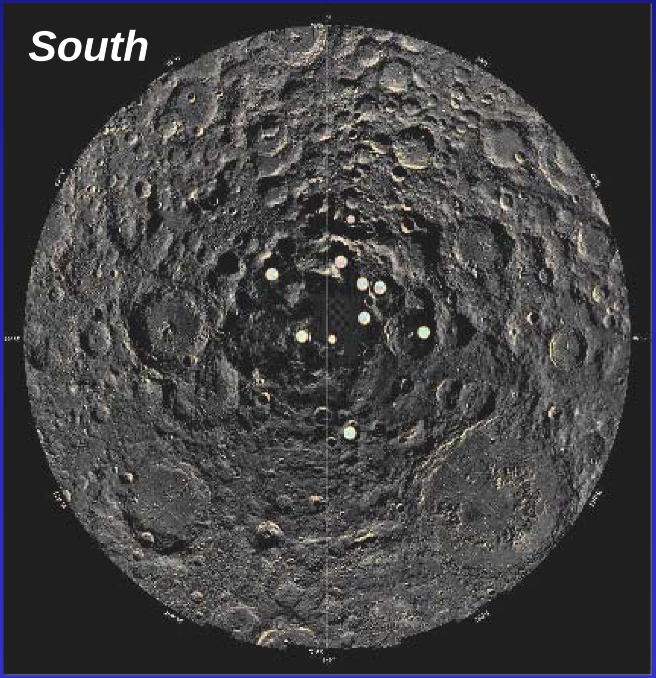






LEND Sensitivity

Deconvolution of LEND sensitivity and distribution of cold traps in the south



South polar region

	Latitude	Longitude	ΔS, km^2	Texpos, sec	PPM
1	-89.9	111.1	380	47066	30.9
2	-88.5	220	400	8093	75.8
3	-87.6	38	575	7272	80.1
4	-87.4	260.2	183	2137	151.5
5	-86.8	75.8	257	2438	141.3
6	-85.2	48.1	99	627	294.4
7	-85.1	184.5	58	360	403.7
8	-84.7	323	100	573	309.4
9	-84.7	12.5	116	665	284.8
10	-84.4	54.8	140	760	264.5
11	-83.7	84.7	140	676	282.3
12	-83.5	164.5	70	328	426.4

Lyman-Alpha Mapping Project (LAMP)

Lyman-Alpha Mapping Project (LAMP)

"Seeing in the Dark"

A Proven Instrument

Lunar Exploration: Polar Mapping and a Search for Water Frost

Atmospheric/ Volatile Transport Exploration

Natural Lighting and Simple Observing Geometry

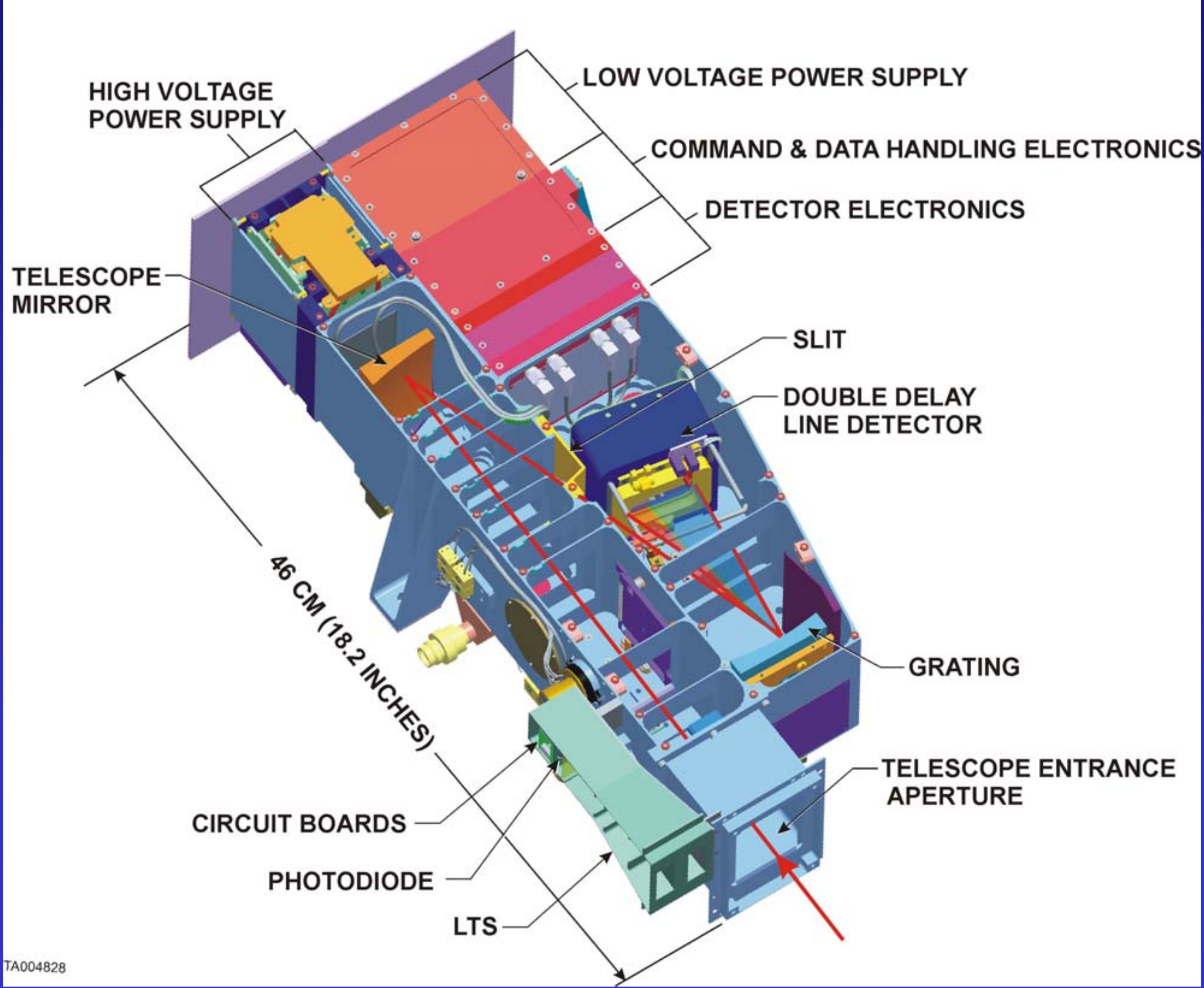
In response to:
An Announcement of Opportunity:
for Lunar Reconnaissance Orbiter
(LRO) Investigations
NASA AO NNH04ZSS003O

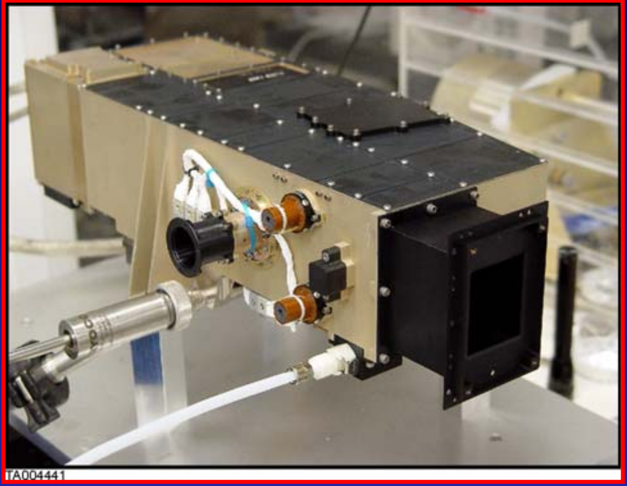
Principal Investigator:
S. Alan Stern
Southwest Research Institute

TA004404

Alan Stern (SwRI), PI
Ron Black (SwRI)
Dana Crider (Catholic U.)
Paul Feldman (JHU)
Randy Gladstone (SwRI)
Kurt Retherford (SwRI)
John Scherrer (SwRI)
Dave Slater (SwRI)
John Stone (SwRI)

LAMP Instrument Overview





LAMP (with LTS):
5.3 kg, 4.6 W
0.2º×6.0º slit
520-1800 Å passband
20 Å point source
spectral resolution

LAMP Science/ Measurement Summary

- Group 1A: LAMP will be used to identify and localize exposed water frost in PSRs.

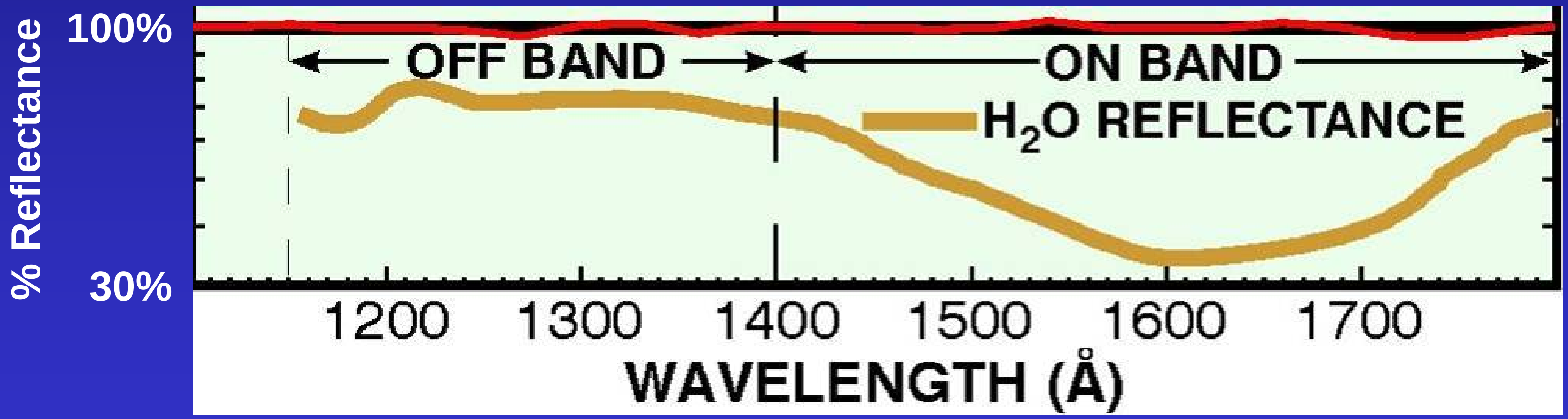
- Group 1B: LAMP will provide landform mapping (using Lyα albedos) in and around the permanently shadowed regions (PSRs) of the lunar surface.

- Group 1C: LAMP will demonstrate the feasibility of using starlight and UV sky-glow for future night time and PSR surface mission applications.

- Group 2A: LAMP will Assay the Lunar Atmosphere and Its Variability

Locate Resources: LAMP sees surface ice and into dark craters

- LAMP has a diagnostic UV absorption feature to identify pure water ice on the Lunar surface
  - H_2O frost has a distinct broad UV absorption near 1600 Å
- Images permanently shadowed regions at ~500m resolution



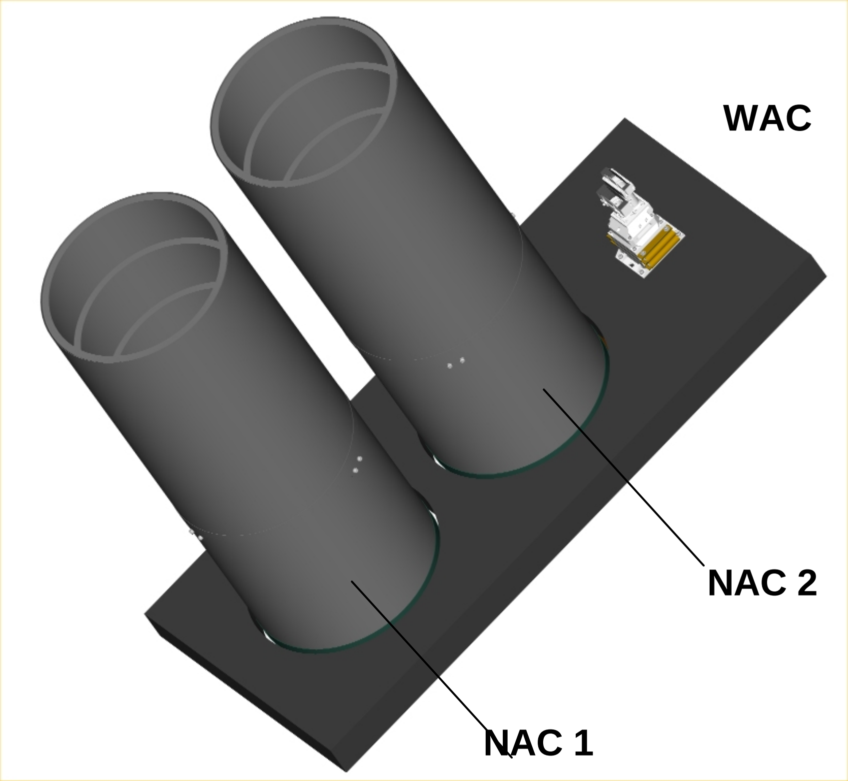
Lunar Reconnaissance Orbiter Camera (LROC)

Team

- Mark Robinson, Northwestern Univ., PI
- Eric Eliason, University of Arizona
- Harald Hiesinger, Brown University
- Brad Jolliff, Washington University
- Mike Malin, MSSS
- Alfred McEwen, University Arizona
- Mike Ravine, MSSS
- Peter Thomas, Cornell University
- Elizabeth Turtle, University Arizona

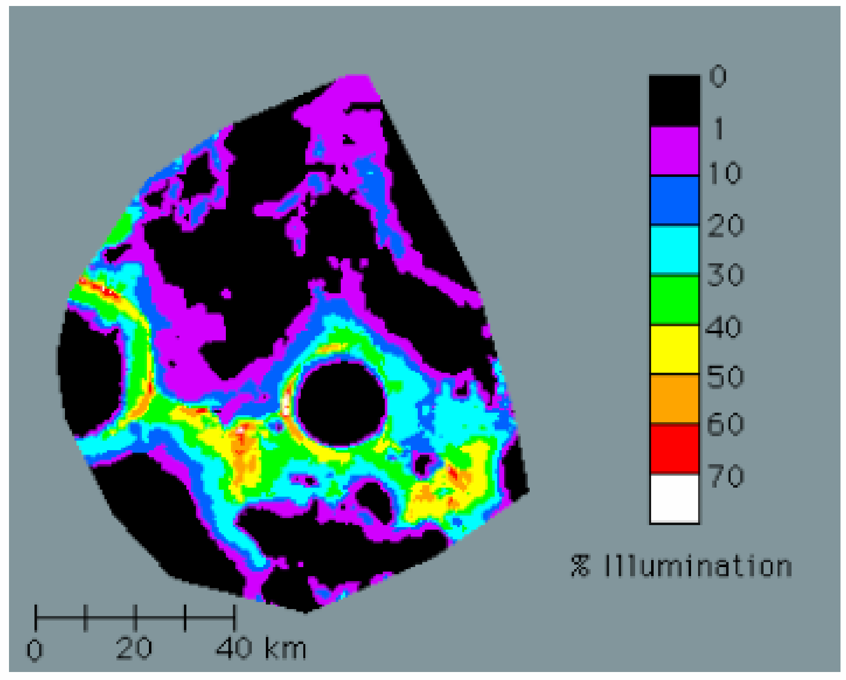
LROC Cameras

- WAC Design Parameters
  - Optics (2 lenses) f/5.1 vis., f/8.7 UV
    - Effective FL 6 mm
    - FOV 90º
    - MTF (Nyquist) > 0.5
  - Electronics 4 circuit boards
    - Detector Kodak KAI-1001
    - Pixel format 1024 x 1024
    - Noise 30 e-
- NAC Design Parameters
  - Optics f/4.5 Maksutov
    - Effective FL 700 mm
    - FOV 2.86º (5.67º for both)
    - MTF (Nyquist) > 0.15
  - Electronics
    - Detector Kodak KLI-5001G
    - Pixel format 1 x 5,000
    - Noise 100 e-
    - A/D Converter AD9842A
    - FPGA Actel RT54SX32-S



WAC Polar Observations

- Determine lighting conditions at both poles through a full lunar year
- 85° latitude in the dark to the pole, onward down to 80° latitude in the light (every orbit, monochrome, full swath width, both poles)
- Every 113 minute time step movie of poles over a full year (occasionally miss an orbit). Requirement of every 5 hours.
- Complete overlap from 88° pole every observation. Time step increases at “low” latitudes (down to 80°).



Illumination map of lunar south pole during 2 months of southern winter Clementine ~10 hr steps, 5° change in Sun azimuth (Bussey et al 1999).

LROC Science/ Measurement Summary

- Landing site identification and certification, with unambiguous identification of meter-scale hazards.
- Meter-scale mapping of polar regions with continuous illumination.
- Unambiguous mapping of permanent shadows and sunlit regions including illumination movies of the poles.
- Overlapping observations to enable derivation of meter-scale topography.
- Global multispectral imaging to map ilmenite and other minerals.
- Global morphology base map.

LROC NAC camera will provide 25 x greater resolution than currently available

Lunar Orbiter Laser Altimeter (LOLA)

- David E. Smith (GSFC) -- Principal Investigator; global geodetic coordinate system
- Maria T. Zuber (MIT) -- Deputy Principal Investigator; global topography & coordination of data products with NASA Exploration objectives
- Oded Aharonson (Caltech) -- Co-I; surface roughness
- James W. Head (Brown U.) -- Co-I; landing site assessment; E&PO representative
- Frank G. Lemoine (NASA/GSFC) -- Co-I; orbit determination & gravity modeling
- Gregory A. Neumann (MIT, NASA/GSFC) -- Co-I; altimetry analysis & archiving
- Mark Robinson (Northwestern U.) -- Co-I; polar regions & surface brightness analysis
- Xiaoli Sun (NASA/GSFC) -- Co-I & Instrument Scientist; instrument performance

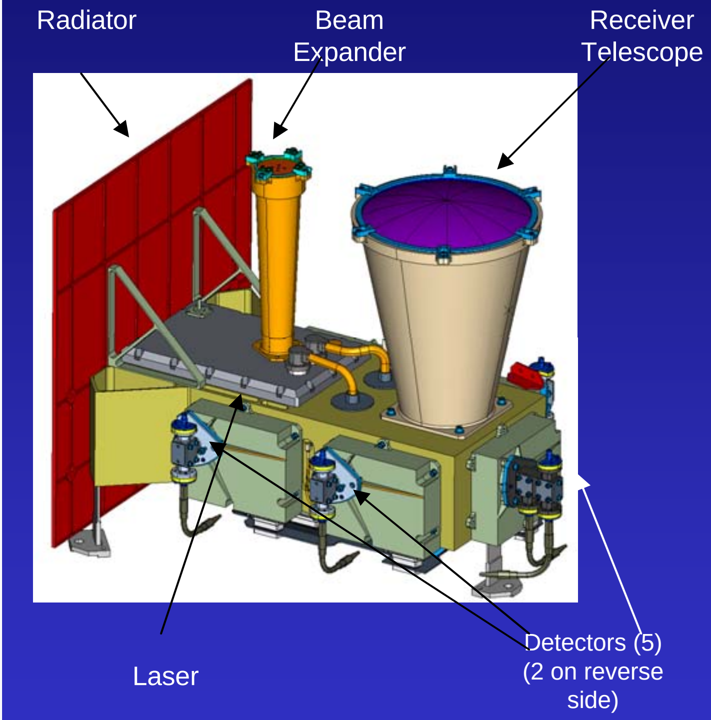
Instrument Overview

- LOLA measures:
  - RANGE to the lunar surface (pulse time-of-flight)

    ±10cm (flat surface)
  - REFLECTANCE of the lunar surface (Rx Energy/Tx Energy)

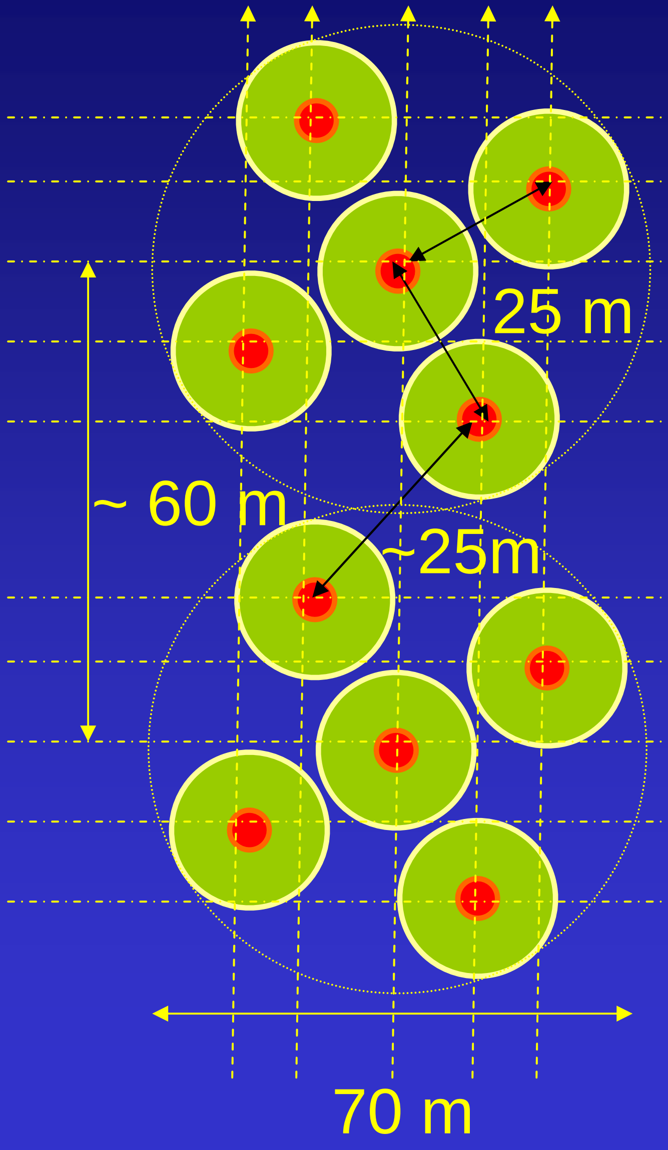
    ± 5%
  - SURFACE ROUGHNES (spreading of laser pulse)

    ± 30 cm
- Laser pulse rate 28 Hz, 5 spots => ~ 4 billion shots on the moon in 1 year.



LOLA Observation Pattern

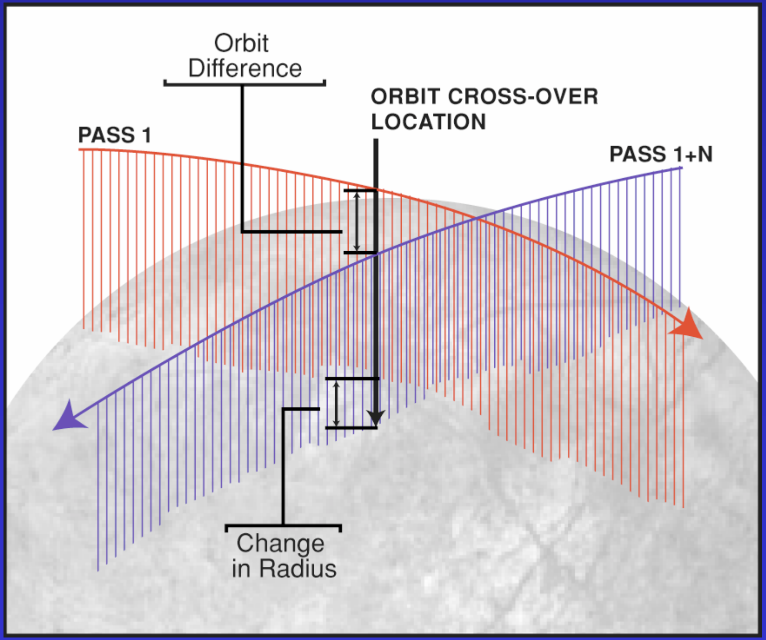
- LOLA is a 70-meter wide swath altimeter (includes field of view of detectors) providing 5 profiles at 10 to 15 meter spacing and ~15 meters along-track sampling
- LOLA characterizes the swath in elevation, slope and surface roughness, and brightness
- Knowledge of pixel locations determines map resolution.



Navigation: LOLA will provide an accurate Global Lunar Reference System

- **LOLA will obtain an accuracy base of ~50 meters horizontal (point-to-point) and 0.5 to 1 meter radially**
  - Current accuracy ~4 km globally

- **LOLA is a geodetic tool to derive a precise positioning of observed features with a framework (grid) for all LRO Measurements**
  - Measure distance from LRO to the surface
  - Five laser spots along and across track
  - Measure distribution of elevation within laser footprint
  - Enhanced surface reflectance (possible water ice on surface)



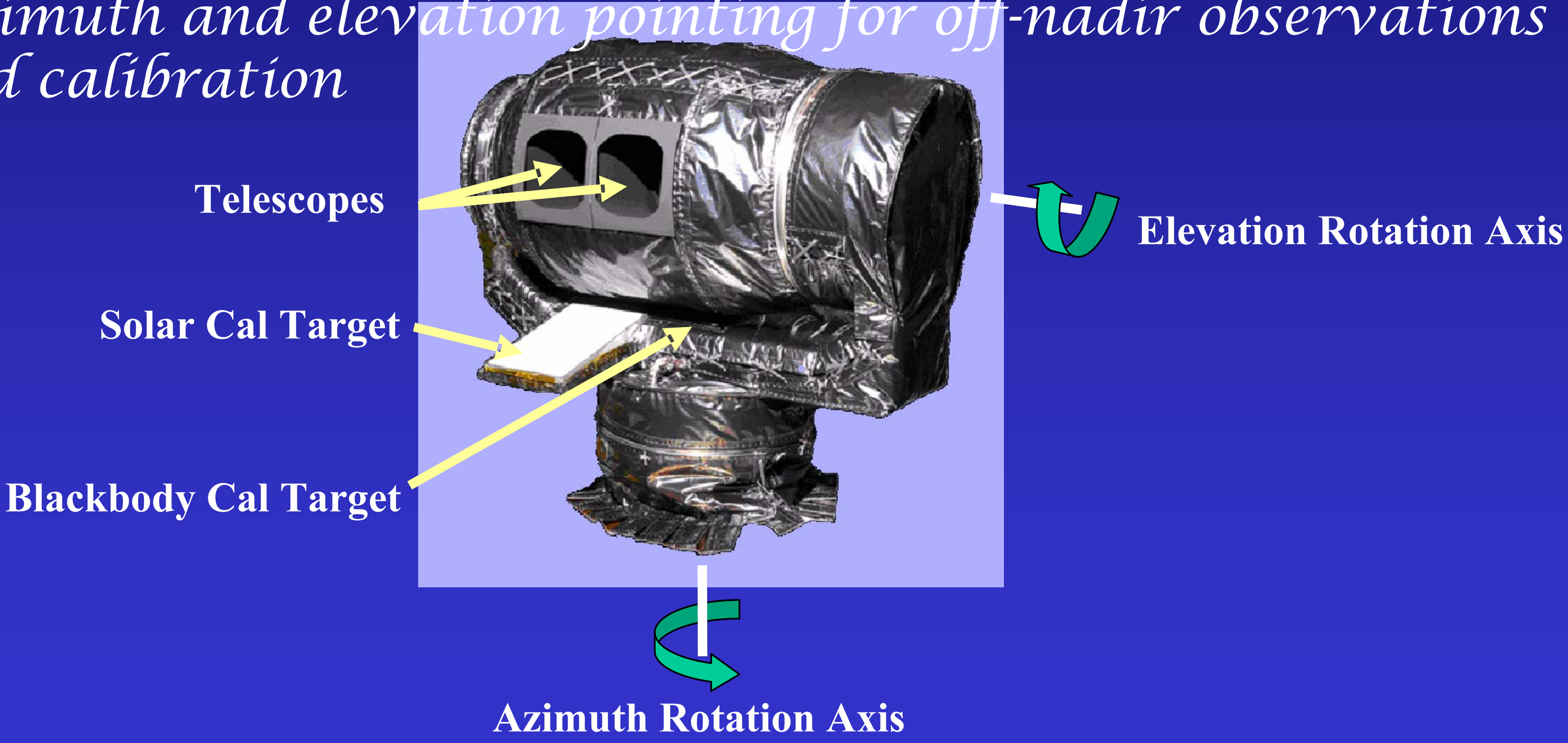
Crossovers occur about every 1 km in longitude and 3 deg in latitude at equator

Diviner Team

Principal Investigator:	
David Paige	UCLA
Co-Investigators:	
Carlton Allen	JSC
Simon Calcutt	Oxford (UK)
Eric DeJong	JPL
Bruce Jakosky	U. Colorado
Daniel McCleese	JPL
Bruce Murray	Caltech
Tim Schofield	JPL
Kelly Snook	JSC
Larry Soderblom	USGS
Fred Taylor	Oxford (UK)
Ashwin Vasavada	JPL
Project Manager:	
Wayne Hartford	JPL

Diviner Overview

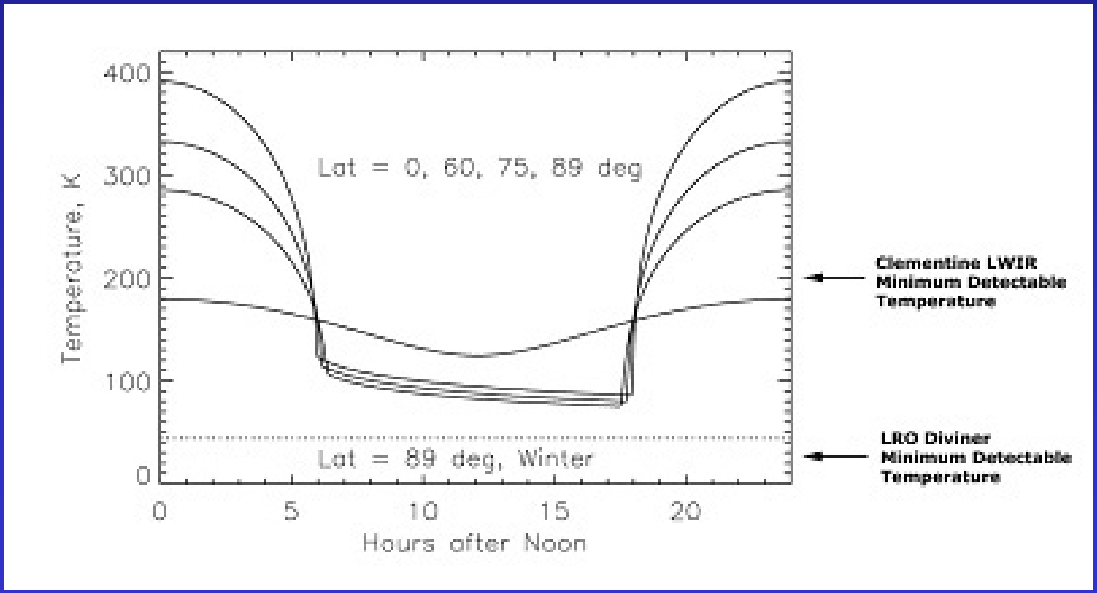
- Close copy of JPL's Mars Climate Sounder (MCS) Instrument on MRO (MOI 3/10/06)
- 9-channel infrared radiometer 40K – 400K temperature range
- 21 pixel continuous pushbroom mapping with ~300 m spatial resolution and 3.15 km swath width at 50 km altitude
- Azimuth and elevation pointing for off-nadir observations and calibration



Diviner Investigation Goals

1. Characterize the moon's surface thermal environment
   - Daytime
   - Nighttime
   - Polar
2. Map surface properties
   - Bulk thermal properties (from surface temperature variations)
   - Rock abundance and roughness (from fractional coverage of warm and cold material)
   - Silicate mineralogy (8 micron thermal emission feature)
3. Characterize polar cold traps
   - Map cold-trap locations
   - Determine cold-trap depths

Clementine LWIR Daytime Thermal Image (20

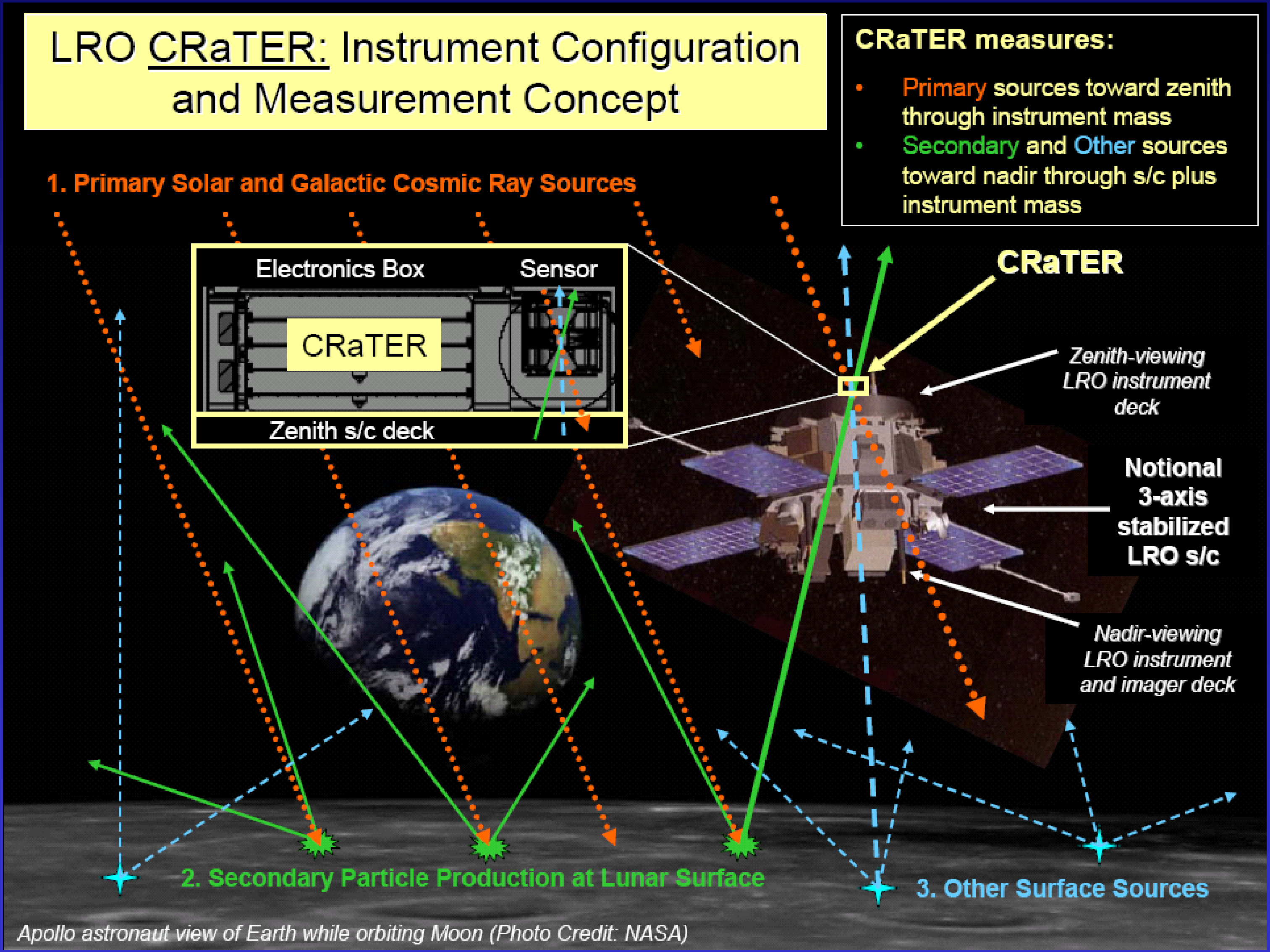


Lunar day, night and polar temperatures

Cosmic Ray Telescope for the Effects of Radiation (CRaTER)

Name	Institution	Role
Harlan E. Spence	BU	PI
Larry Kepko	“	Co-I (E/PO, Cal, IODA lead)
Justin Kasper	MIT	Co-I (Project Sci.)
Bernie Blake	Aerospace	Co-I (Detector lead)
Joe Mazur	“	Co-I (GCR/SCR lead)
Larry Townsend	UT Knoxville	Co-I (Measurement lead)
Michael Golightly	AFRL	Collaborator
Terry Onsager	NOAA/SEC	Collaborator
Rick Foster	MIT	Project Manager
Bob Goeke	“	Systems Engineer
Brian Klatt	“	Q&A
Chris Sweeney	BU	Instrument Test Lead

Instrument Overview



LRO CRaTER: Instrument Configuration and Measurement Concept

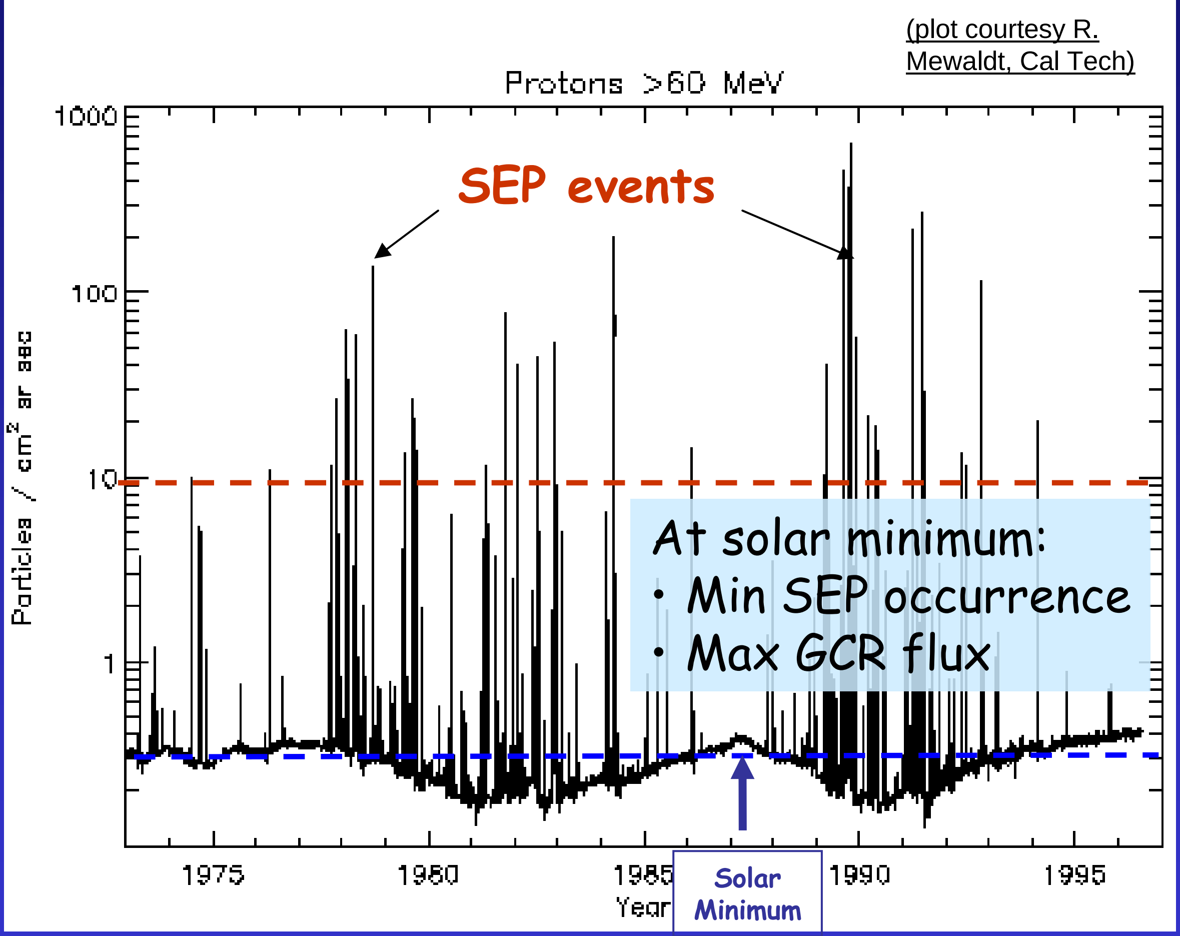
CRaTER measures:

- Primary sources toward zenith through instrument mass
- Secondary and Other sources toward nadir through s/c plus instrument mass

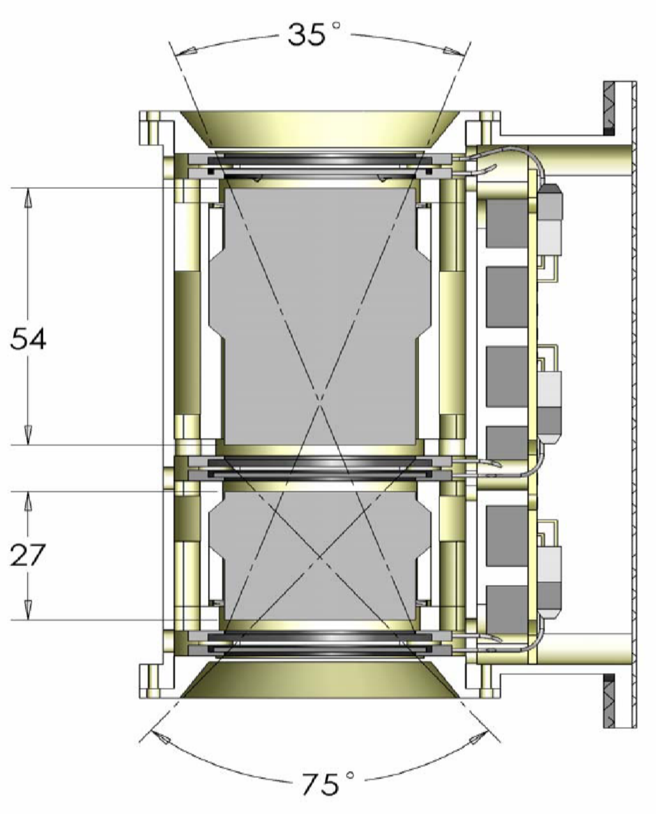
Apollo astronaut view of Earth while orbiting Moon (Photo Credit: NASA)

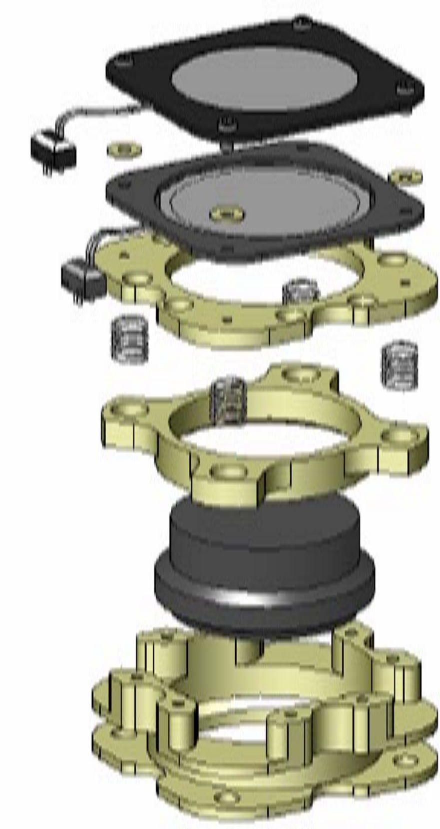
When Is It Safe? Almost never.

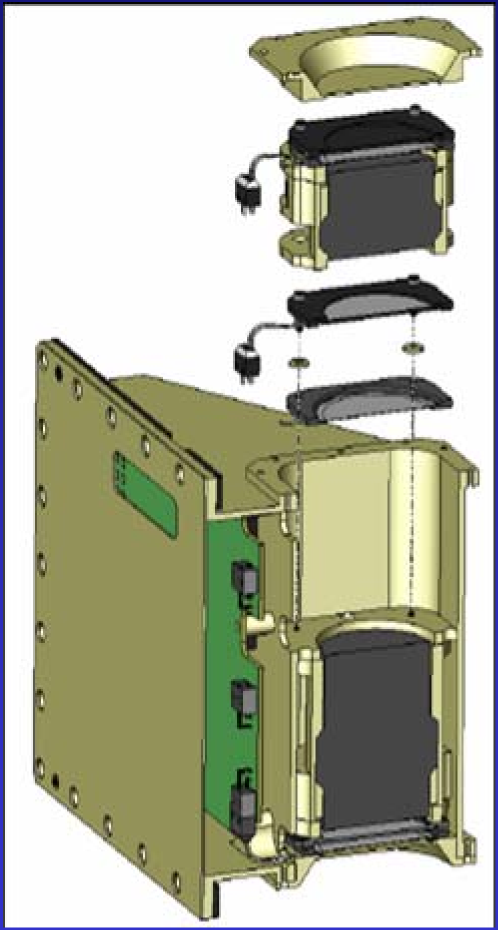
- GCR flux is low-level but continuous and has weak solar cycle dependence
- Intense SEPs (>10 MeV p+) are episodic and approximately follow the solar cycle
- SEP event occurrence varies with the solar cycle in anti-phase with weaker galactic cosmic ray fluxes



Crater Instrument Configuration





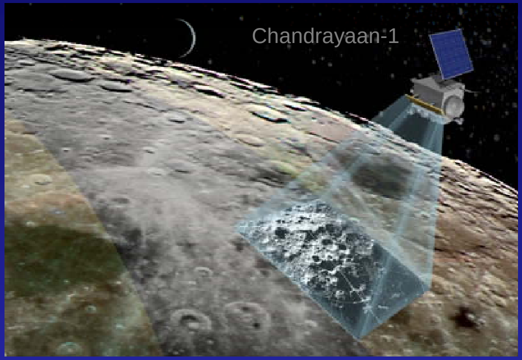


Mini RF Instrument Team

Name	Institution	Role
Chris Lichtenberg	Naval Air Warfare Center	Principal Investigator
Paul Spudis	Johns Hopkins University APL	Co-Investigator
Keith Raney	Johns Hopkins University APL	Co-Investigator
Benjamin Bussey	Johns Hopkins University APL	Co-Investigator
Brian Butler	National Radio Astronomy Observatory	Co-Investigator
Mark Robinson	Northwestern University	Co-Investigator
John Curlander	Vexcel	Member
Mark Davis	USAF/Rome Laboratory	Member
Erik Malaret	Applied Coherent Technology	Member
Michael Mishchenko	NASA Goddard Institute for Space Studies	Member
Tommy Thompson	NASA/JPL	Member
Eugene Ustinov	NASA/JPL	Member

Possible Mini-RF Lunar Demonstrations

SAR Imaging (Monostatic and Bistatic)



Monostatic imaging in S-band to locate and resolve ice deposits on the Moon.

Communications Demonstrations

Component Qualification

Monostatic imaging in S-band and X-band to validate ice deposits discoveries on the Moon

X-Band Comm Demo

Coordinated, bistatic imaging in S-band, to be compatible with the Chandrayaan-1 and LRO spacecraft, can unambiguously resolve ice deposits on the Moon

Other Coordinated Tech Demos: e.g ranging, rendezvous, gravity

LRO Instrument Locations