The Moon

Some Recent Discoveries and a New Destination for America in Space

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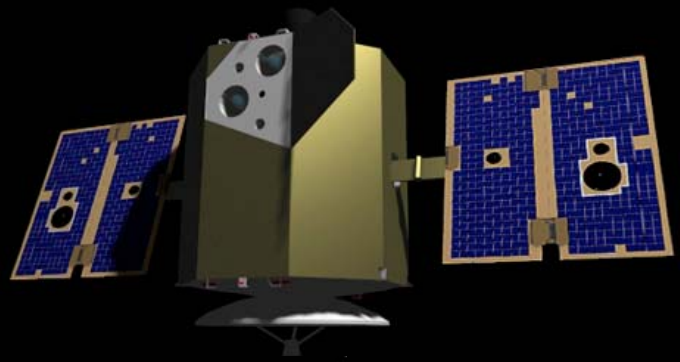
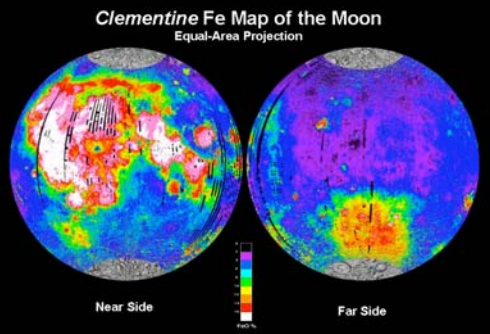
Outline

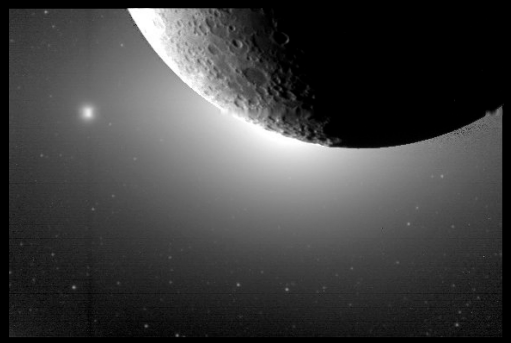
- New findings from Clementine and Lunar Prospector missions
- Composition of the lunar crust
- South Pole-Aitken basin: Biggest crater on the Moon
- The Lunar poles: the light, the dark, and the cold
- A new destination in space

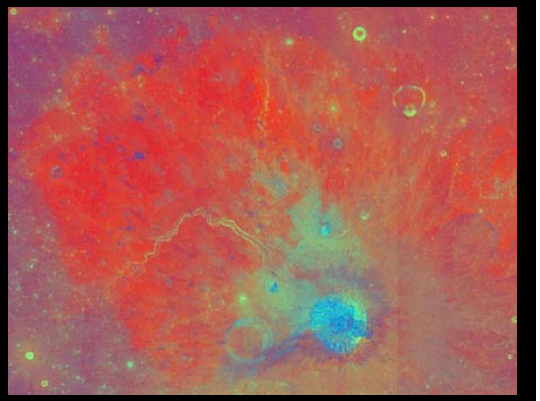
Clementine

- Launched Jan, 1994
- Orbited Moon 71 days
- Mapped surface in 11 colors in visible and near-IR
- Mapped global topography
- Bistatic radar experiment; evidence for ice at poles



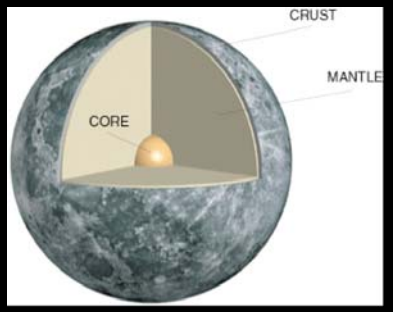


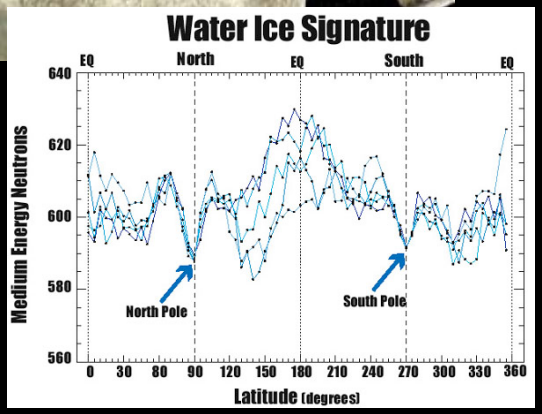


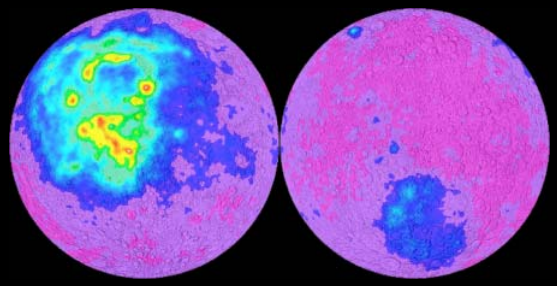


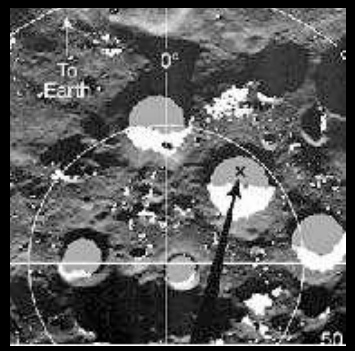
Lunar Prospector

- Launched Dec, 1997
- Orbited Moon for 18 months
- Mapped major (Fe, Ti) and trace elements (Th, Sm)
- Mapped hydrogen content of soil
- Mapped gravity and magnetic fields

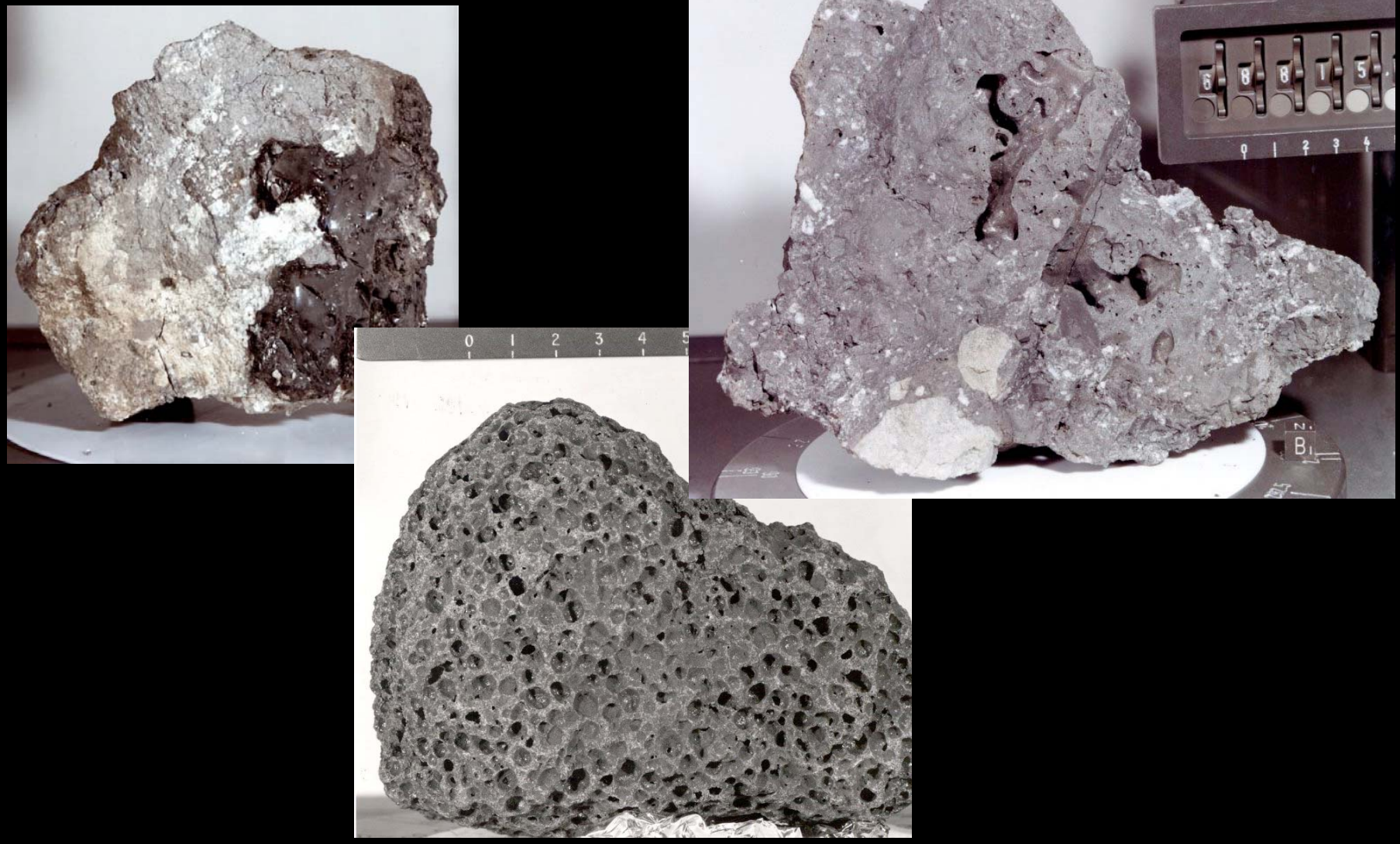




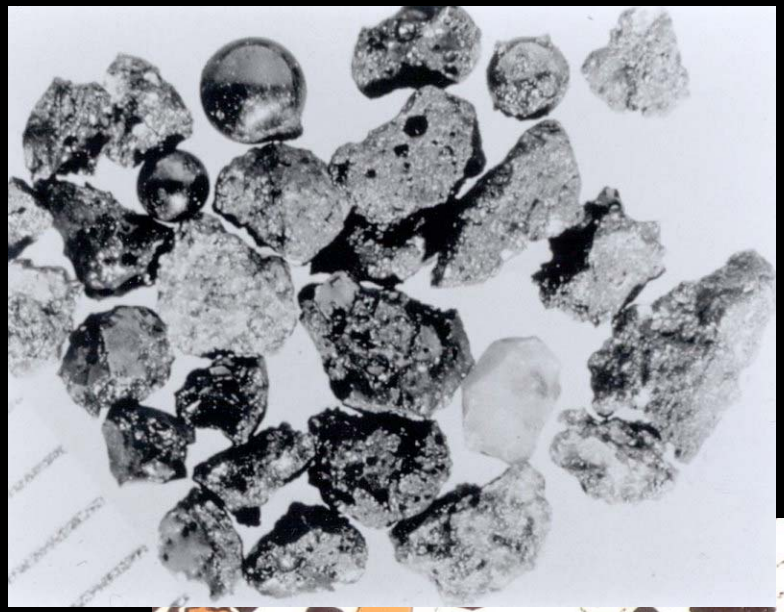


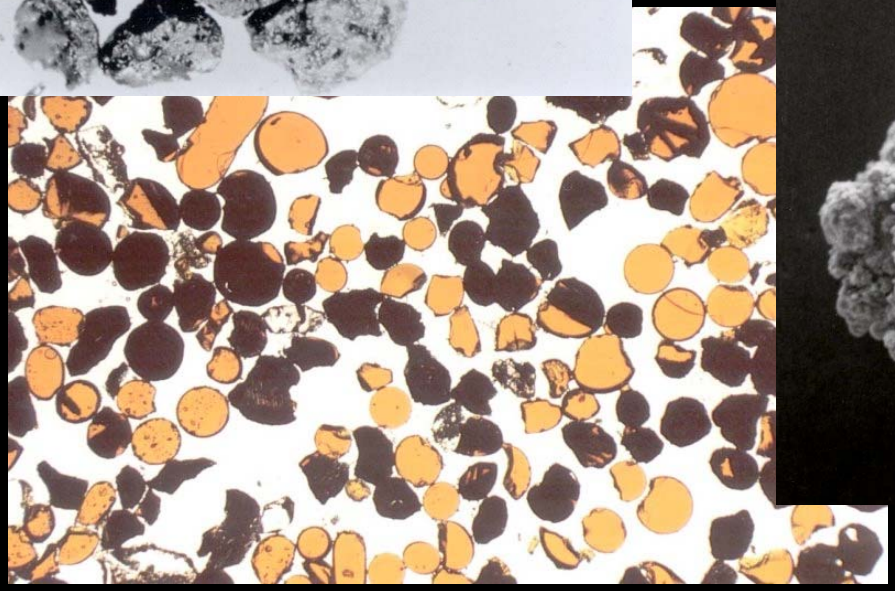


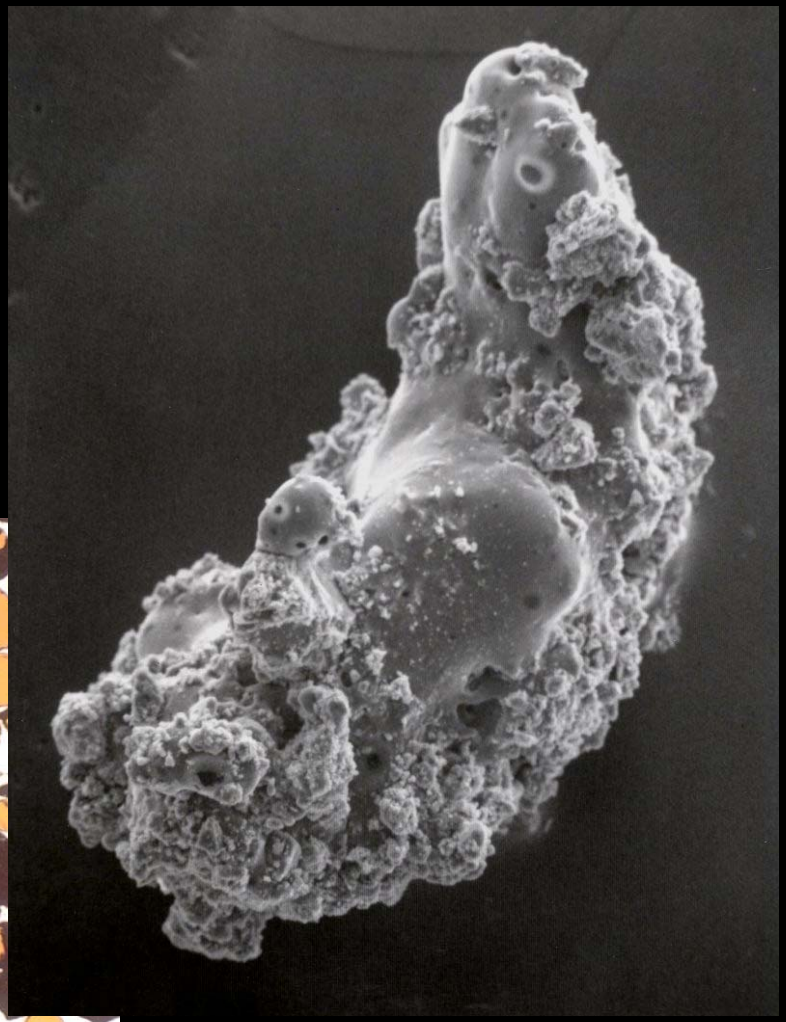
Types of Apollo samples - rocks



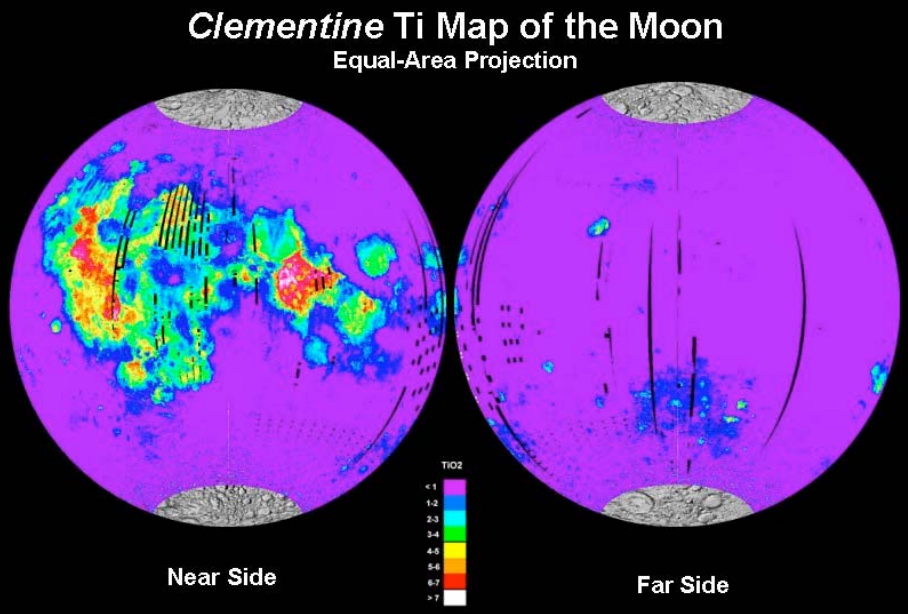
Types of Apollo samples - regolith

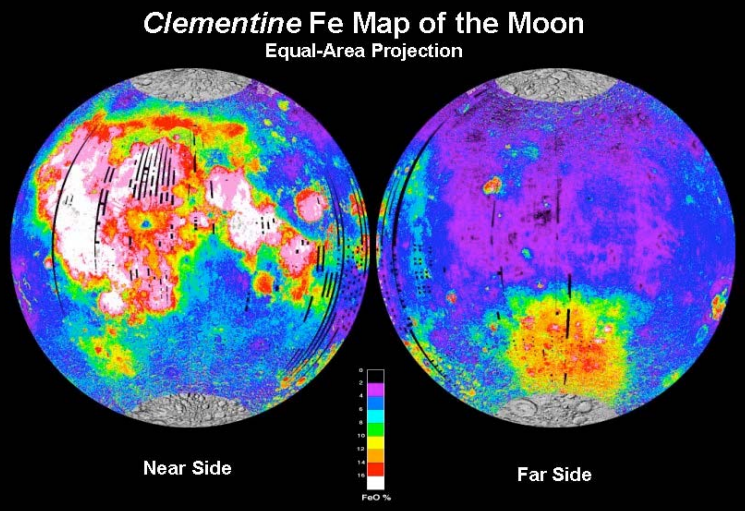


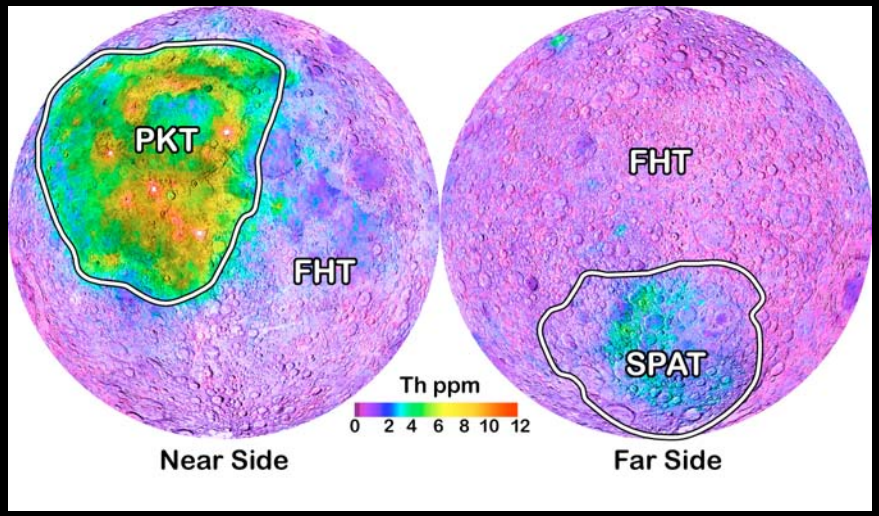




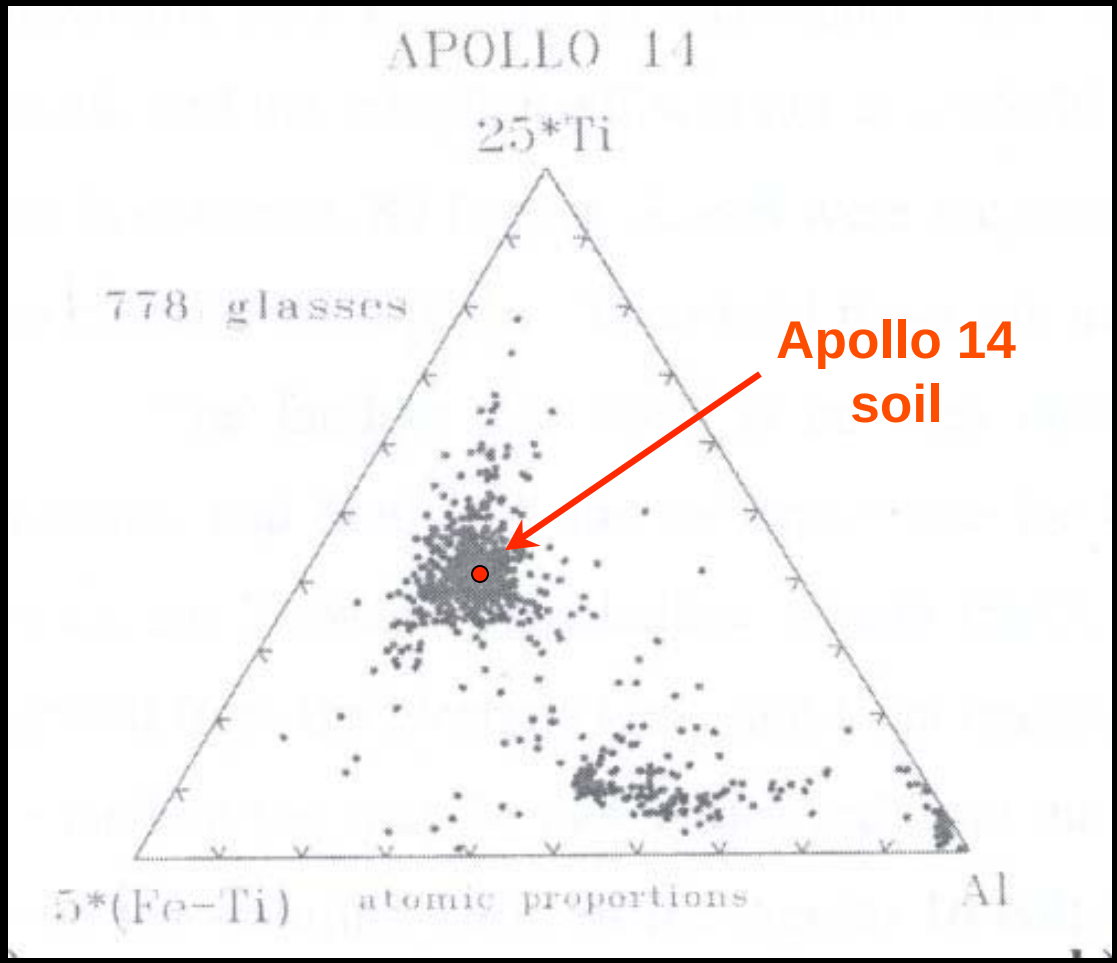
Clementine and LP data sets



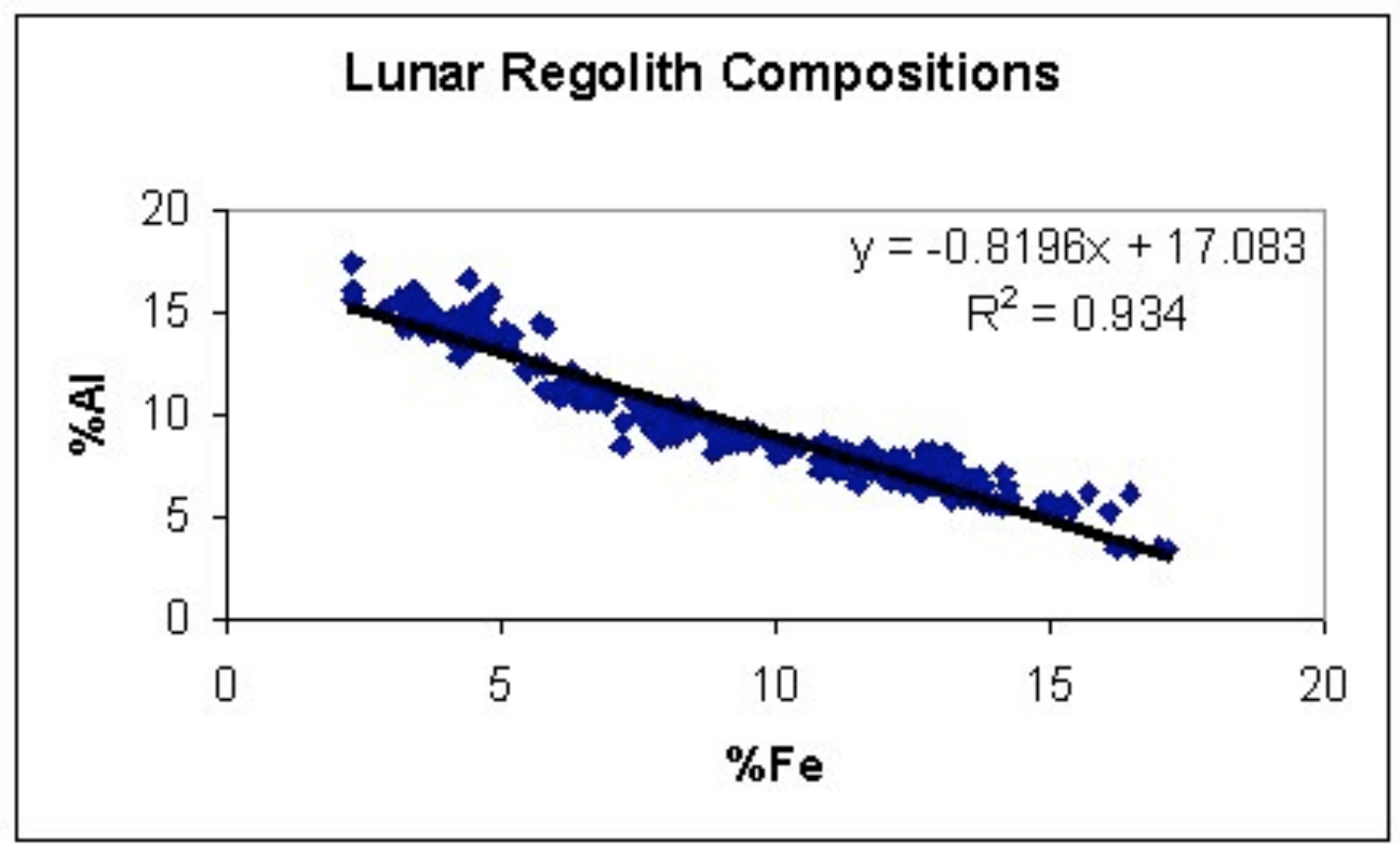


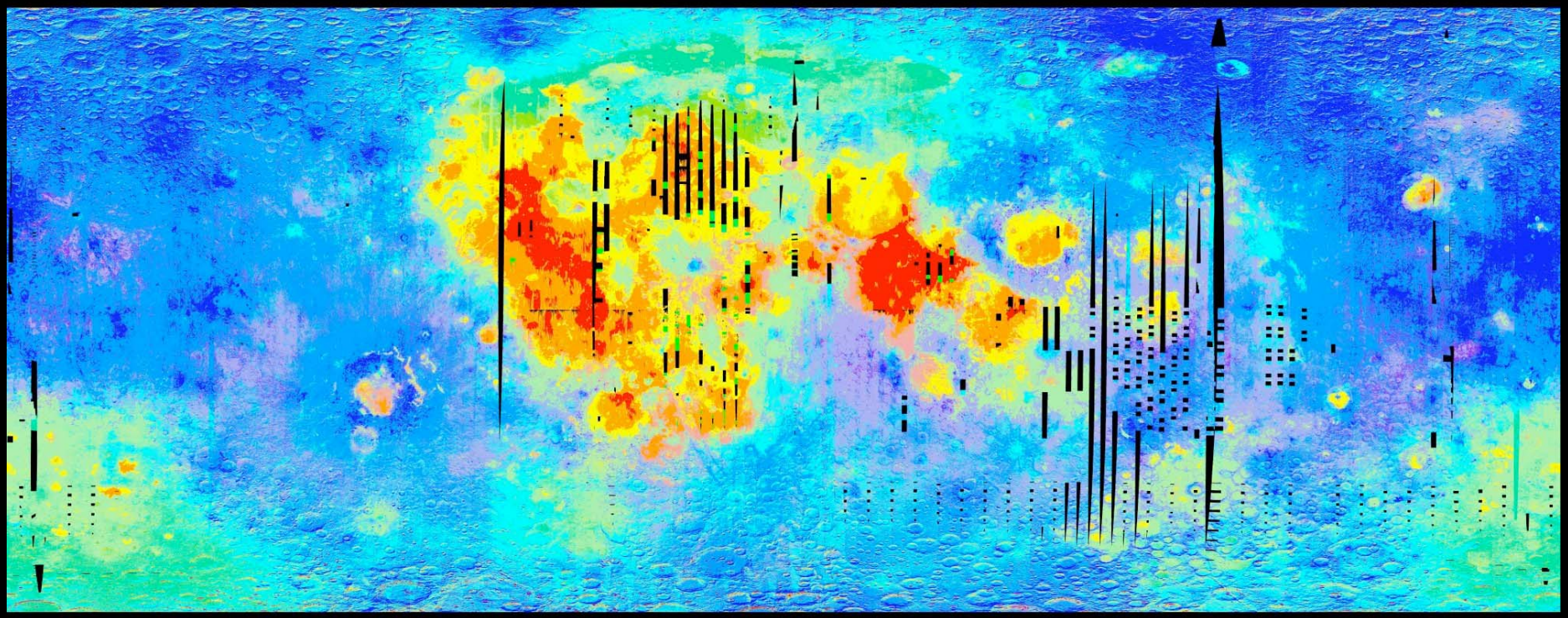


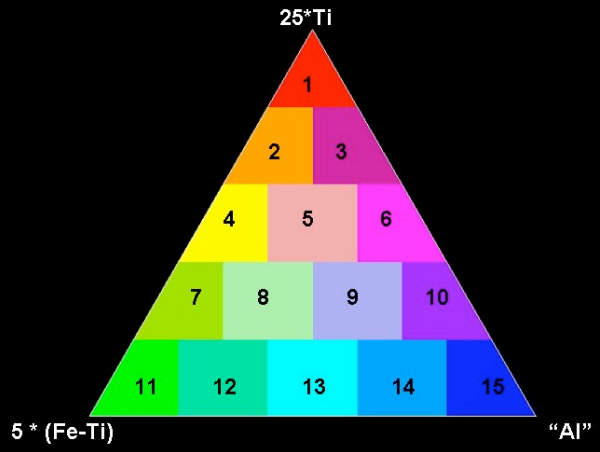
Lunar regolith impact melt glasses and soils

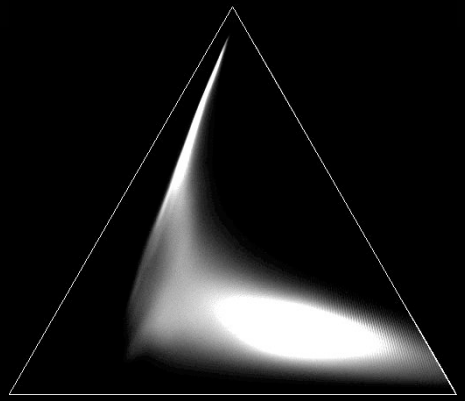


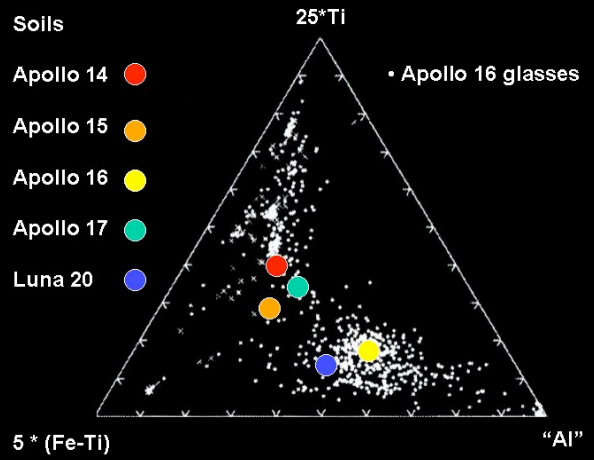
The Fe-Al relation among lunar soils





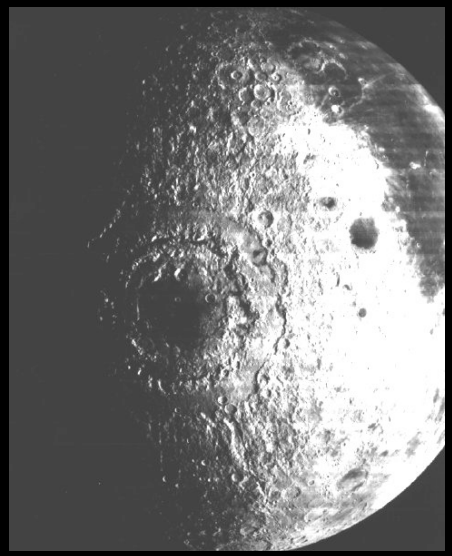

25*Ti
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
5 * (Fe-Ti)
"Al"

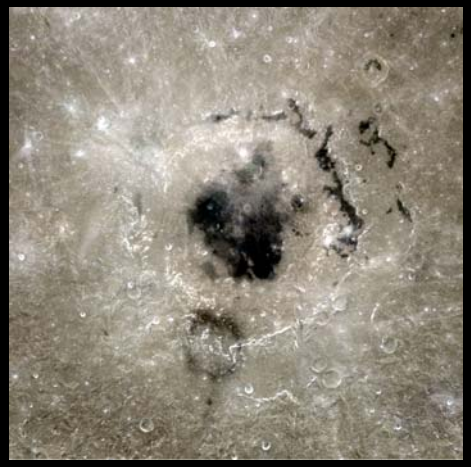


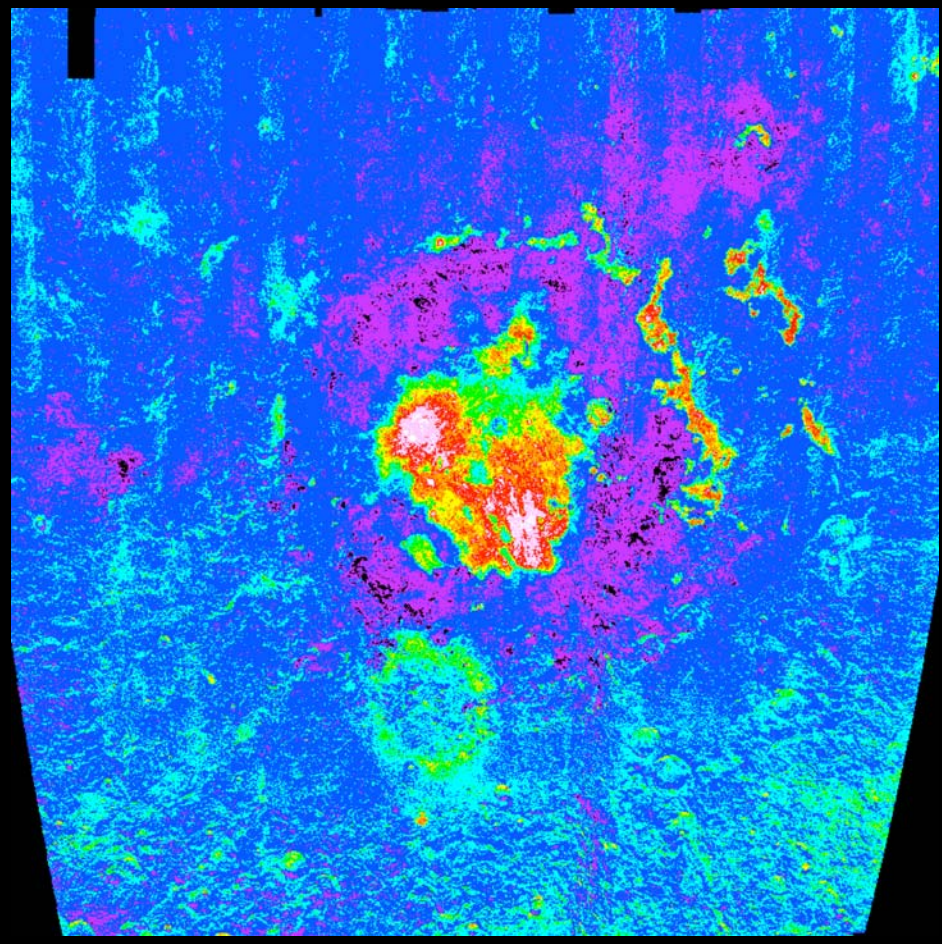

Soils
Apollo 14
Apollo 15
Apollo 16
Apollo 17
Luna 20
25*Ti
• Apollo 16 glasses
5 * (Fe-Ti)
"Al"

Orientale basin and its ejecta

Orientale basin
930 km dia.



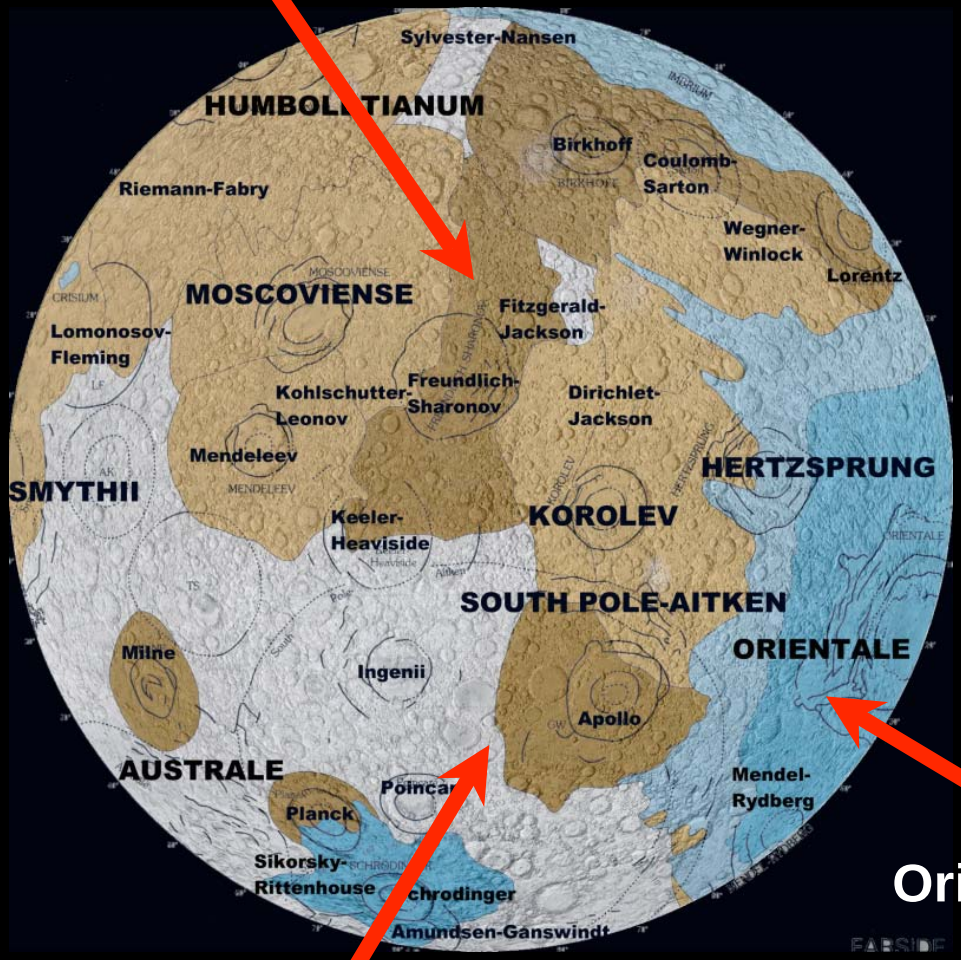


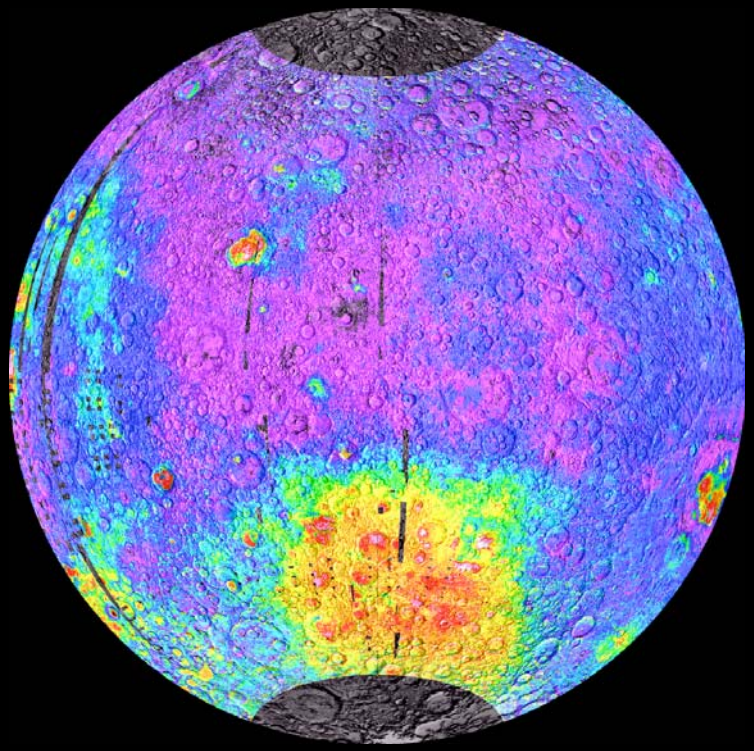


Orientale iron map

Lunar far side basins and crustal provinces

Ancient highlands





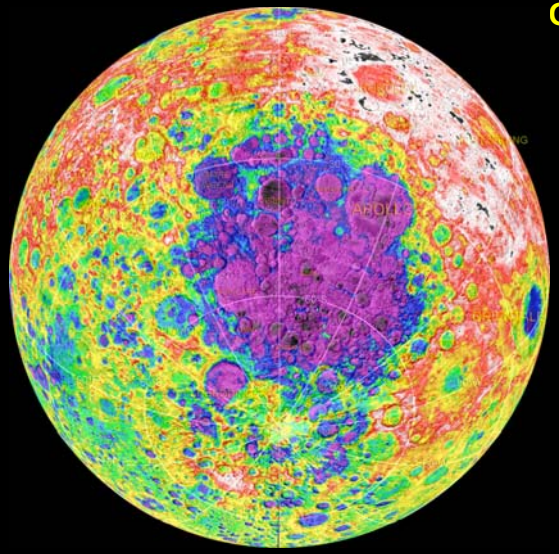
Far side iron map

Orientale basin ejecta

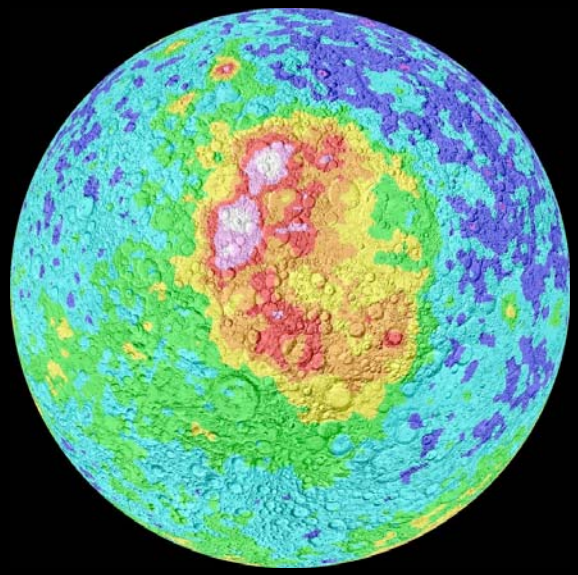
South Pole-Aitken basin floor

South Pole-Aitken Basin

Orthographic Projections centered at -56, 180

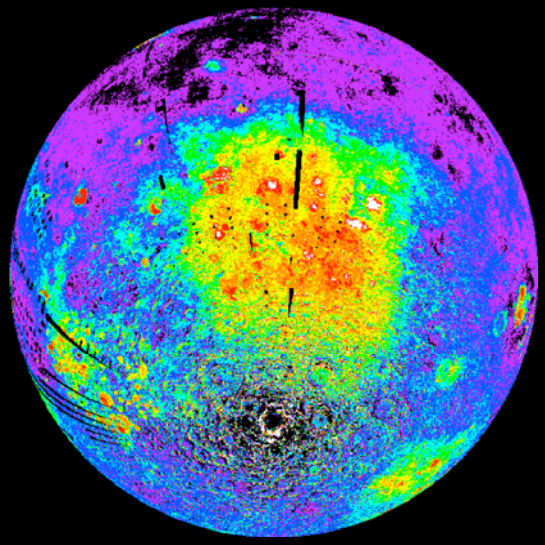


Topography

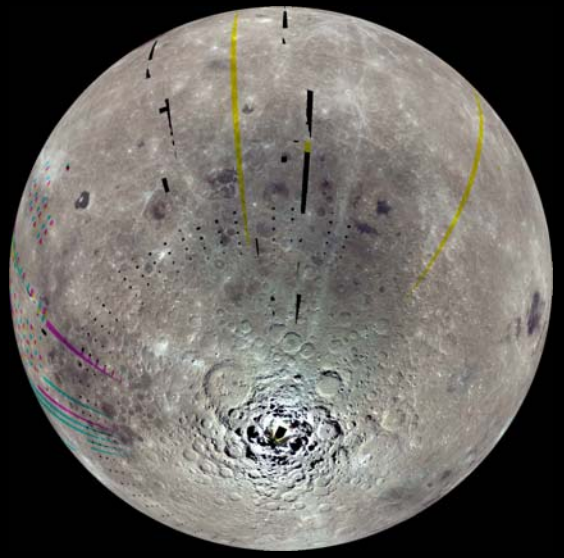


Thorium

Geology



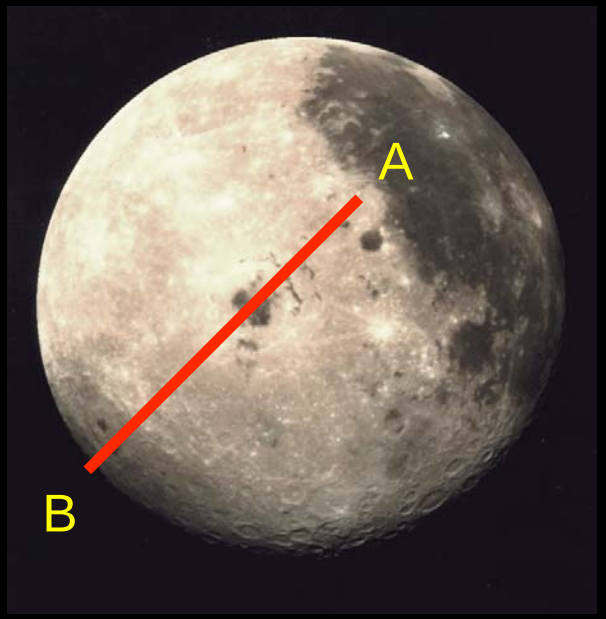
Iron

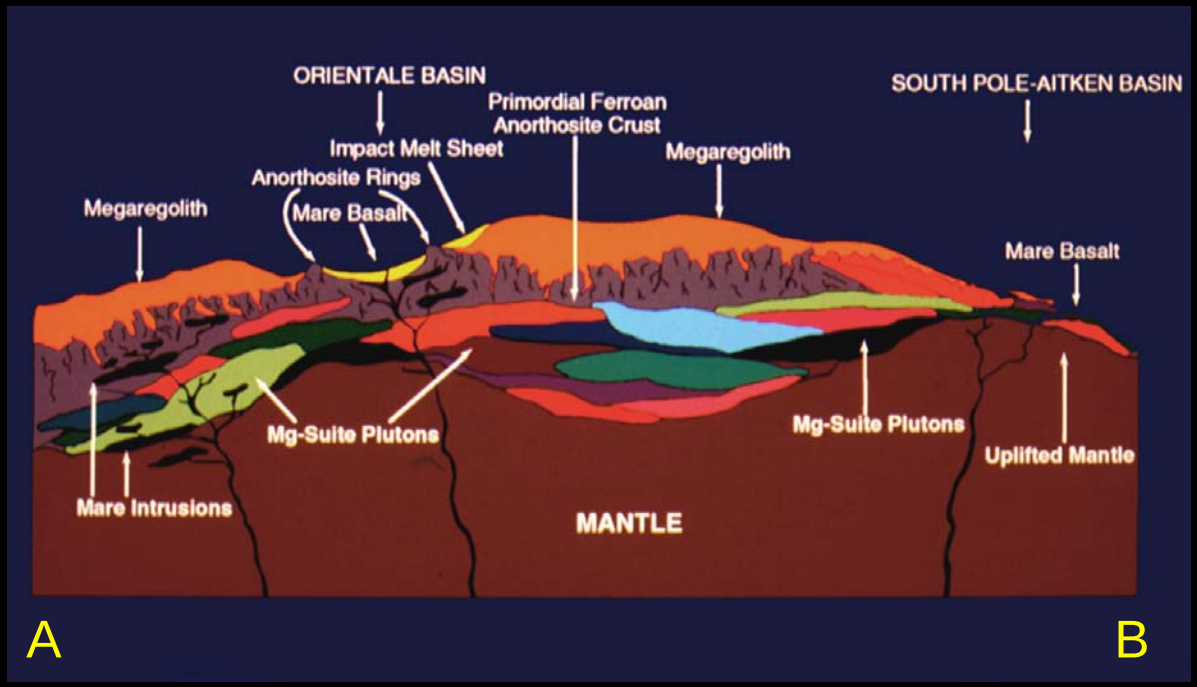


“True” color

The Lunar Crust

A section through the Orientale and SPA basins





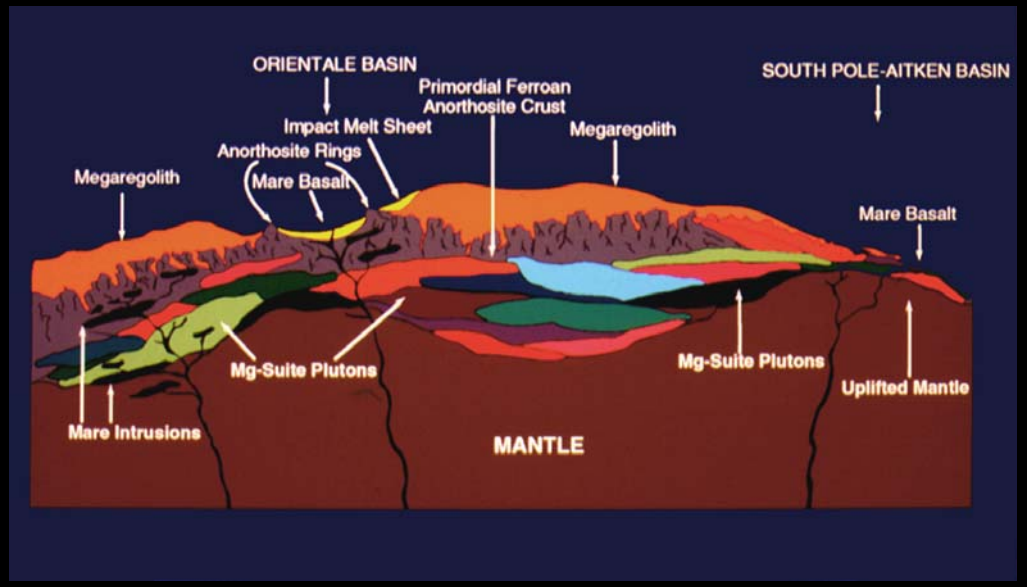
Possible origins of SPA floor

SPA basin impact melt sheet

- **“mafic”, but mineralogy appears wrong**
- **Thick sheet did not differentiate?**
- **Where is it exposed in situ?**

Lower crust/ upper mantle

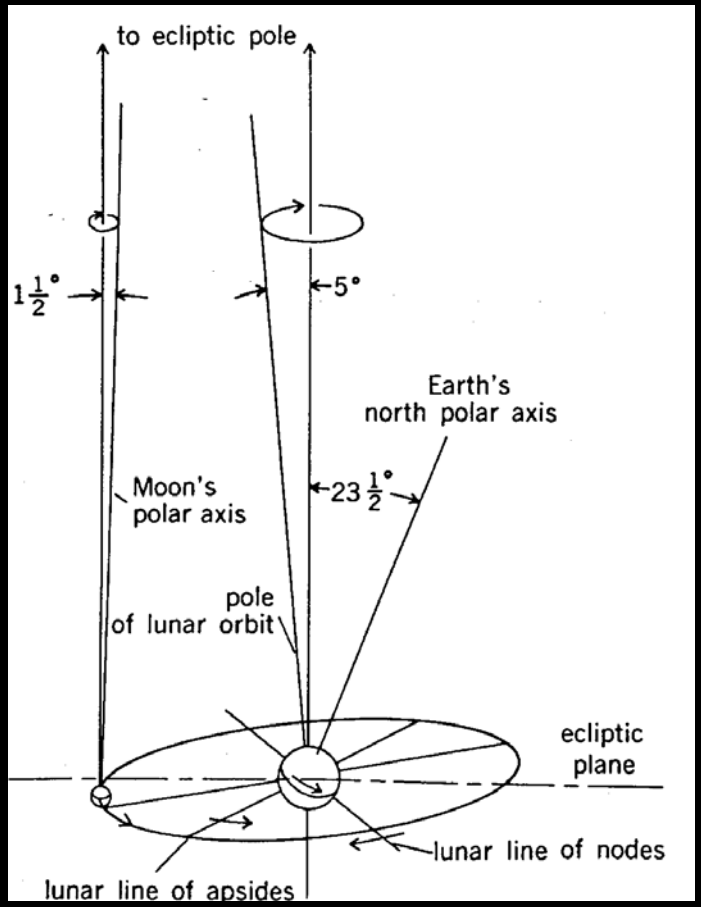
- **If FAN is removed by impact, is lower crust exposed?**
- **Where is melt sheet?**



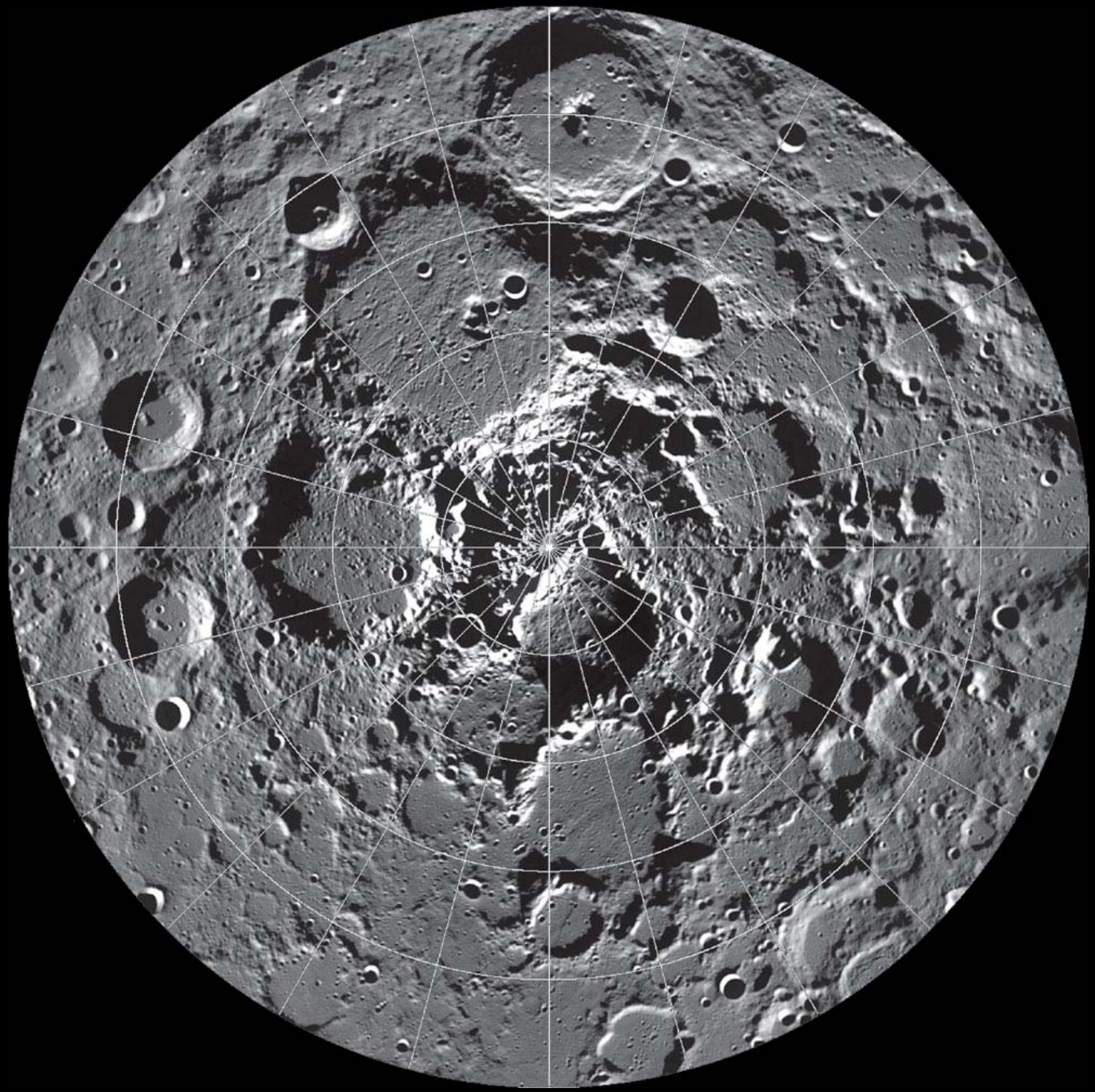
- Other?
  - –Intrusive/extrusive origins; crustal plutonism after basin impact
  - –Basin depth appears to indicate no significant infilling

The unique environment of the poles

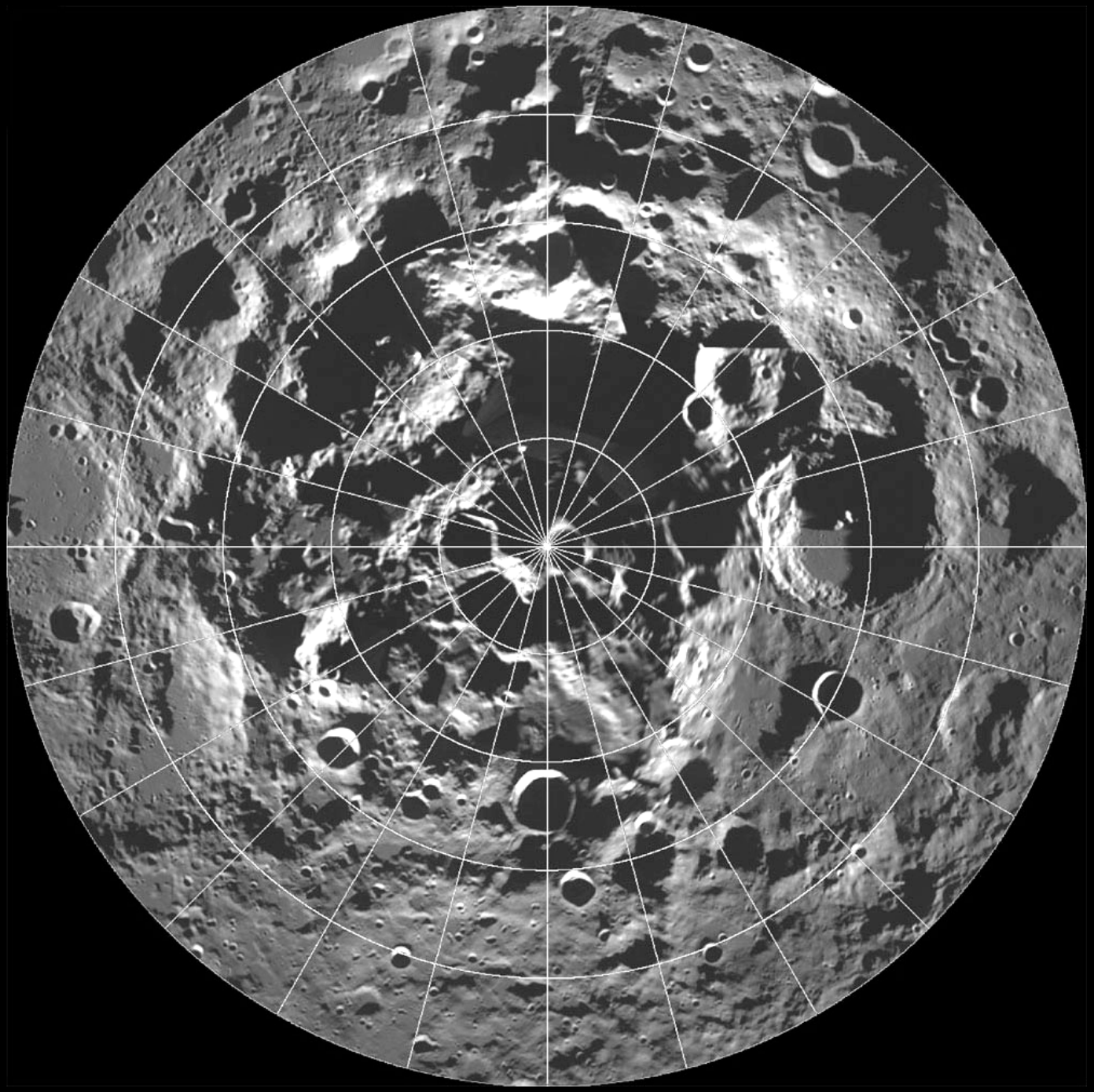
- Lunar spin axis nearly perpendicular to ecliptic
- Topography creates dark and sunlit areas
- At pole, any peak > 600 m in permanent sunlight
- any peak < 600 m in permanent darkness
- Required relief ~ 400 m per degree of latitude



North Pole



South Pole



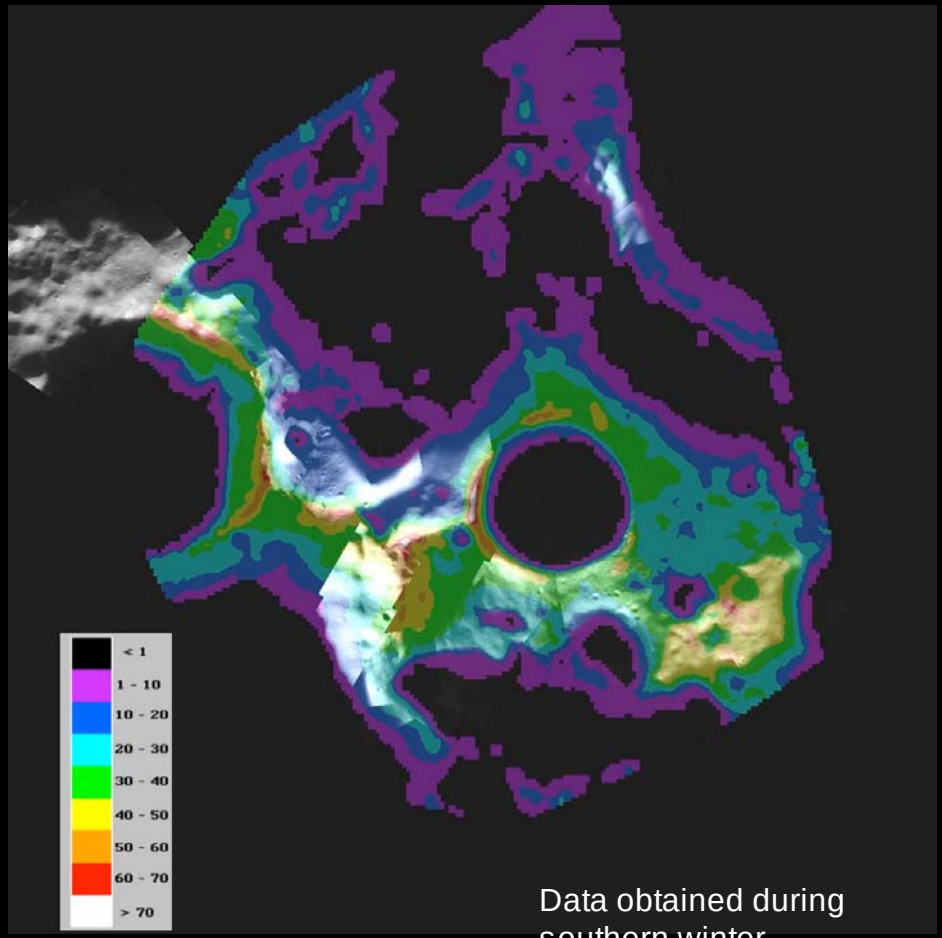
Permanent sunlight?

South Pole

Three areas identified with sunlight for more than 50% of lunar day

One zone receives 70% illumination during dead of southern winter

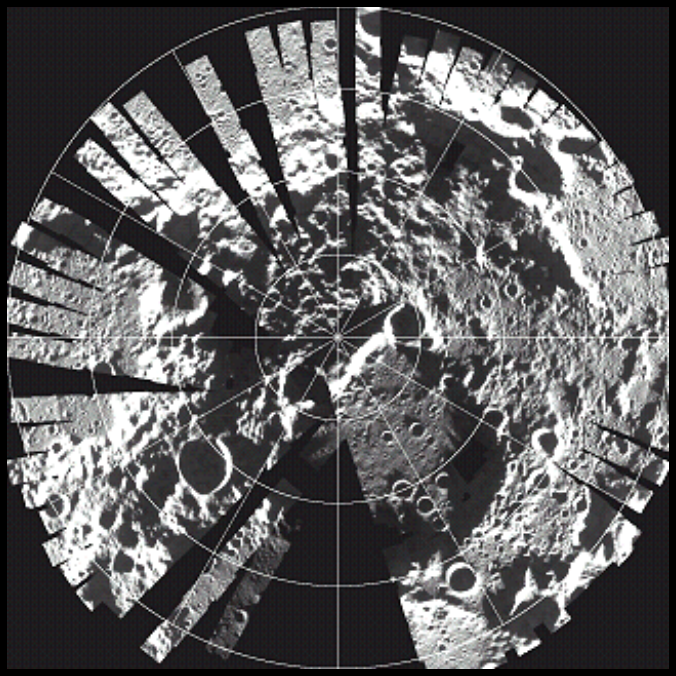
Lit areas in close proximity to permanent darkness (rim of Shackleton)

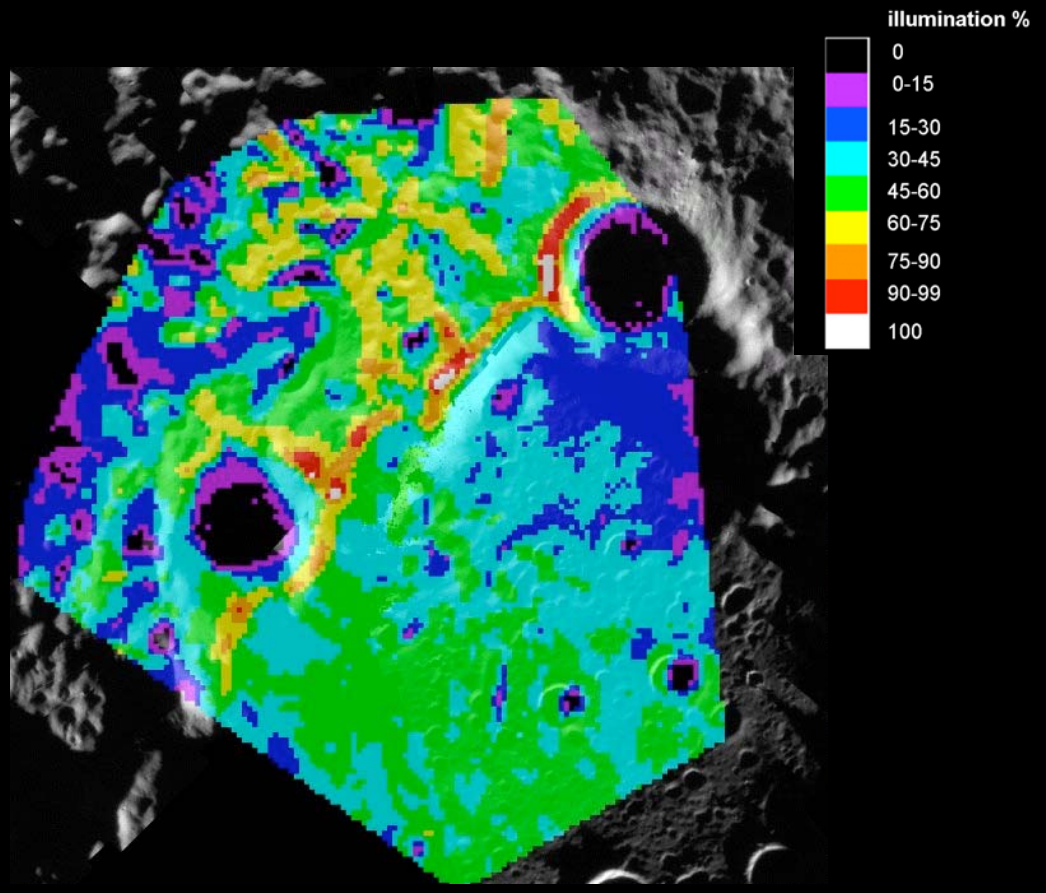


Data obtained during southern winter (maximum darkness)

Permanent sunlight?

North Pole

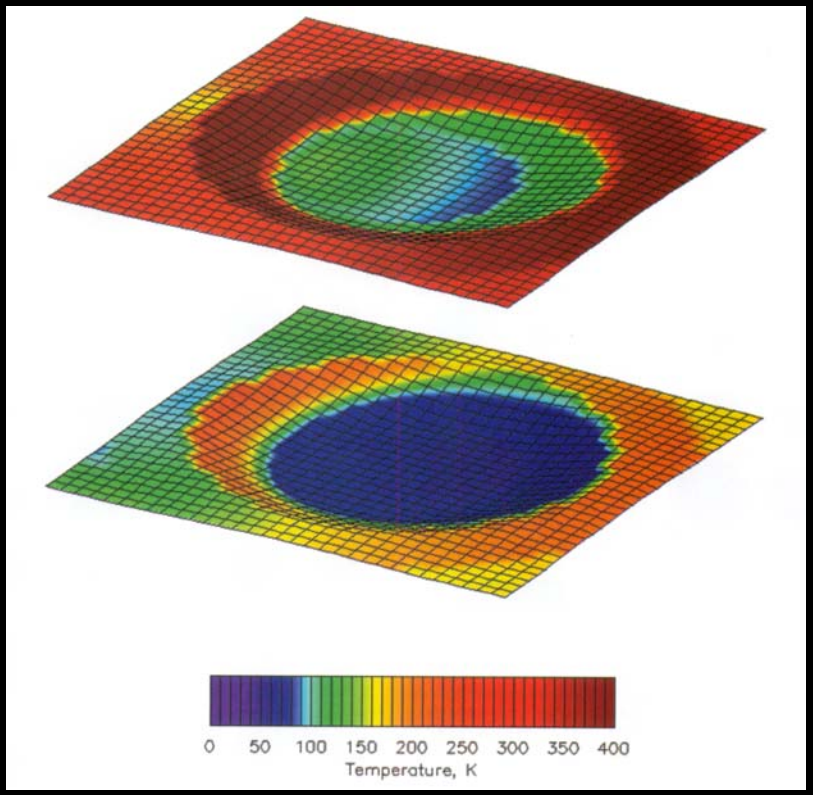


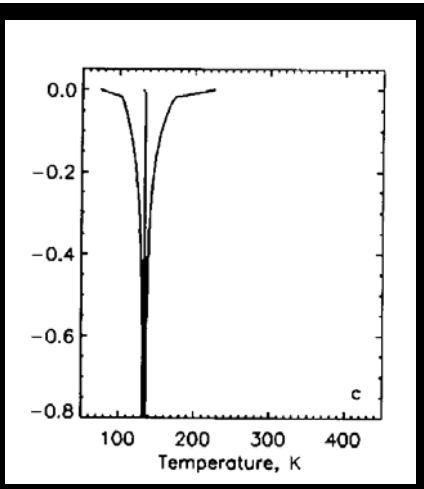


Data obtained during northern summer (maximum sunlight)

Polar Temperatures

- Permanently shadowed areas have very low model temperatures (~ 50-70 K) to act as cold traps (e.g. Vasavada, et al. 1999)
- Uncertainty largely a reflection of unknown value for heat flow of Moon
- Temperatures vary substantially in the shallow subsurface





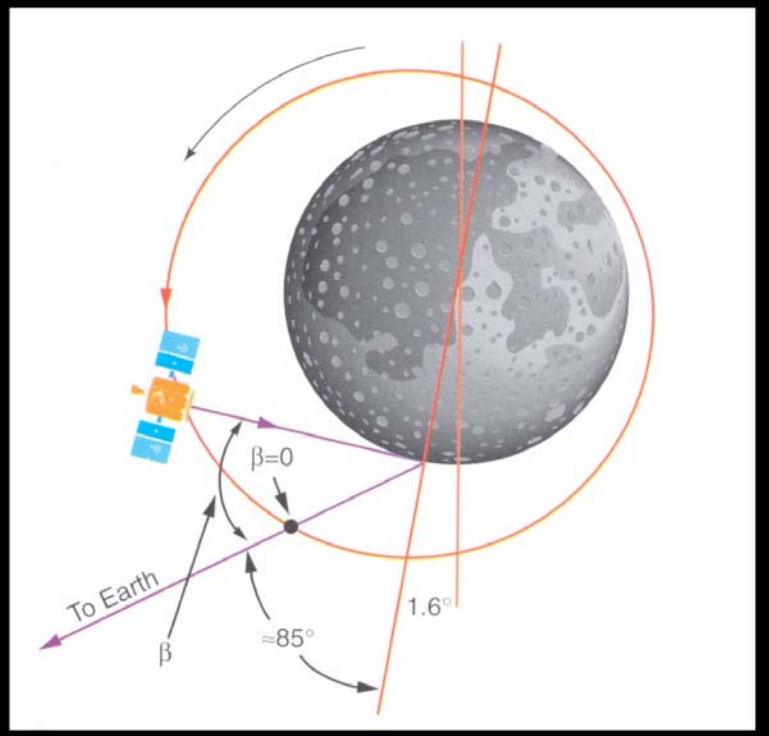
Clementine Bistatic Radar Experiment

Use RF transmitter of s/c as source of RCP CW radio; stare at pole continuously

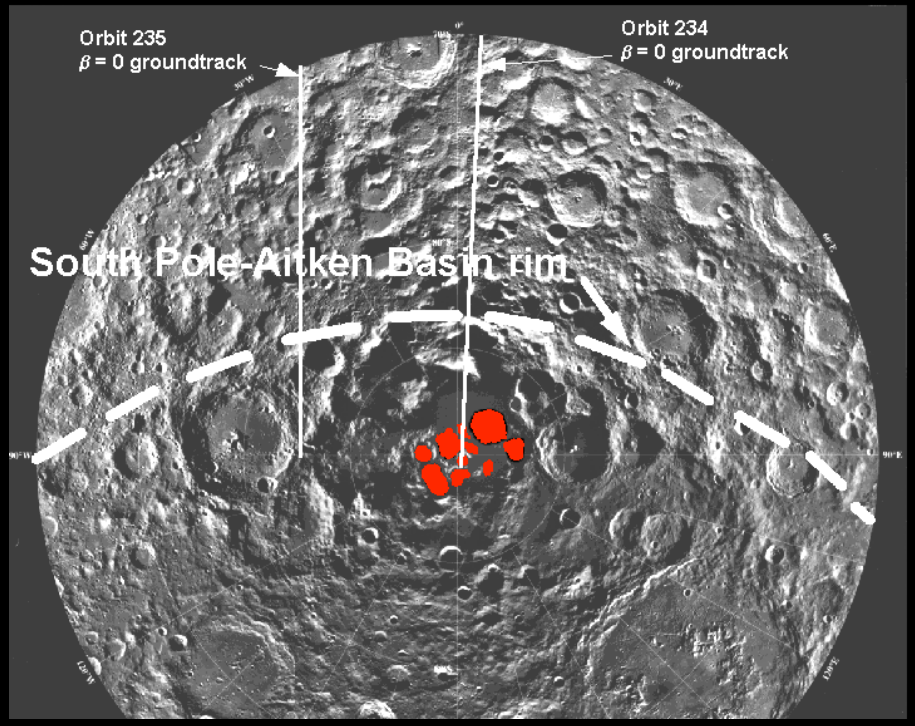
Listen to echoes on DSN in RCP and LCP

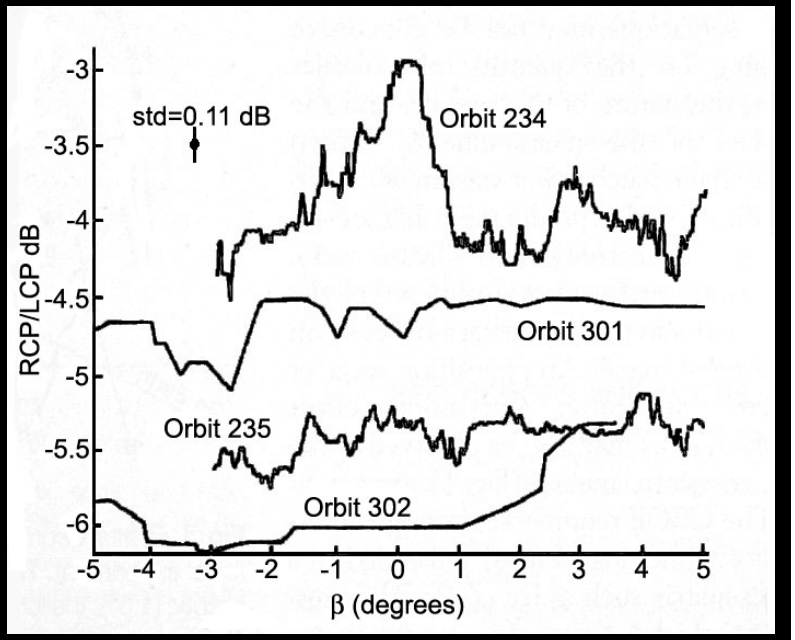
Observe reflection behavior through phase angle

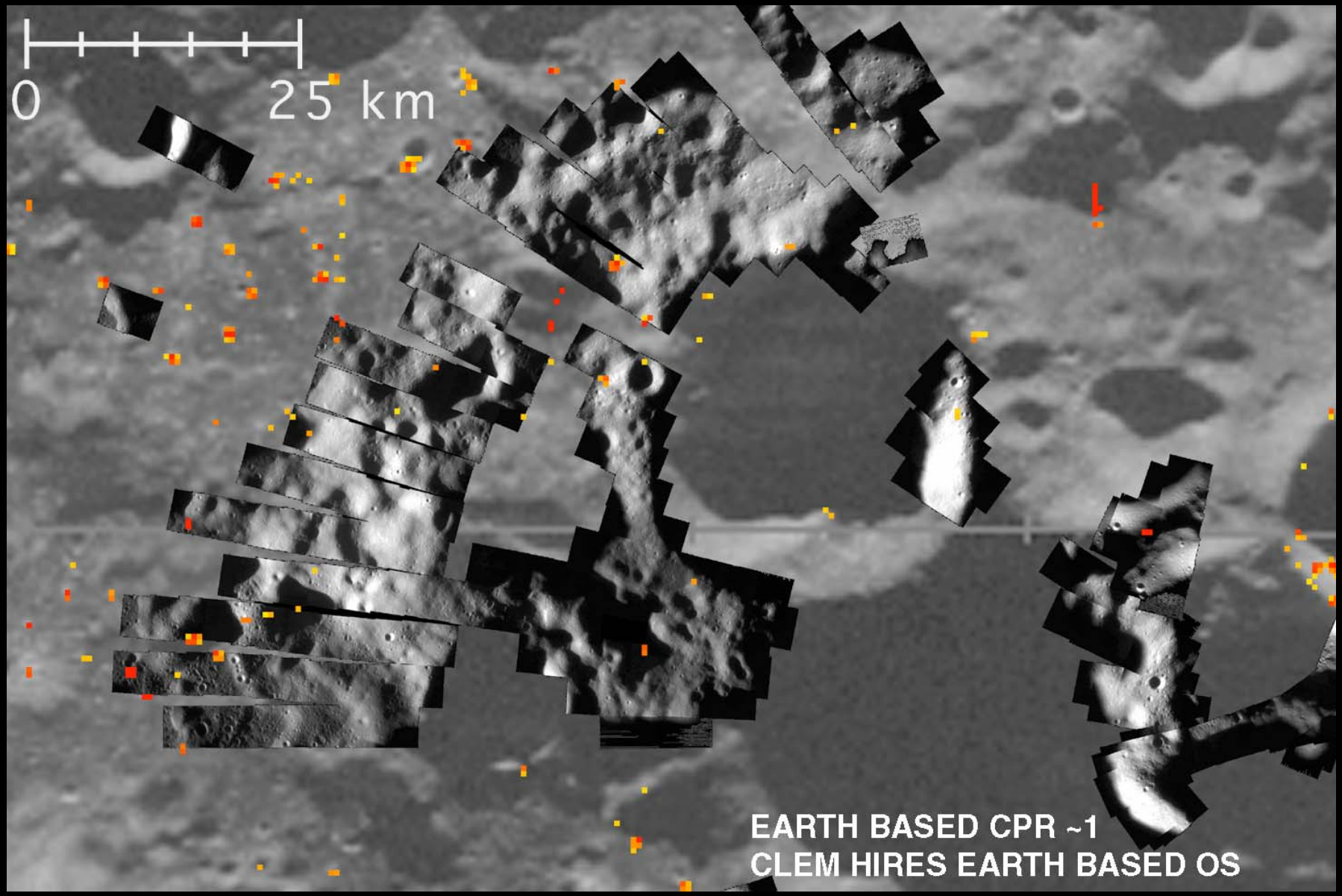
Get control from sun-illuminated groundtracks to compare with polar dark groundtracks

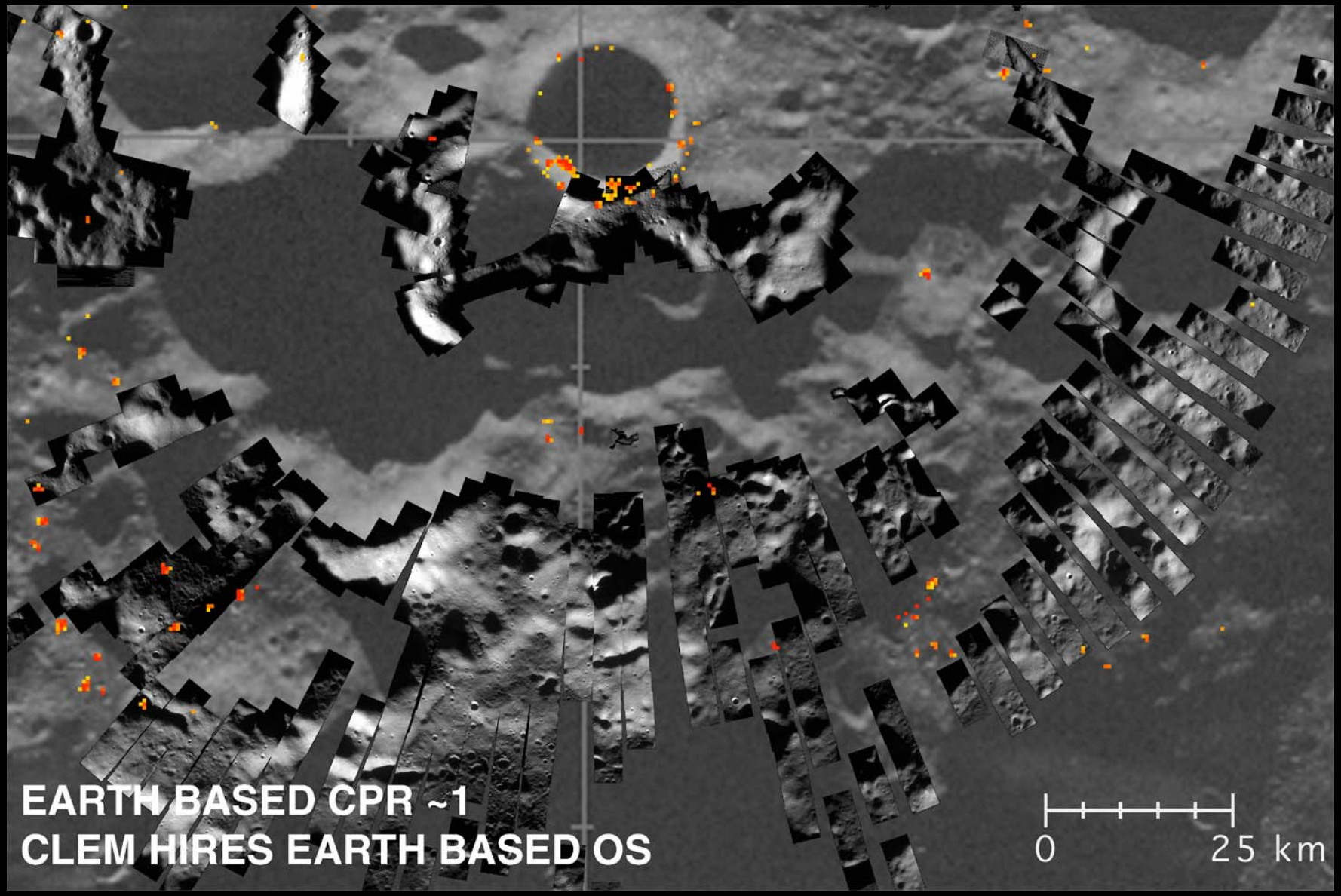


Clementine Bistatic Radar Experiment

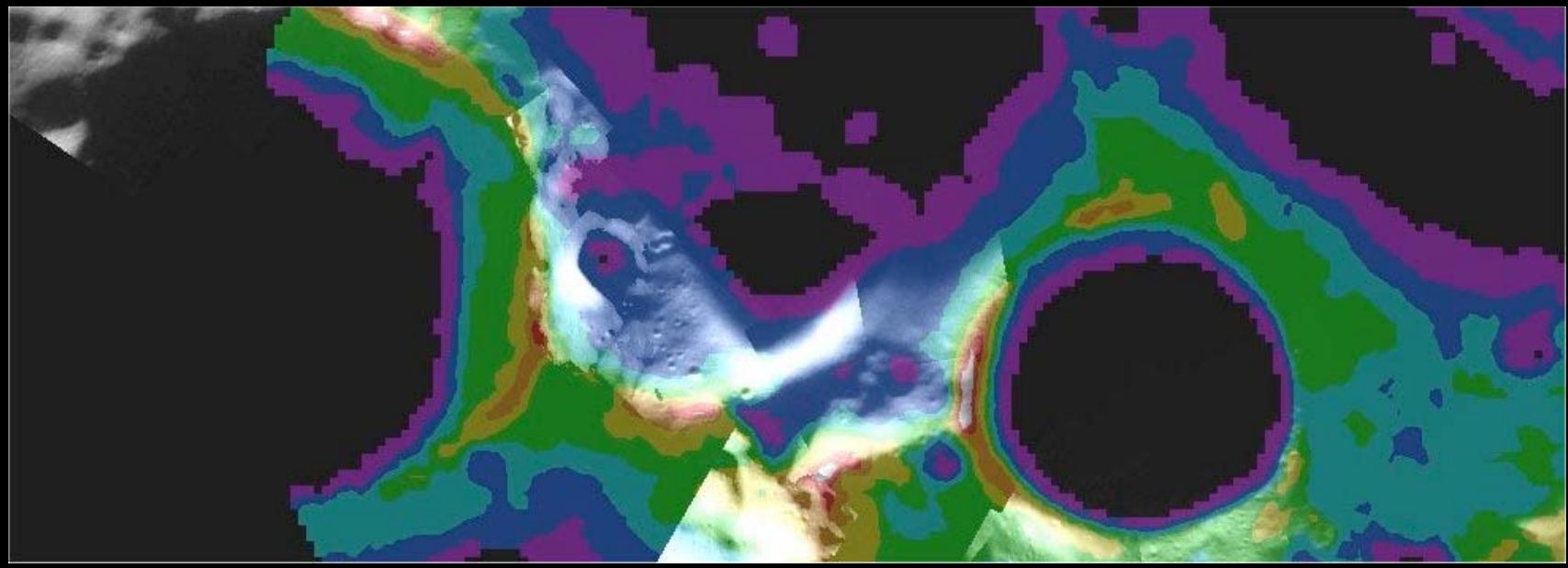




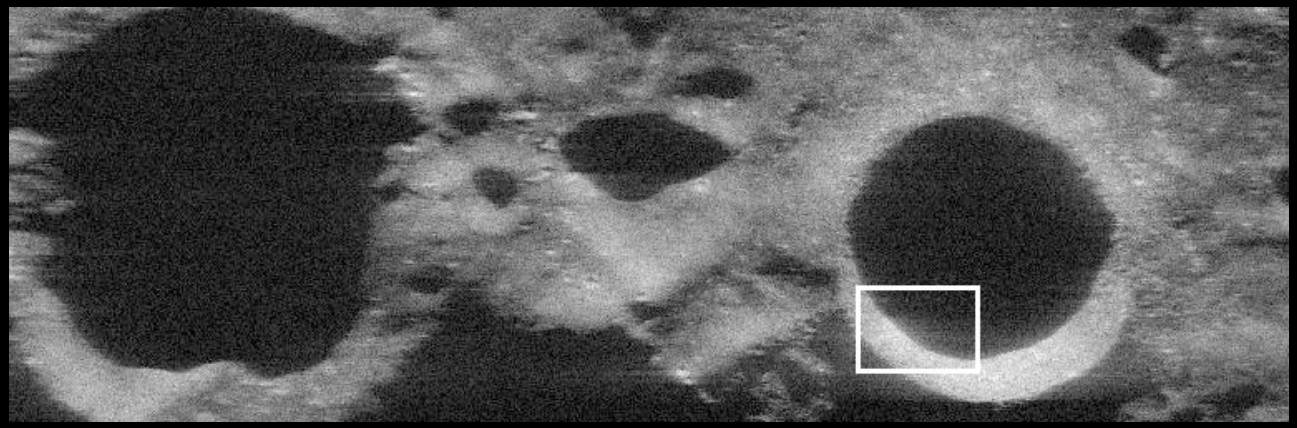

0
25 km
EARTH BASED CPR ~1
CLEM HIRES EARTH BASED OS


EARTH BASED CPR ~1
CLEM HIRES EARTH BASED OS
0
25 km

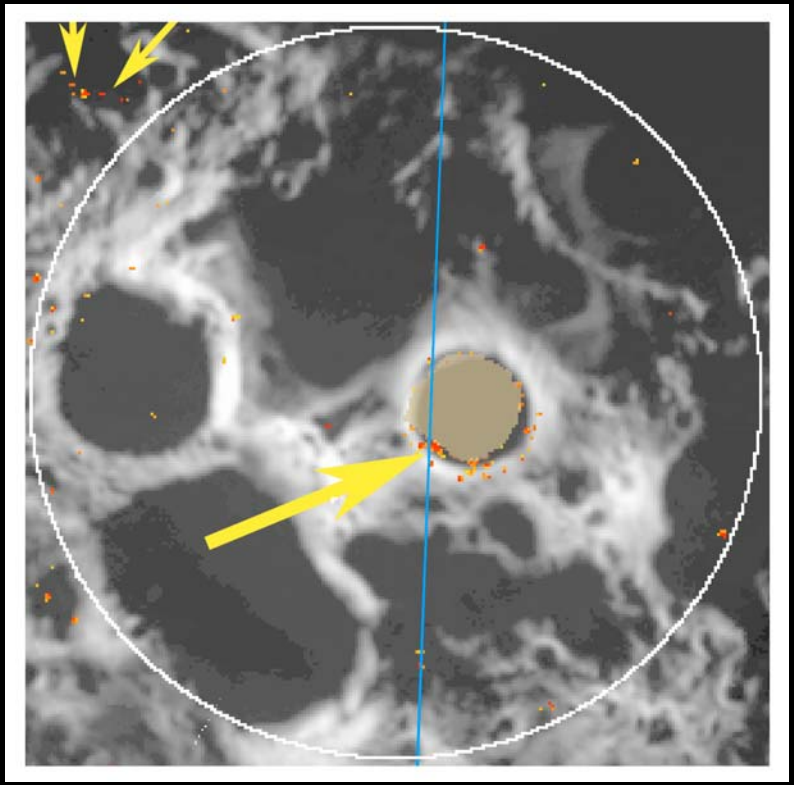
Goldstone bistatic “same sense polarization” image

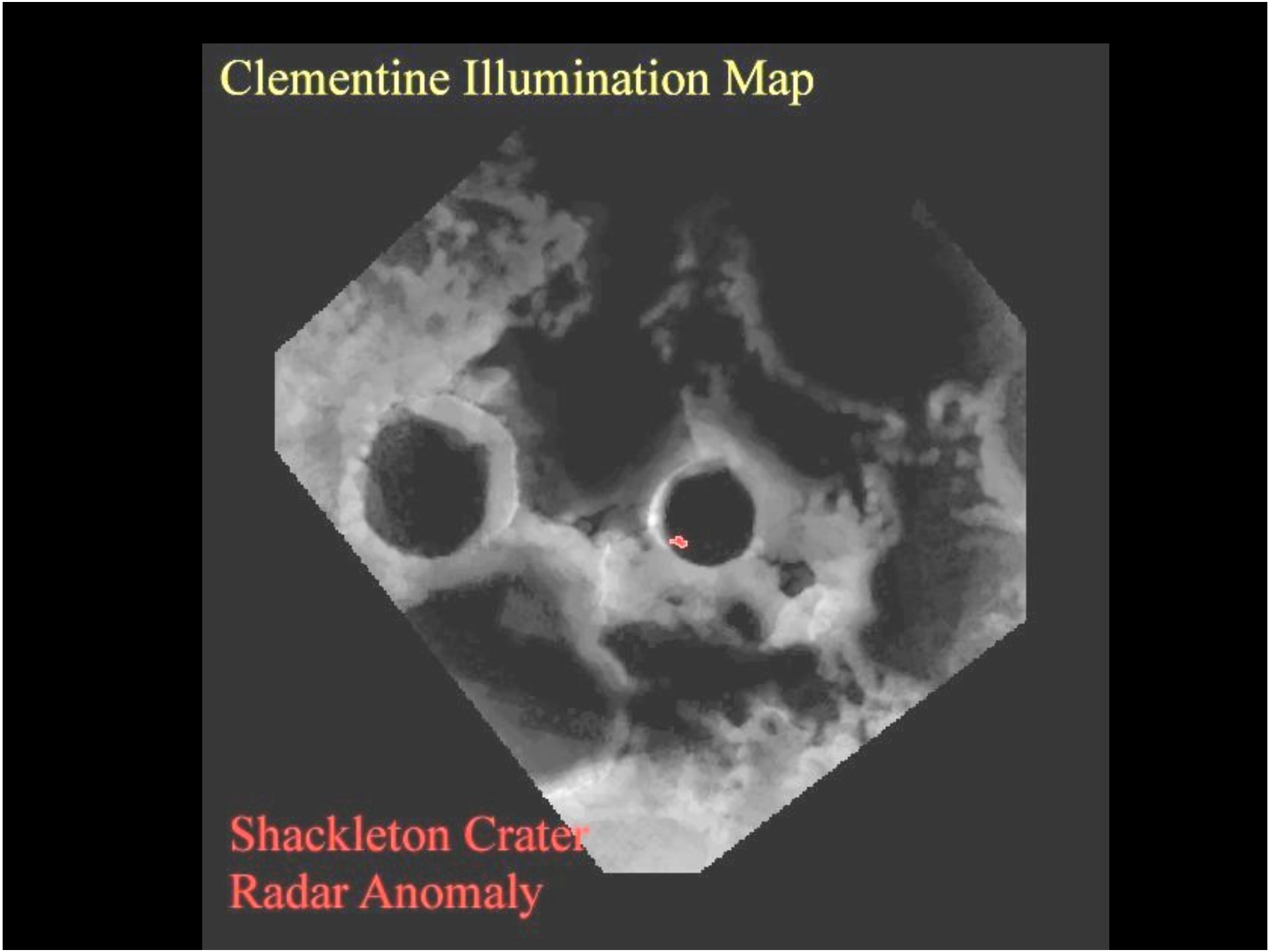


Clementine lighting map



- Goldstone new bistatic image shows enhanced same sense polarization (box)
- Clementine orbit 234 groundtrack (blue) passes directly through this anomaly
- Radar anomaly (red) occurs in sunlight dark region (gold) of crater Shackleton
- Likely patch of water ice




Clementine Illumination Map
Shackleton Crater
Radar Anomaly

Is there a discrepancy between Clementine and Arecibo Radar Results?

- Very high correlation of Clementine orbit 234 ß=0 track and high CPR areas observed by Arecibo within the dark regions of Shackleton
- Shadowed high CPR areas in Shackleton exceed minimum detection thresholds for Clementine BSR (1km^2) by factor of 10-20
- Inconclusive Earth-based radar measurements likely caused by poor viewing geometry, which allows limited access to shadowed areas at very high incidence angles (~ 85°); (Shackleton is an exception)
  - Geometry emphasizes surface texture over composition
  - Geometry accounts for the difficulties in interpretation of lunar v. Mercury polar ice data, probably not compositional difference
  - Clementine BSR Is Crucial to CBOE Interpretation

Radar Albedo and CPR

Water-ice radar signal:

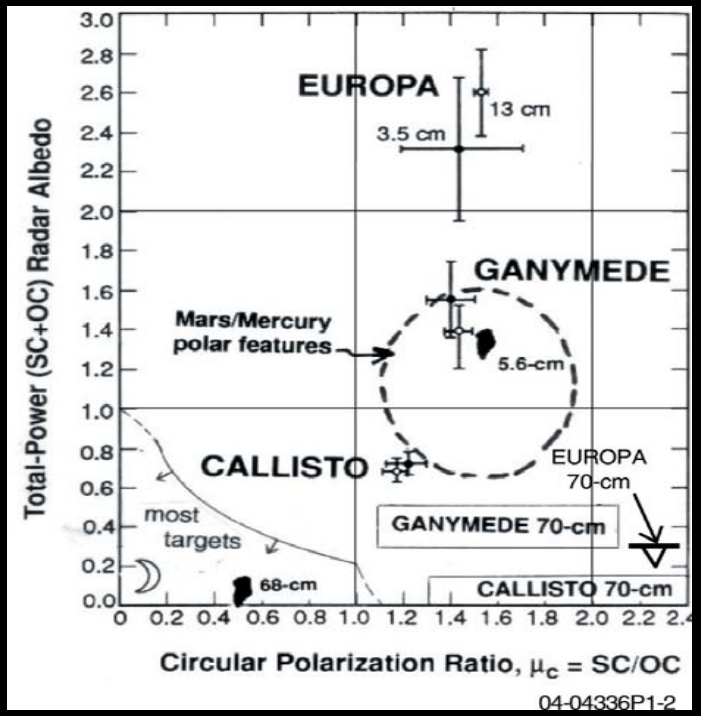
Albedo + CPR > 1.2

Implied requirements

- Transmit circular polarization
- Receive LCP *and* RCP

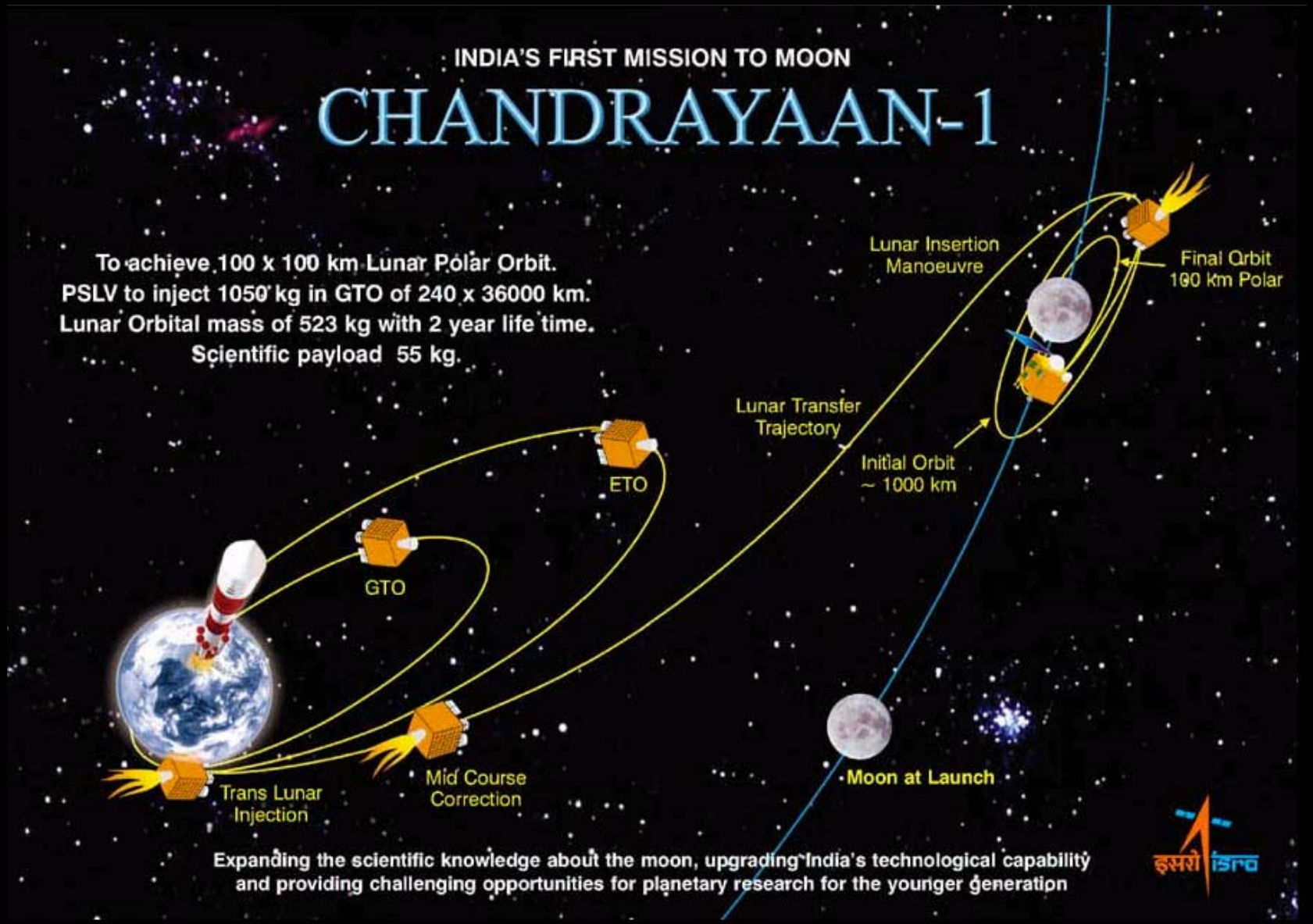
Expected variation on σ^0 -30 dB to +6 dB

Robustness: *Water-ice reflections must be clearly distinguishable from that of "most targets"*



Chandrayaan Mission Overview

- Polar orbiting lunar satellite
- Launch September, 2007; Two year mapping cycle
- Global maps of topography and composition
  - Laser altimeter
  - Hyperspectral imager (64 channels between 400-900 nm)
  - X-ray fluorescence spectrometers
  - Terrain Mapping Camera
- Invited proposals for foreign participation, Jan. 2004
  - Instrument must fit within 10 kg mass allocation
  - Over 20 proposals received, short-listed to 5 in June, 2004
  - Announcement that all 5 short-listed instruments would fly at International Lunar Conference 6 in Udaipur, November 2004
  - Selected foreign instruments:
    - Mini-RF (USA)
    - Solar wind spectrometer (Bulgaria)
    - Magnetometer (Sweden)
    - Near-IR spectrometer (900-2800 nm) (Germany)
    - X-ray imager (UK)


INDIA'S FIRST MISSION TO MOON
CHANDRAYAAN-1
To achieve 100 x 100 km Lunar Polar Orbit.
PSLV to inject 1050 kg in GTO of 240 x 36000 km.
Lunar Orbital mass of 523 kg with 2 year life time.
Scientific payload 55 kg.
Lunar Insertion Manoeuvre
Final Orbit 100 km Polar
Lunar Transfer Trajectory
Initial Orbit ~ 1000 km
ETO
GTO
Trans Lunar Injection
Mid Course Correction
Moon at Launch
Expanding the scientific knowledge about the moon, upgrading India's technological capability and providing challenging opportunities for planetary research for the younger generation
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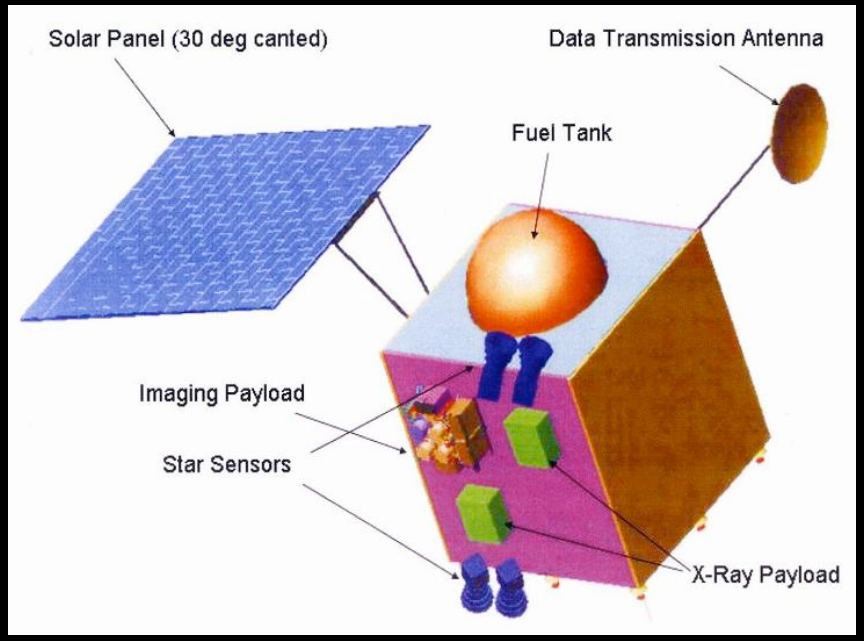
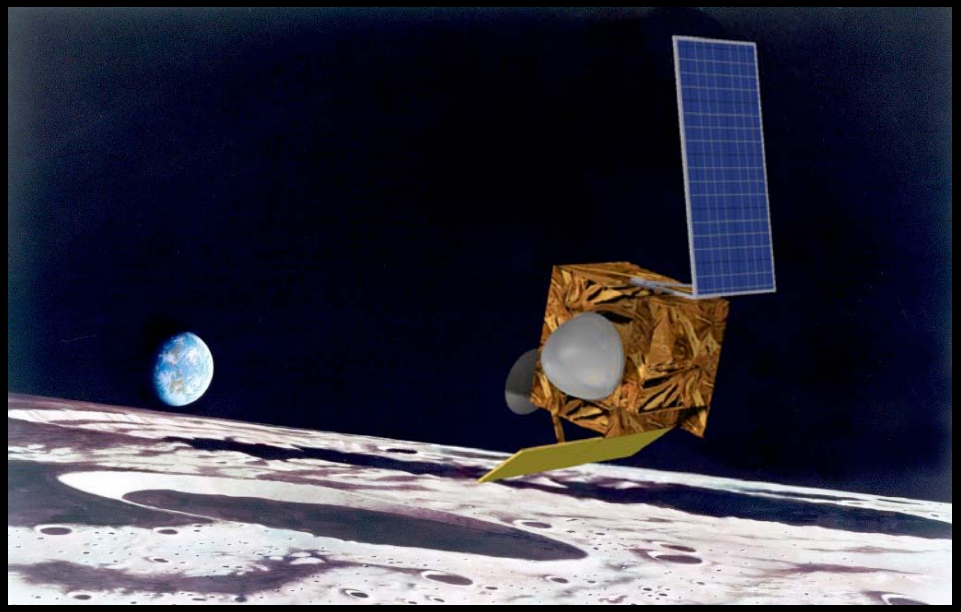
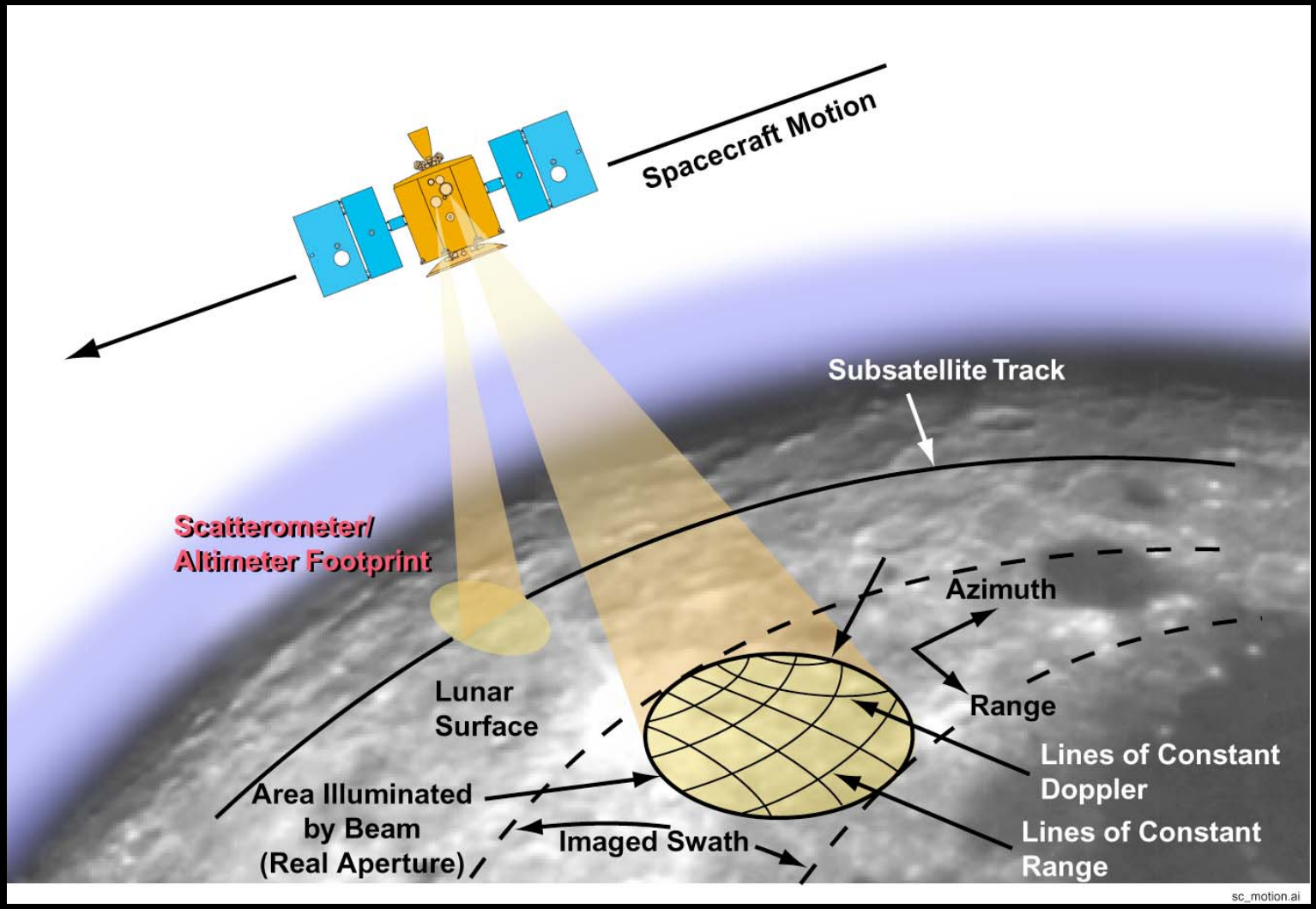
Chandrayaan Spacecraft





Spacecraft – 3-axis stabilized
  mass – 524 kg
  size – 1.5 m, cuboid
Orbit – 100 km, circular, polar
Payload mass – 55 kg + 10 kg of contributed international instruments
Mission duration – 2 years
Comm – S-band telemetry, downlink
  X-band payload data

Imaging Modes



Mini-RF Objectives

Differentiate potential water-ice from lunar regolith

Transmit **circular polarization,** ***receive*** **same-sense and opposite-sense polarizations**

Nominal incidence 45^{o} to preserve responsiveness to various ice-regolith ratios

Minimize false indications of anomalous reflectivity
Weak backscatter -27 dB (Stacy, Campbell & Ford 1997)

Map water-ice deposits

Radar image maps (from 80^{o} poleward), N & S

Resolution (*pixel*): 150 m (*75 m*), range and azimuth
ref: NASA LRO ORDT (2004) recommendation

Drives geolocation accuracy; Multi-look imagery

Left-looking and right-looking aspect, N & S

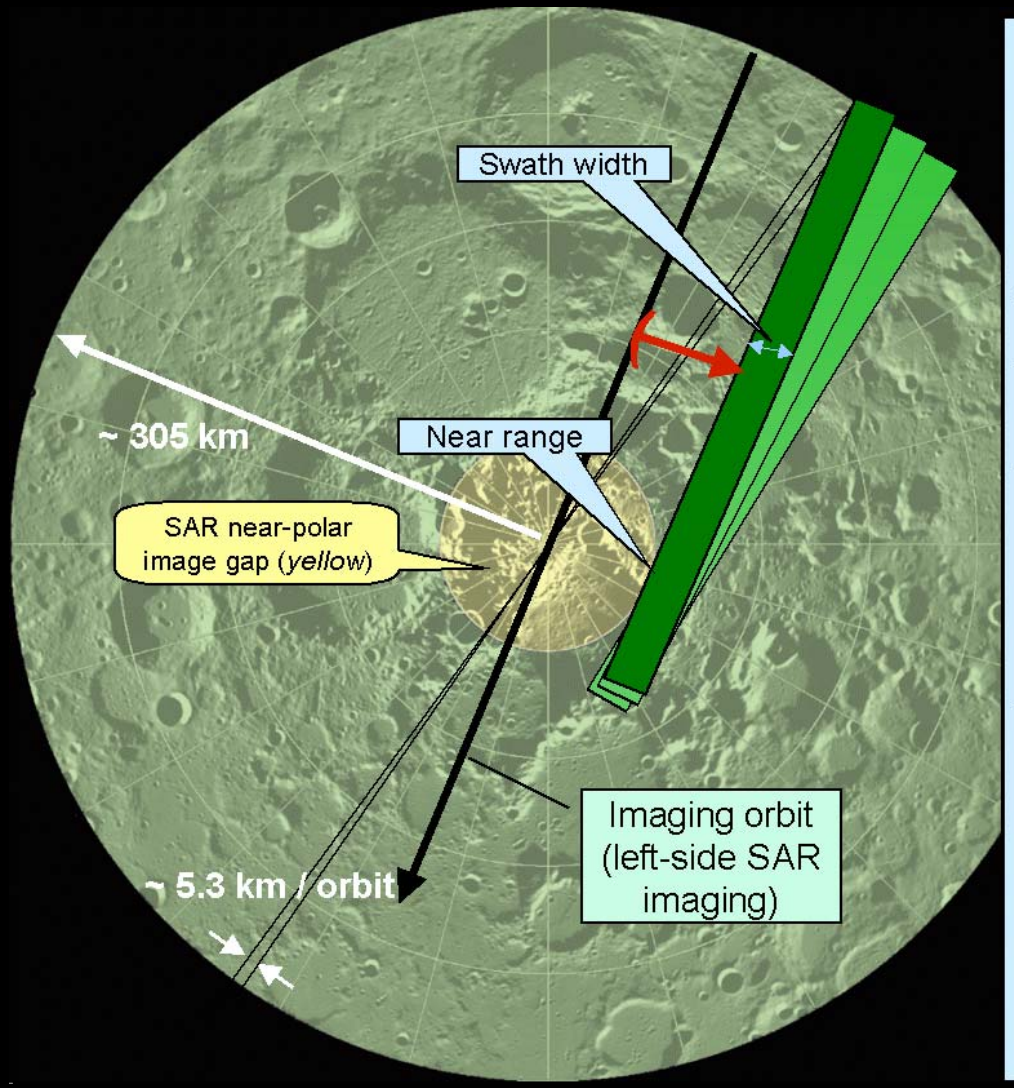
Full coverage: Terrain & altitude height tolerance

Nadir-viewing radar (scatterometer)

Top Level Radar Requirements

Parameter	Requirement	Comment
• Frequency	S-band	*Penetrates regolith*
• Polarization	*Tx* Circular	
	Rx RCP & LCP	*Relative & absolute calibration*
• Imager: Strip maps		
– Poleward of 80°	N & S , 2 image sets	*1 Left-looking, 1 Right-looking* *Full coverage*
• Scatterometer	S-band	*Reflectivity profiles along track*
• Height tolerance		
– Terrain	+ 3 km, - 6 km	*Mean, > 100-km scale*
	± 3 km	*Local, < 100-km scale*
– Altitude	100 km ± 20 km	*Primary objectives*
	50 km ± 20 km	*Secondary objective (bistatic)*
• Geolocation	± 100 m	

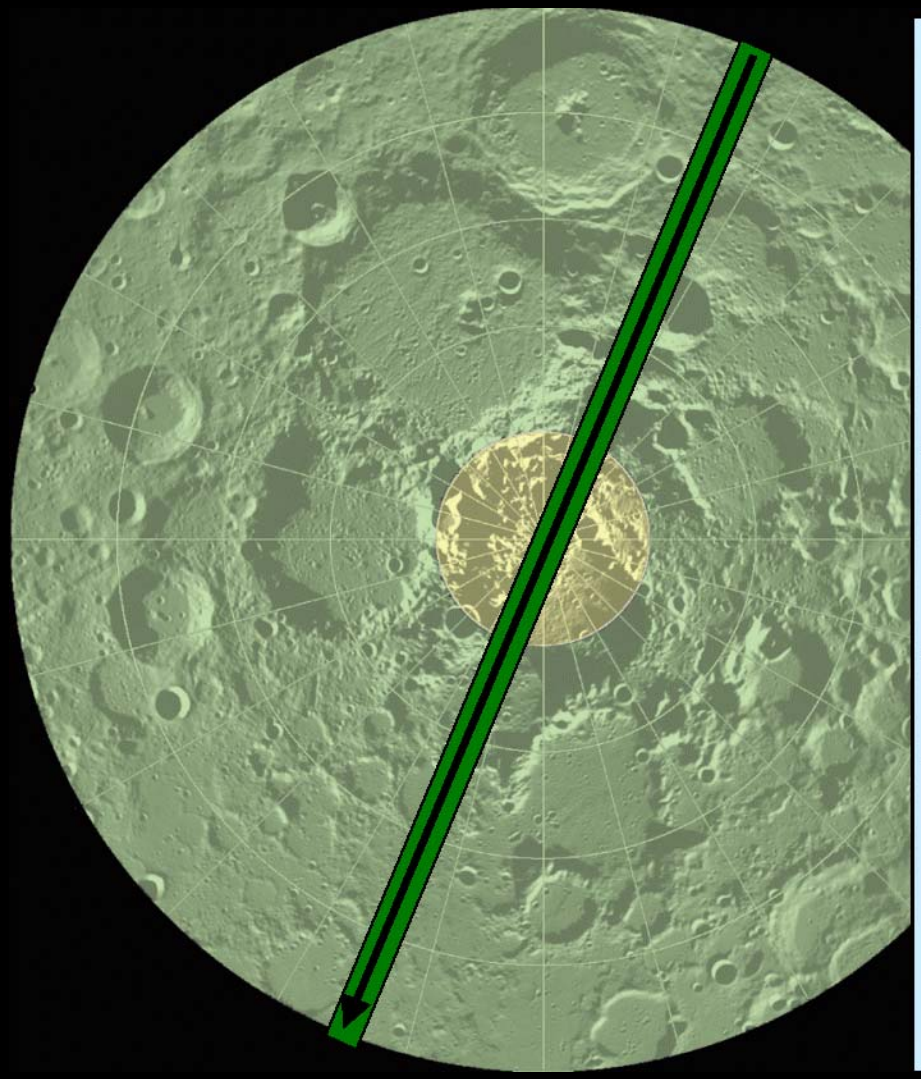
Mapping Strategy - SAR



SAR Coverage

- Sequential **strip maps**
- **Mosaic** assembled from ~180 strips (~28 days)
- **Swath width** minimum:
  2 x orbit-to-orbit precession
  10.6 km + margin =>
  12 km
- **Near-pole** minimum:
  Limited by incidence & altitude from a given orbit plane *implies near-polar image* ***gap***

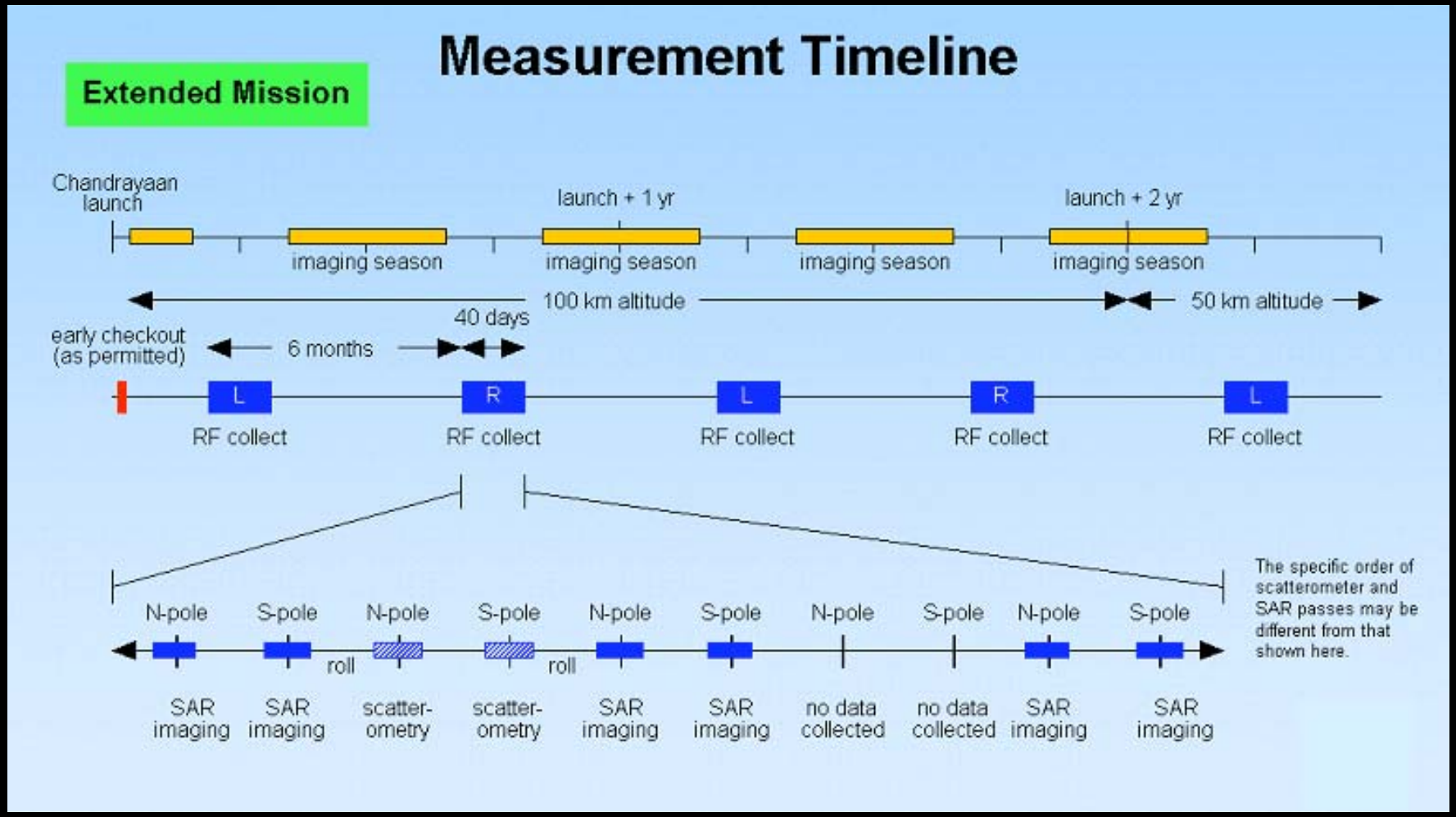
Mapping Strategy - Scatterometry



Scatterometer Coverage

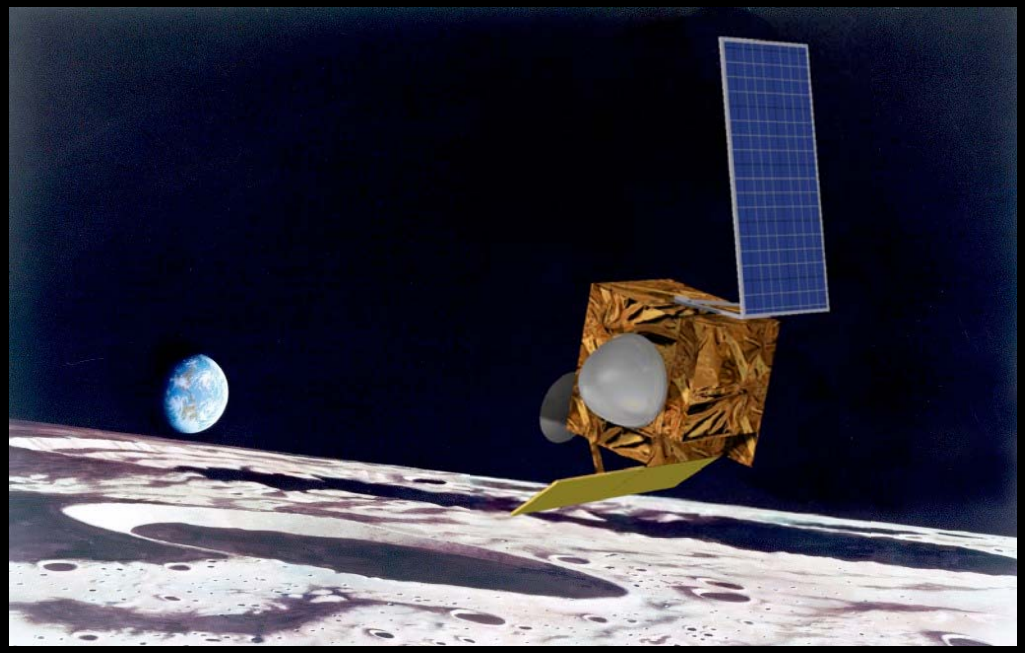
- Nadir-viewing: generates **reflectivity (power) profiles**
- **80° to 80°**, alternate orbits
- **Scatterometer mosaics** assembled from ~90 strips (~14 days)
- Effective **width of footprint** "pulse-limited" ~ 10 km
- Dense nadir coverage (at low resolution) at all latitudes polewards of 80°

Operational Strategy



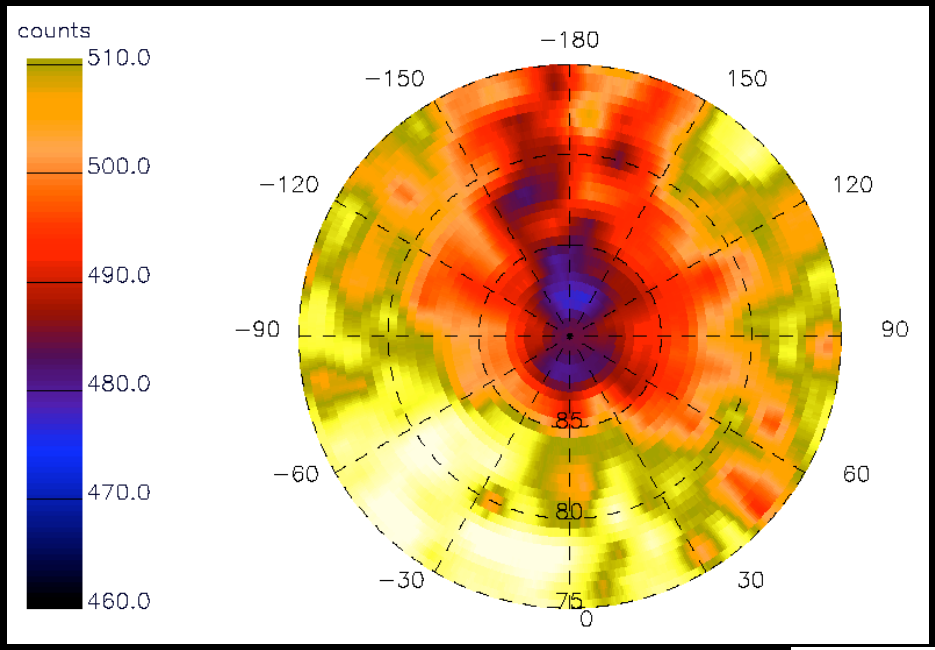
Mini-RF Physical Characteristics

Item	Units	Value
Physical Properties		
Antenna		
Size	m	0.6 (W) x 1.8 (L) x 0.05 (H)
Mass	kg	1.8 ± 0.2
Radar Electronics		
Size	cm	17 (L) x 17 (W) x 10 (H)
Mass	kg	3.1 ± 0.4
Interface/Interconnecting components/cabling		
Mass	kg	0.9 ± 0.1



Lunar Prospector results

- Neutron Spectrometer detected significant H_2 concentrations near both poles
- Highest resolution data (15 km) strongly correlates with permanent shadow, as mapped on Clementine mosaics and modeled for small craters
- Fast neutron data show no significant H_2 content; implies that ice is not present at surface, but may occur at depths below a few cm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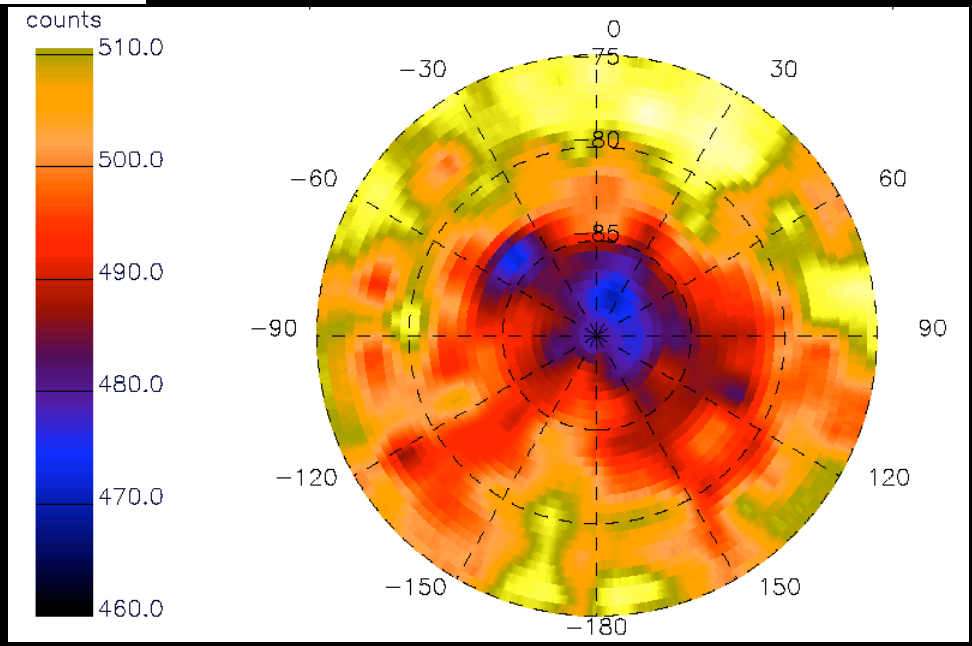
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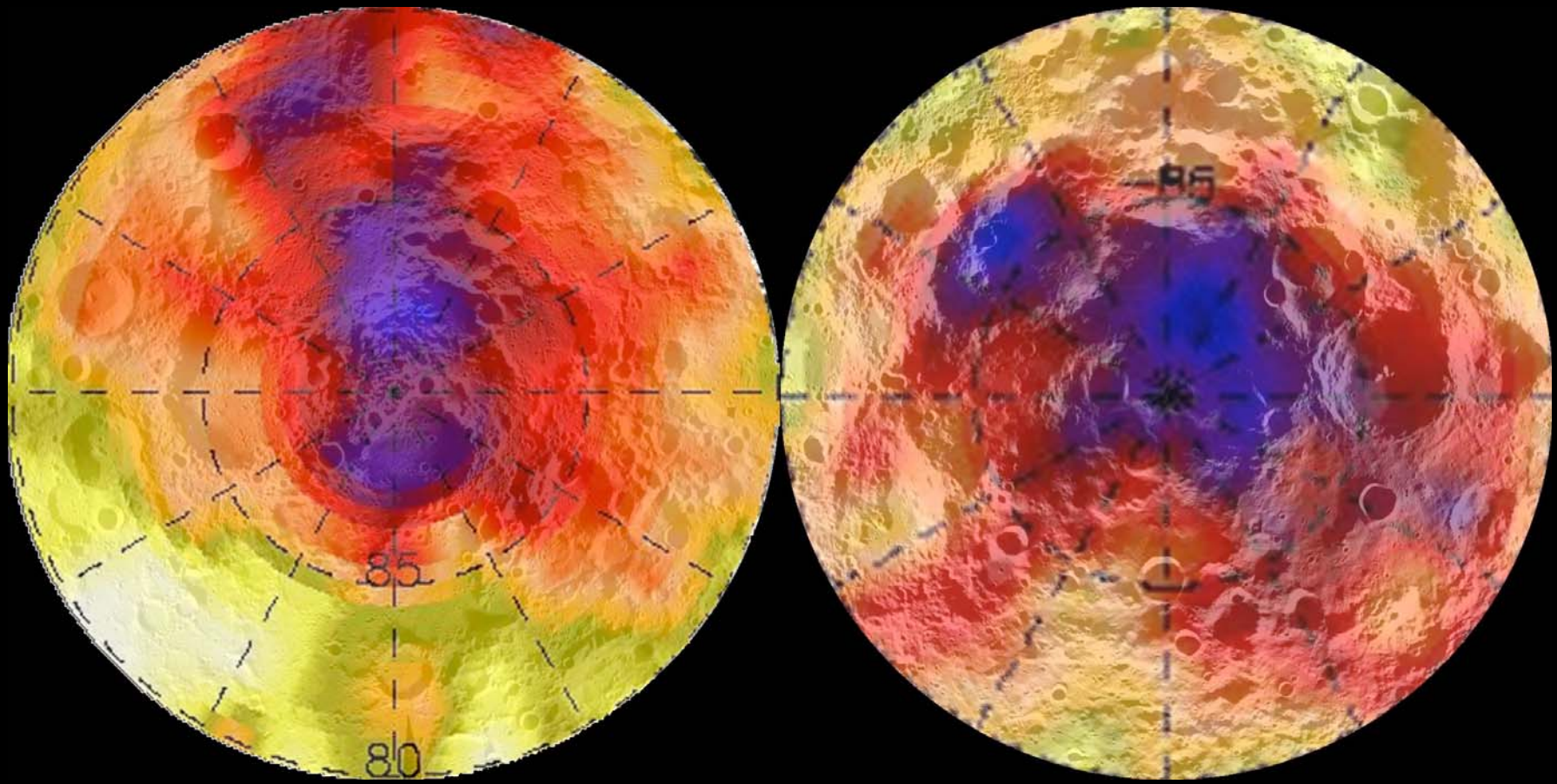
90
−120
120
−150
150
−180

Lunar Prospector NS data



Composition of Polar Volatile Deposits

We do not have solid data on composition of polar volatile deposits

Best guess is that they are dominated by gases from comets. For example, in Hale Bopp:

H_2O: 100	CO_2: 6
CO: 20	NH_3: 0.7
CH_3OH: 2	CH_4: 0.6

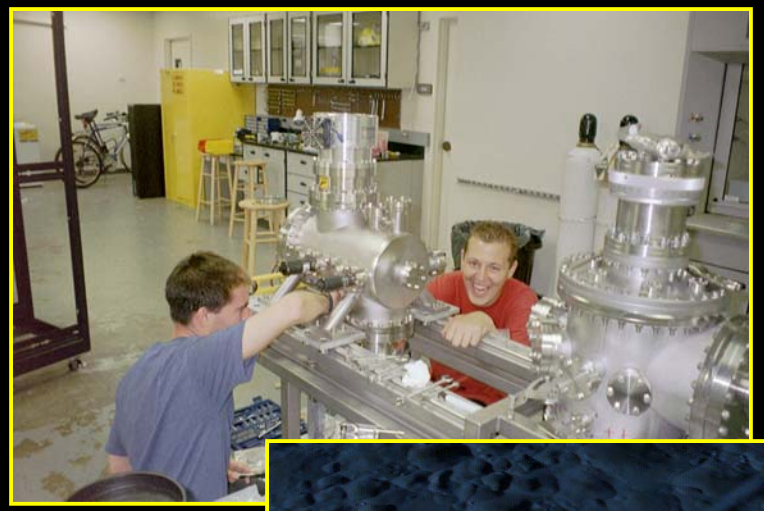
Addition of solar wind gases, fluctuations in temperature, and micrometeorite impacts allows for possibility of chemical reactions to form organic compounds.

Temperature in cold traps might range from 25 K to 125 K, depending on how much reflected sunlight and radiated heat.

Extracting Volatiles

We do not know:

- Full inventory of trapped ice.
- Composition of ice
- Compositional variability in ice composition
- State of volatiles (ices, amorphous compounds, separate phases, clathrates)
- Distribution with depth
- How it binds soil grains
- Whether it reacts with soil grains
- Geotechnical properties of ice-bearing regolith



In principle, we can address these issues by experiments or lunar surface missions.

Determining the Inventory of Polar Volatiles

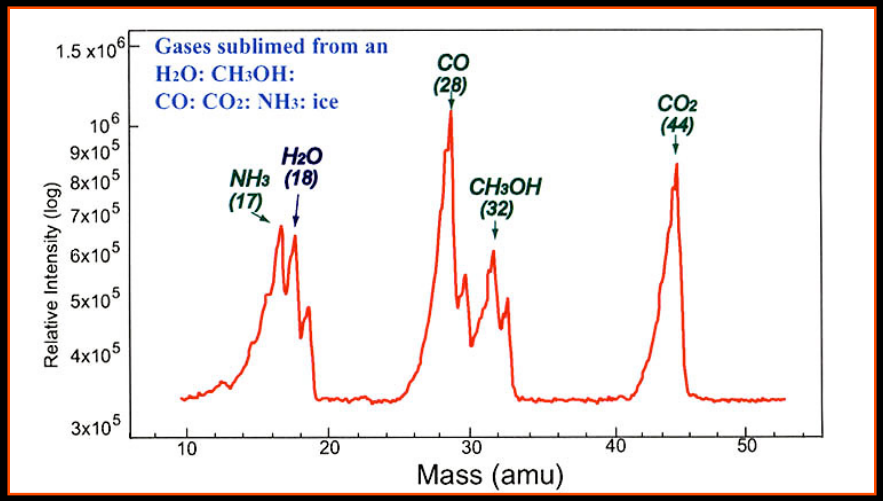
Need orbital and *in situ* measurements

Orbital:

- Map temperatures on surface
- Determine all permanently shadowed locations (imaging)
- Map ice concentrations and distributions with imaging radar
- Obtain H concentrations at higher spatial resolution
- Map topography of permanently shadowed regions

In situ:

- Determine nature of ice: chemical composition, structure
- Measure geotechnical properties of ice-bearing regolith



Orbital and landed missions

The Poles of the Moon

- From the radar mapping, we will locate probable deposits of water ice and estimate their extent
- We then need to land on these deposits to characterize the chemical and physical state of the ice
- The lunar poles offer areas of terrain that are illuminated for extended periods and possess a benign thermal environment
- They also offer permanently dark regions that contain trapped volatiles, which can be mined to support a lunar base
- Thus, as accessible and viable footholds on our nearest planetary neighbor, the poles of the Moon are the most valuable pieces of real estate in the Solar System

The Value of Lunar Resources

- Volatiles at the poles of the Moon can be easily processed to make hydrogen and oxygen for use on the Moon and for export to Earth-Moon (cislunar) space
- Propellant produced on the Moon can make travel within and through cislunar space routine
- This eventuality will completely change the spaceflight paradigm
- Routine access to cislunar space has important national economic and strategic implications