VORTICES SSERVI Team Summary

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SSERVI: *VORTICES*

Volatile Regolith Thermal Investigations Consortium for Exploration & Science

Expand our understanding of the life cycle of volatiles and planetary regoliths as well as their interaction

- Major Research Themes
- Volatiles
  - Sources, Processes, and Sinks
- Regolith
  - Origin and Evolution on Airless Bodies
- Exploration
  - Resources: Identification and Exploitation
  - Filling Strategic Knowledge Gaps

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VOlatile Regolith Thermal Investigations Consortium for Exploration & Science

The Team

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The Team

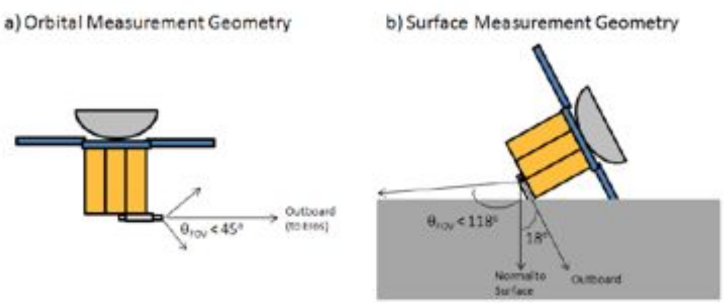
Volatile Species, Migration, Evolution

- What are the volatiles on the Moon, Asteroids, Phobos and Deimos?
- What is the origin of the volatiles?
- How do the volatiles move across and interact with the surface?
- What is the ultimate fate of the volatiles?
  - Destroyed, or a potential resource?

What are the volatiles on the Moon, Asteroids, Phobos and Deimos?

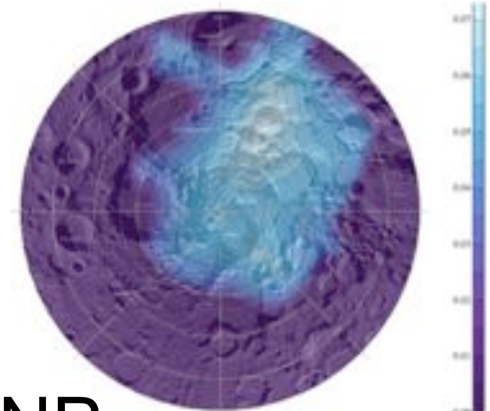
- Understanding the inventory relies on remote sensing (spectral, particle interactions)
  - Neutron
    - Lunar Prospector
    - Lunar Reconnaissance Orbiter
    - DAWN
  - Continue enhanced model development incorporating additional data sets.

- NEAR gamma-ray may provide indirect measure of H concentration



NEAR Orbital and Landed Geometry

H concentration



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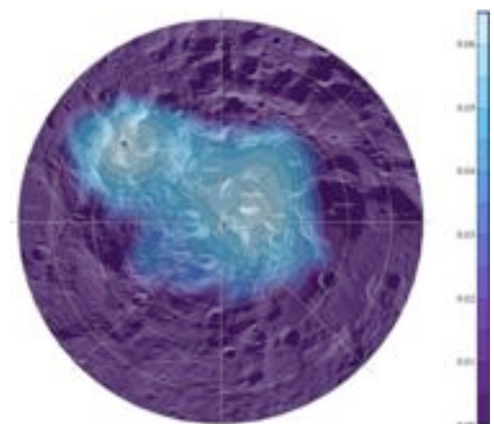
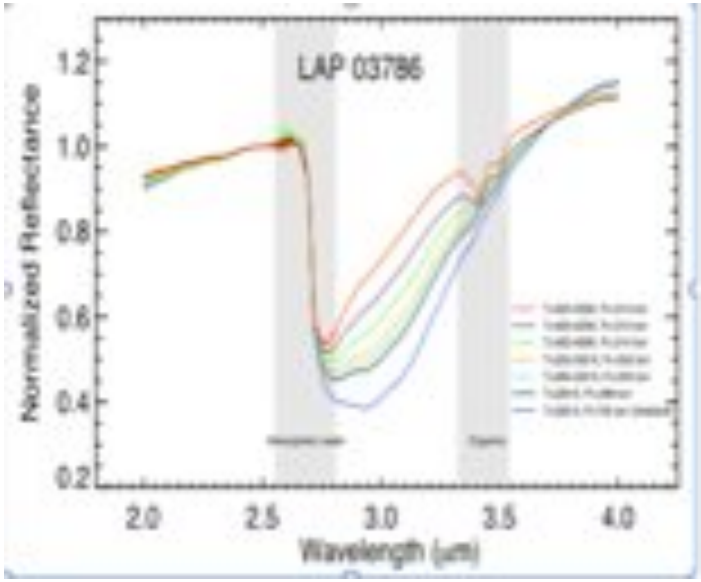


SP

Spectral Characterization of Volatile Species Interaction

Measure hydration band in anhydrous materials

- OH/H_2O being discovered in “unexpected” places
  - Impactor contamination (Vesta?)
  - Solar wind created (Moon?)
  - Reinterpret body history
  - (Moon? Eros?)
- Spectral libraries usually contain non-optimized data in 3-μm region
  - Affected by terrestrial water (see next slide)
- *Take new measurements of anhydrous materials (olivine/pyroxene/HED/etc.) through heating sequence to get “water free” spectrum for mixture modeling*

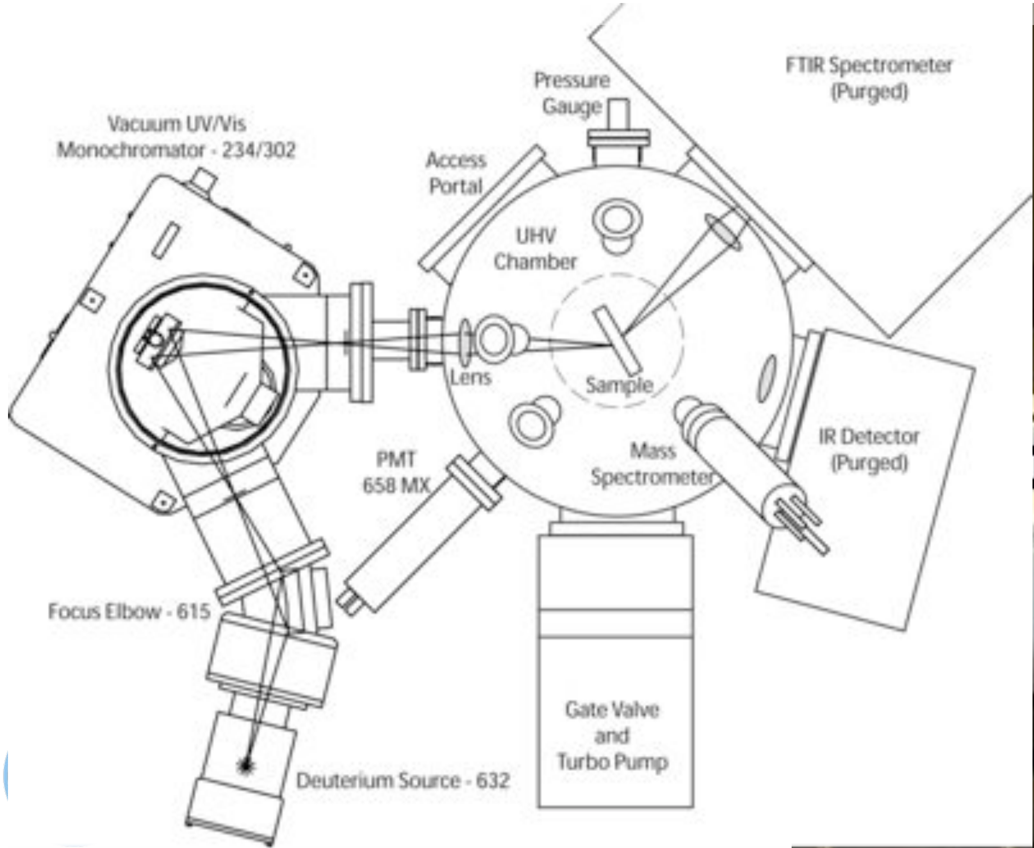


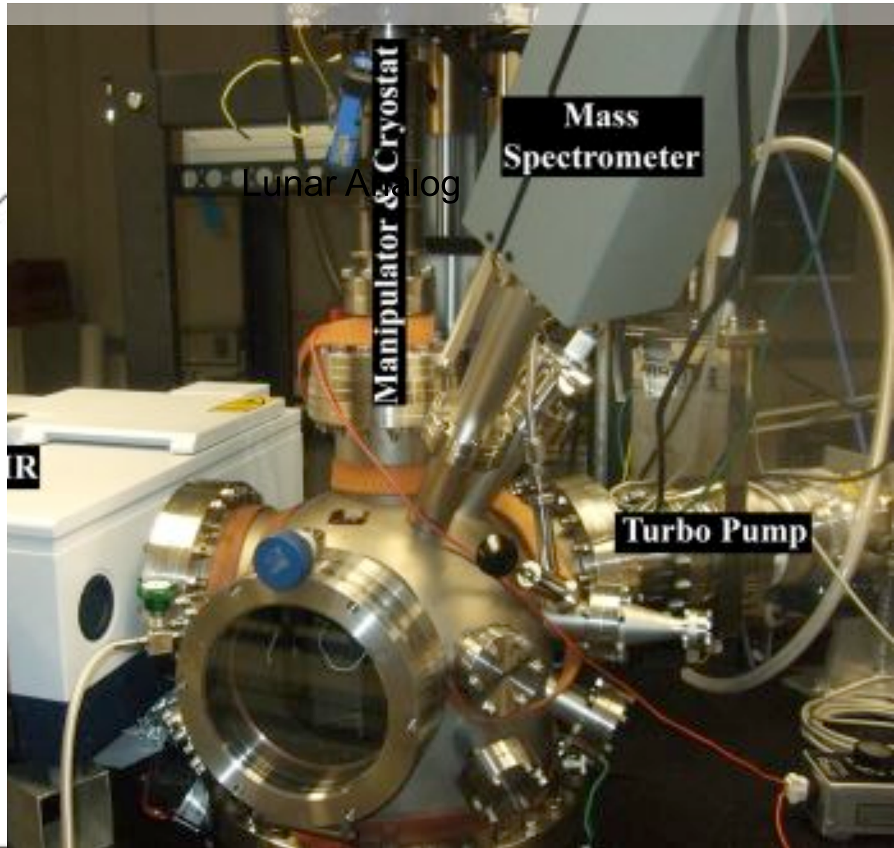
As material is heated, adsorbed H2O is removed. This spectrum, taken in the APL spectral lab by Takir et al. uses a carbonaceous chondrite with native OH. We will use anhydrous materials.

Volatile-Regolith Studies

NLSI Lunar Polar Science & Exploration

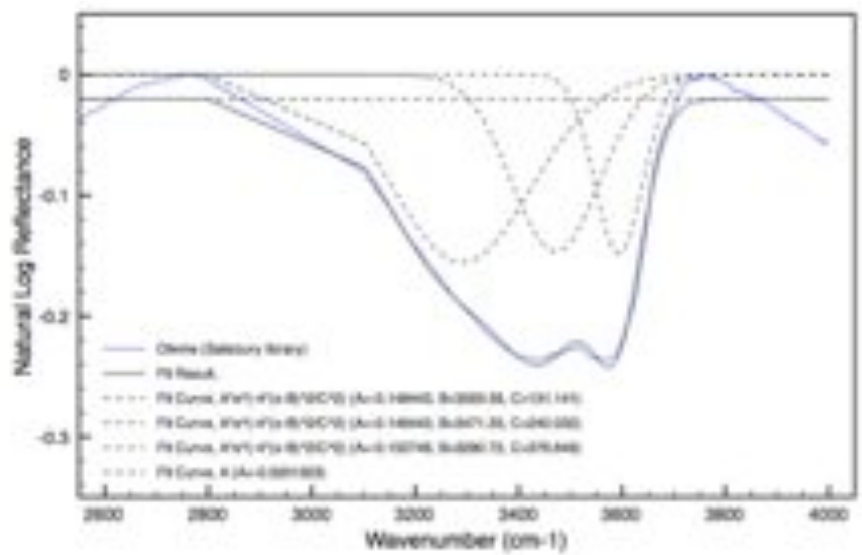
- Unique Laboratory Capabilities (JHU-APL Planetary Science Optics Lab):
  - Unique VUV – Mid-IR bidirectional reflectance measurements (same type of measurements as made by spacecraft.
  - Unique temperature range (140K – 650 K) to simulate surfaces of asteroids to Mercury.
  - Ultra-high vacuum conditions (relevant to airless bodies).





Model the water-free spectrum of anhydrous materials

- Spectral libraries often contain but non-optimized data in 3-μm region
  - Often not worth extra effort for specific investigations to remove effect of terrestrial water
  - If desired to use data for 3-μm studies, must remove effect of terrestrial water
- *Model water in these materials, create water-free spectra, greatly expand set of end members for spectral modeling*

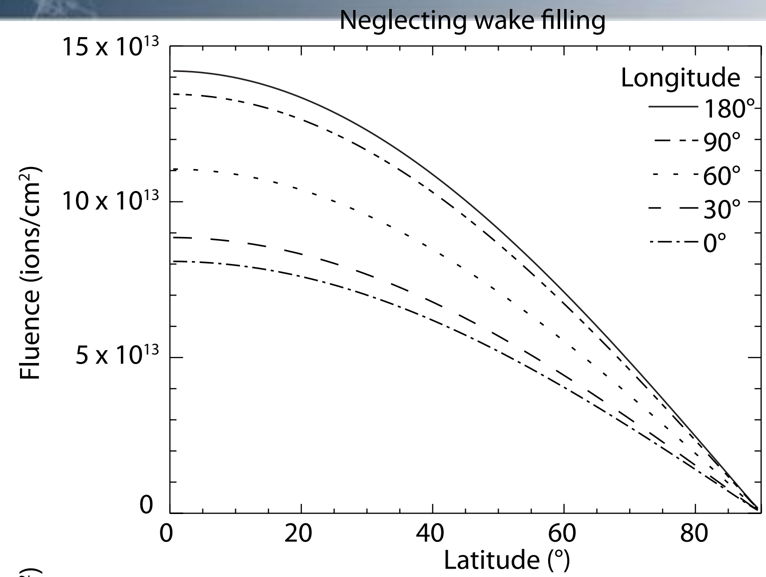


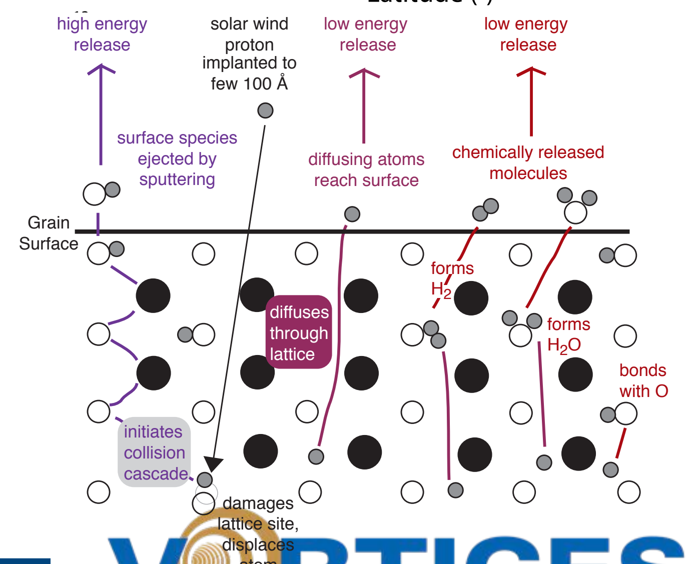
Example fit: olivine spectrum (blue), with water fit by Gaussians using band decomposition analysis technique (dashed lines) and total fit (black line).

Modeling volatile formation/deposition

- Objective
  - Quantify the initial distribution of solar wind implanted elements in exposed regolith on the Moon, NEAs, Phobos, and Deimos

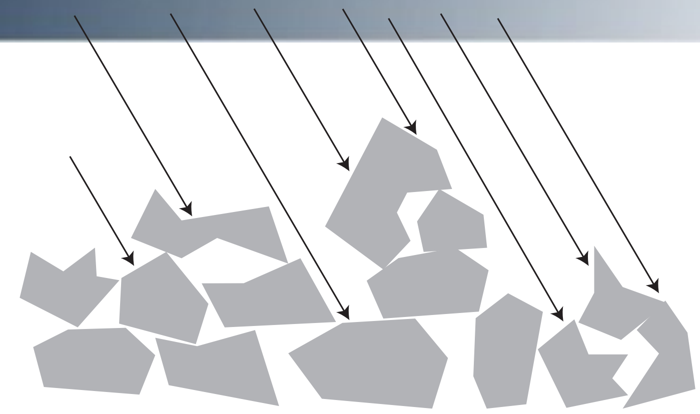
- Significance
  - Integrated over long time periods, the steady stream of solar wind supplies large amounts of volatile elements, which are potential resources for exploration

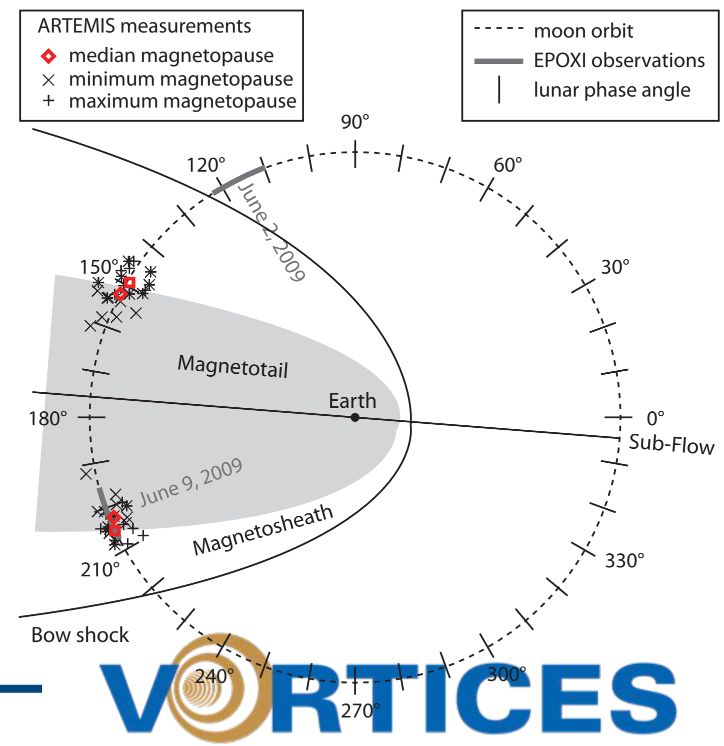




Modeling volatile formation/deposition

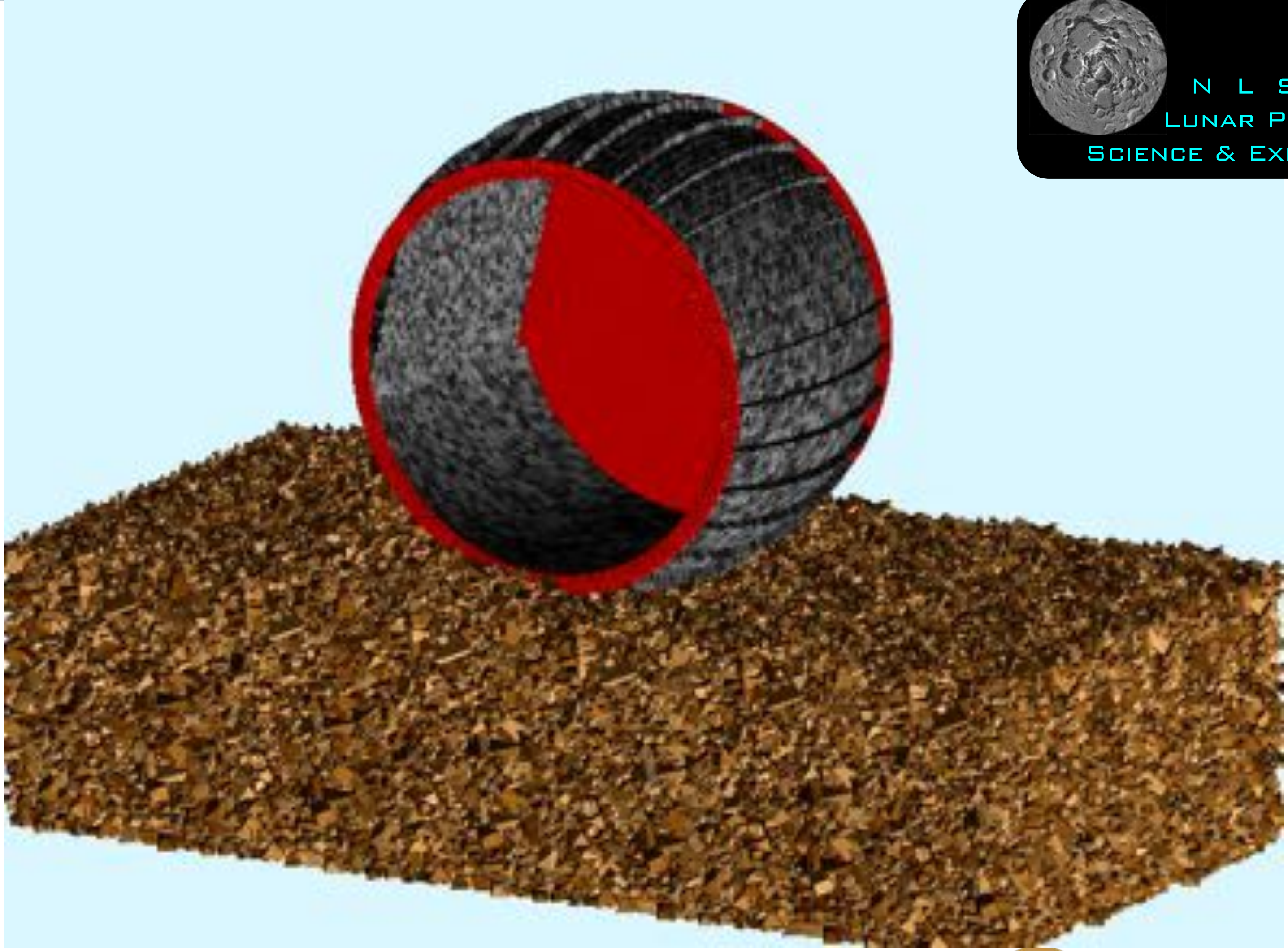
- Methodology
  - Use the COUPi DEM to simulate solar wind access with roughness on the size scale of individual reolgith grains
  - Use spacecraft data to quantify the monthly effect of passage through the magnetotail on the map of fluence of solar wind to the moon’s surface





COUPi

Controllable Objects Unbounded Particles interactions (COUPi)



N L S I
Lunar Polar
Science & Exploration

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How do the volatiles move across and interact with the surface?

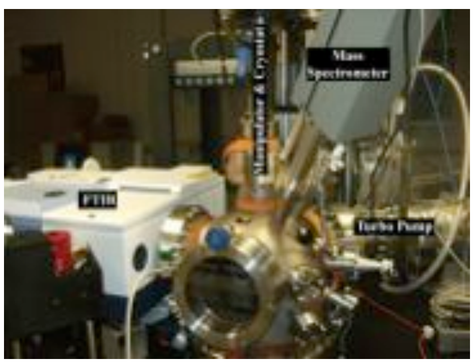
- Volatile migration is thermally driven
  - Surface temperature distribution (*f*(day, season))
  - Subsurface temperature profile
    - Shape
    - Rotation
    - Thermal properties
- Volatiles interact with the surface grains physically and chemically
  - Adsorption, absorption, chemical bonding

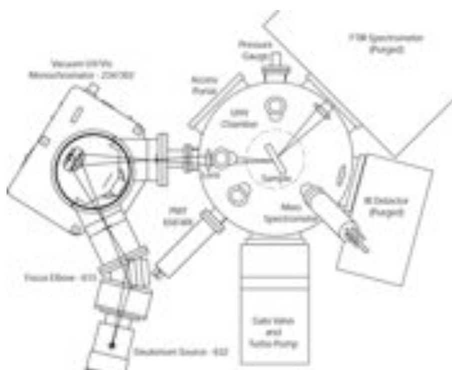
Volatile-Regolith Interaction Studies

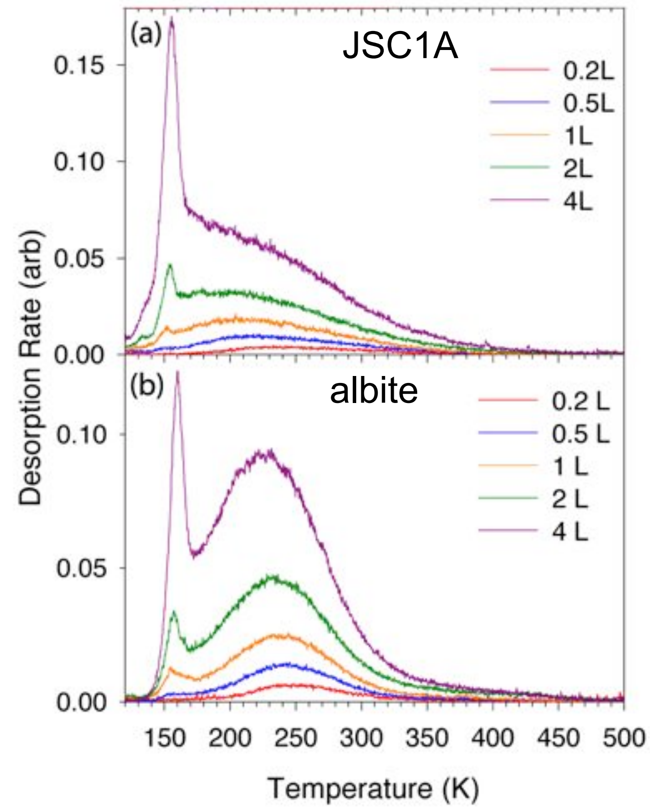
Temperature Programmed Desorption to understand the water at the poles and its evolution over time (not the formation of solar wind OH).

Mare analog (top) adsorbs less water than the high lands analog (bottom). The peak at 155K is due to water-ice subliming and is not adsorbed water.

Even the most adsorptive material will not retain adsorbed molecular water on any part of the illuminated Moon



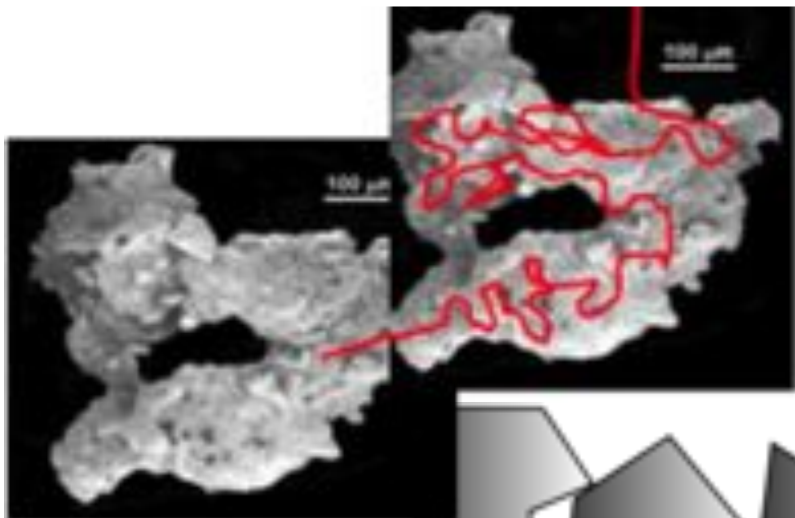


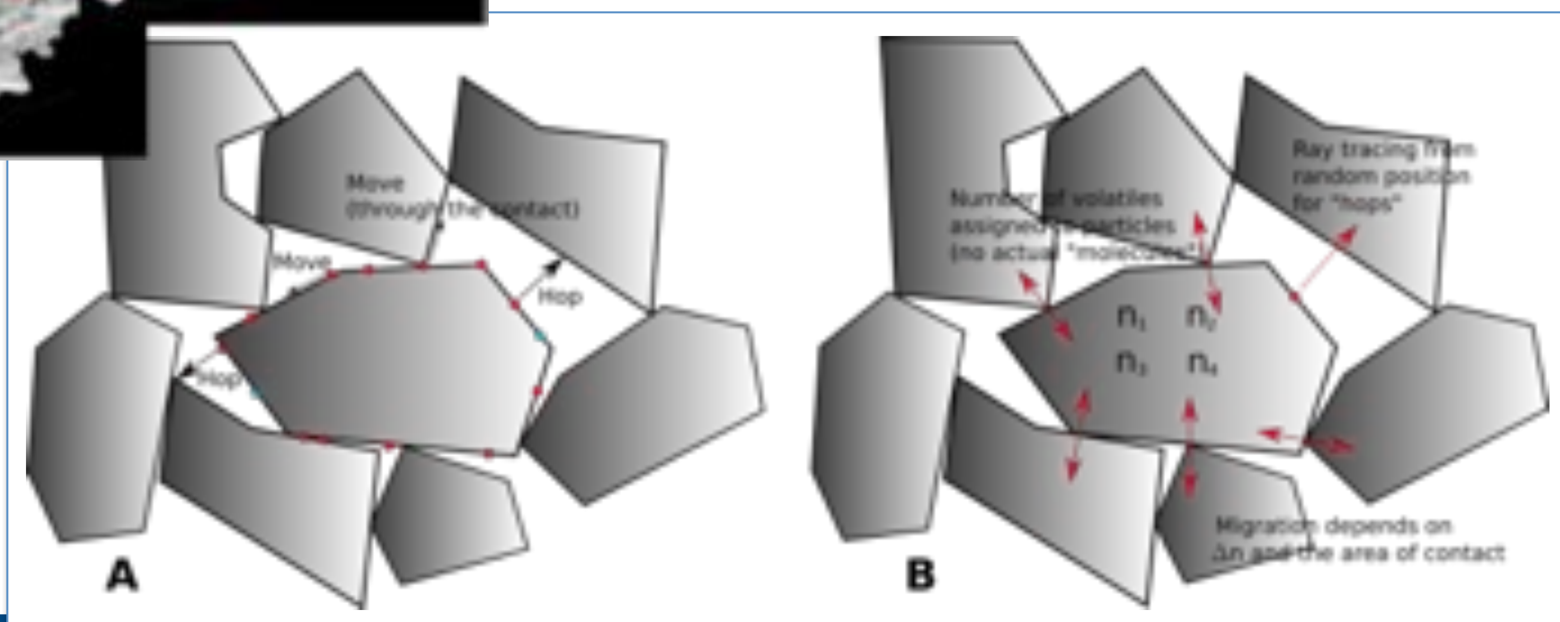


Volatile Transport within Regolith

Migration of H_2O or other volatiles along grains on airless body.

Couple Monte-Carlo modeling with “surface science” knowledge of sticking coefficients and residence times for more complete understanding of water evolution in surfaces of airless bodies.



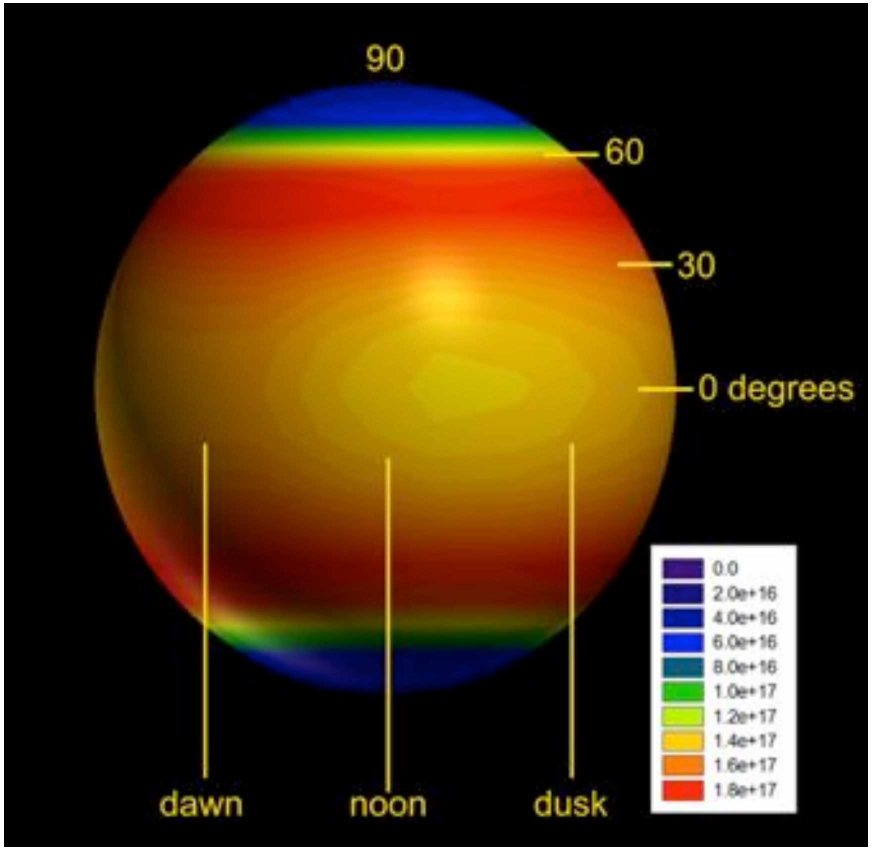


H_2O and OH Interactions with Regolith

- Source - Proton Implantation
- Defect production, H trapping
- Evolution - Diffusion
- Known rates, effects of defects
- Sink - Destruction
- Recombinative, photodesorption

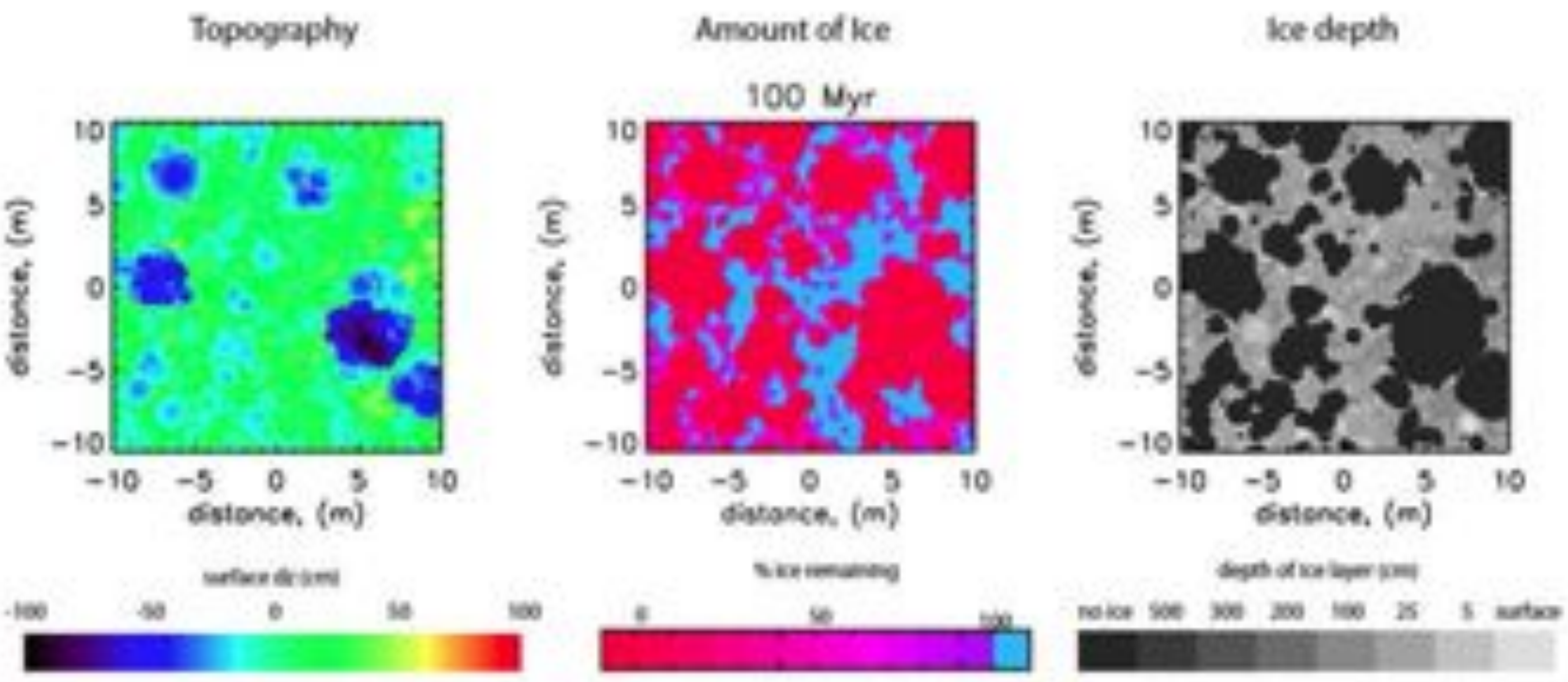
- **OH mobility – It may be that what's really mobile is just the H, it temporarily bonds with O in silicate grain (producing observed OH signature). Then the H moves on.**

- H_2O could be made in micrometeorite impacts, reduce FeO to nanophase iron, release O, combine with H_2 .



Equilibrium OH column density (Grieves and Hibbitts).

Global Gardening Model.



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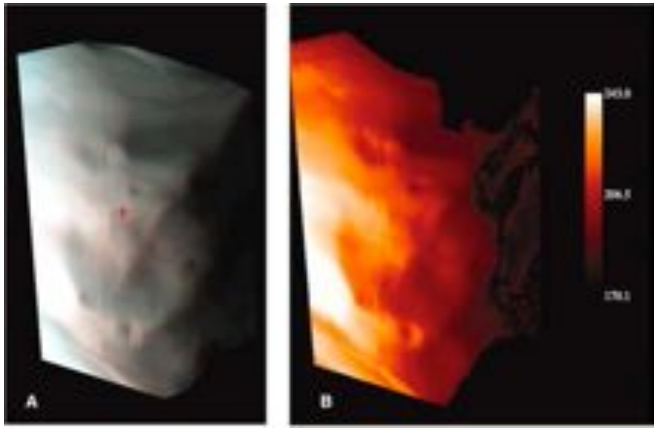
What is the ultimate fate of the volatiles?

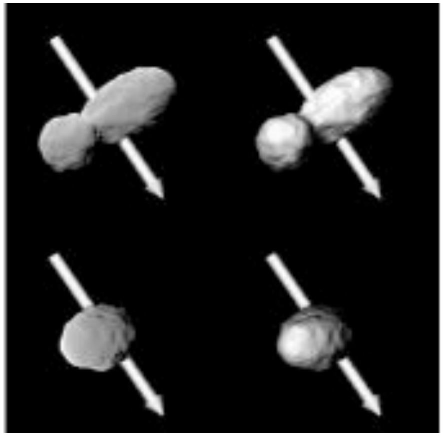
- Do they “run free”?
- Are they destroyed?
- Are they trapped for ever?

Surface & subsurface temperatures

- Moon – relatively straight forward, well understood topography, insolation, rotation and orientation
- Small bodies – more poorly defined and large range of parameters
- SHERMAN thermophysical model to identify locations where volatiles may be stable
  - Incorporate temperature-dependent thermal conductivity
  - Adapt lunar regolith density profiles to asteroids
  - Investigate lateral heat transport
  - Implement more realistic sun, Earth, and Mars as illumination/ heat sources
  - Model thermal infrared spectra
  - Move towards modeling binary asteroids and lunar eclipses
- Validate SHERMAN against Diviner lunar observations



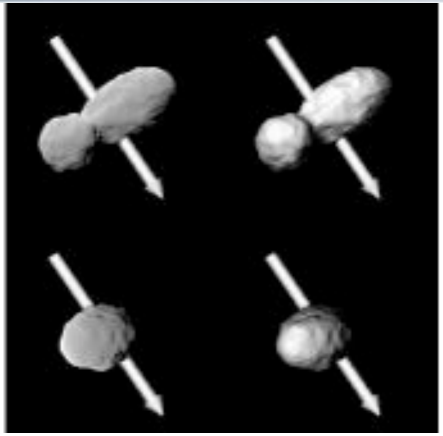
Baetica region of Lutetia. (A) False color; (B) surface temperature derived from VIRTIS (figure from Coradini et al., 2011).



1996 HW1 shape model

Evaluate the potential for thermally stable volatiles on NEAs

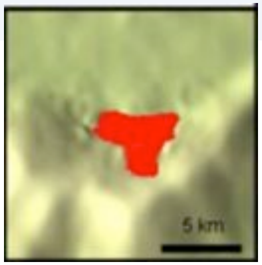
- Model and investigate the surface and subsurface temperature distributions on various NEAs
- Actual observations will constrain the range of orbital, size, shapes, and spin states for a range of regolith types under different illumination conditions

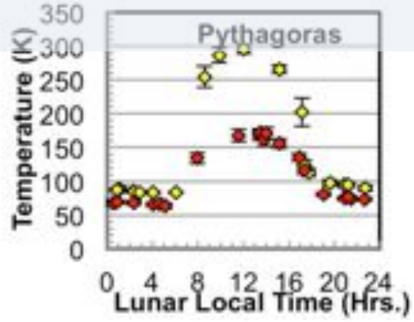


Above: 1996 HW1 shape model

Thermal and physical analysis of lunar non-polar PSRs

- Characterize non-polar PSRs (<80°) and evaluate their ability to sequester volatiles
- Combine SHERMAN models with observations from Diviner, Mini-RF, LAMP, LROC, and M3

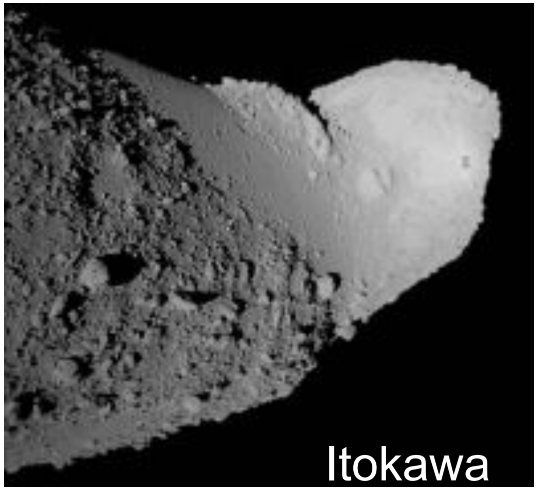




Left: Non-polar PSR (red) on Pythagoras central peak. Right: Diviner temps of PSR (red) and crater floor (yellow).

Regolith Formation and Evolution

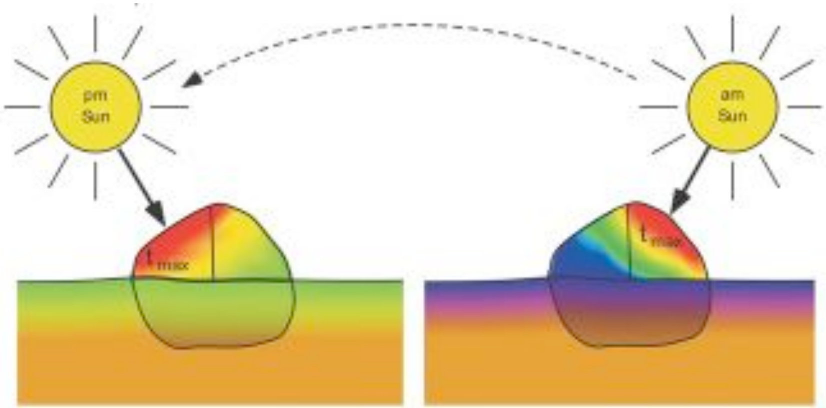
- How do regoliths form on air-less planetary bodies?
- Is the same process responsible everywhere?
- What are the properties of regolith and how do they evolve over time?



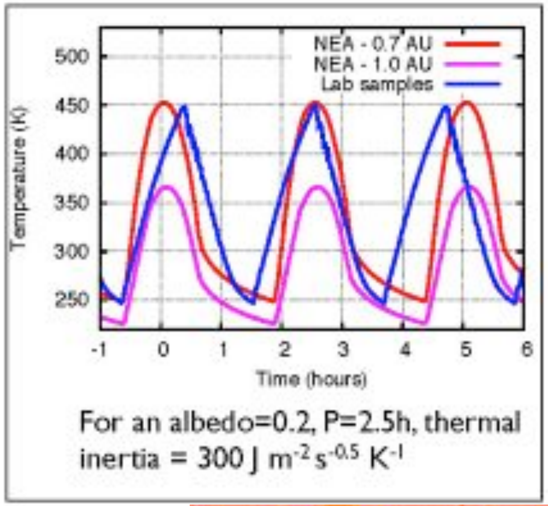
Micrometeorite bombardment vs. thermal fatigue

- Micrometeorite bombardment is the canonical model for lunar regolith formation (progressive mechanical abrasion over time).
- But for asteroids... lower impact velocities (~5 km/s vs. ~15 km/s on the Moon); lower surface gravity, lower escape velocities on asteroids (particularly small bodies like Itokawa).
- For MBA, micrometeorite velocities are too (?) low for such mechanical abrasion. Thermal fatigue has been proposed to disaggregate rocks.

Apollo 15 zap pit. A15 15555.



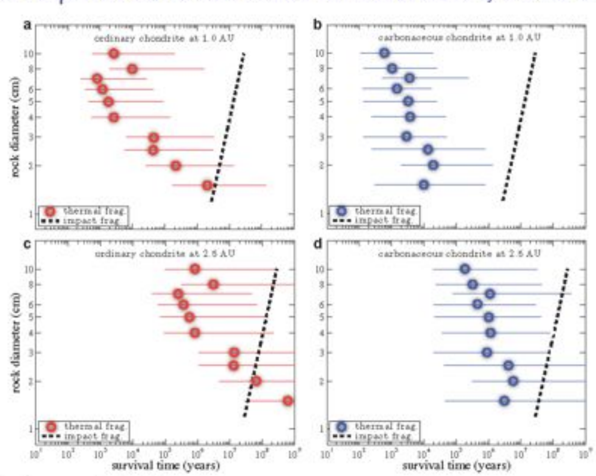
Thermal fatigue



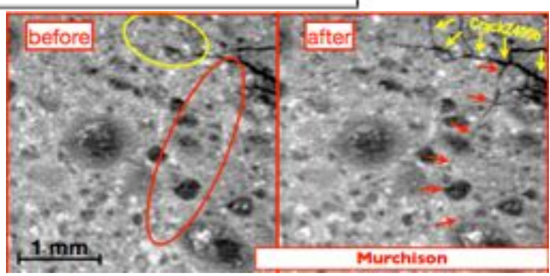
Thermally cycle samples to understand how they weaken as a function of composition, grain size, thermal amplitude and period.

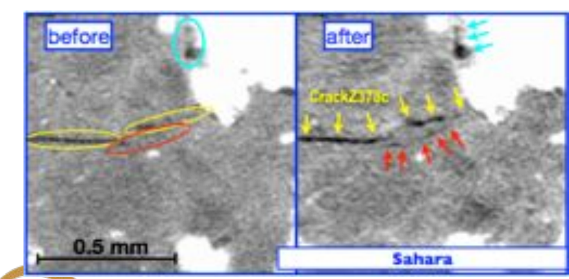
- Development of regolith models
  - Develop a scaled thermal fragmentation model
    - Model regolith evolution and the coupling of multiple mechanisms

Time required to break rocks on asteroids by thermal fatigue



Delbo et al. 2014.





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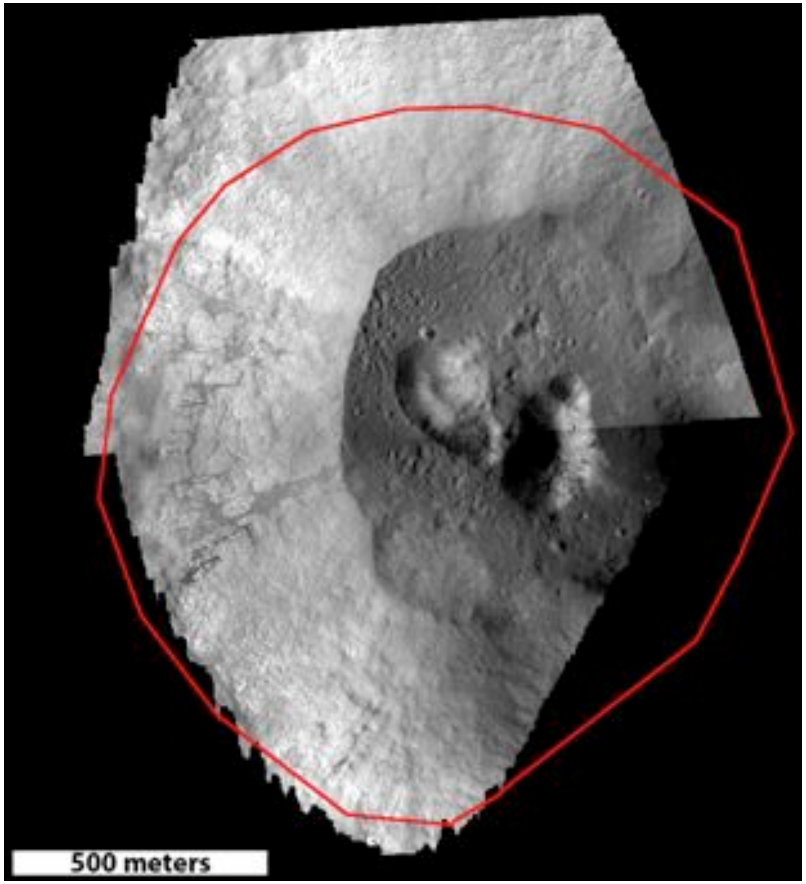
Thermal fatigue

We can test this on the Moon.

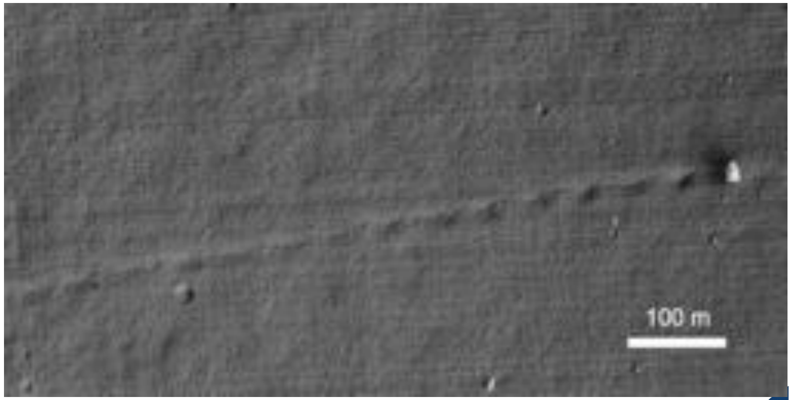
Areas of permanent shadow can be imaged. These low-temperature areas are isothermal and thus should not experience thermal fatigue stresses.

If micrometeorite is the sole mechanism on the Moon, rock size-frequency distribution and regolith properties should be similar to illuminated areas.

If thermal fatigue is important on the Moon, materials may be different.

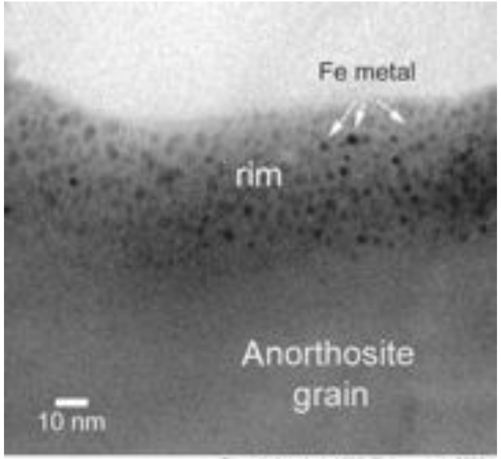


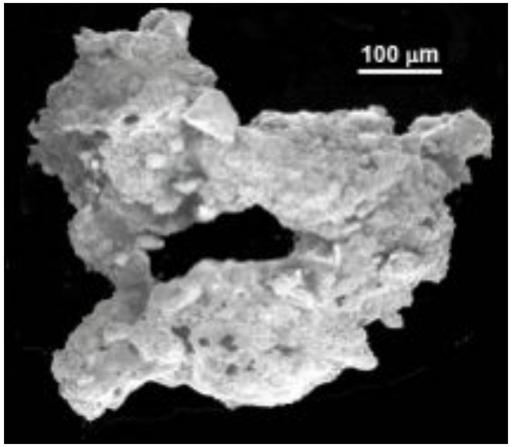
Red line encloses area of permanent shadow



Space Weathering

- What processes are responsible for changing the surface chemistry, fine-scale morphology, and spectral signature?
- Micrometeorite bombardment
  - Heating, melting vaporization – agglutinate formation, nanophase Fe formation, O liberation.
  - Creating fresh, unrequited surfaces – activate chemistry
- Irradiation – solar and galactic cosmic rays
  - Crater radiation damaged surface – activate chemistry
- Influences the ability of the surface to hold / modify H, O, OH, H_2O.
- Influence of both processes will vary with composition, exposure history, location in the solar system (Cis-lunar space vs. MBA)
- Affects our interpretation of what we are remote sensing



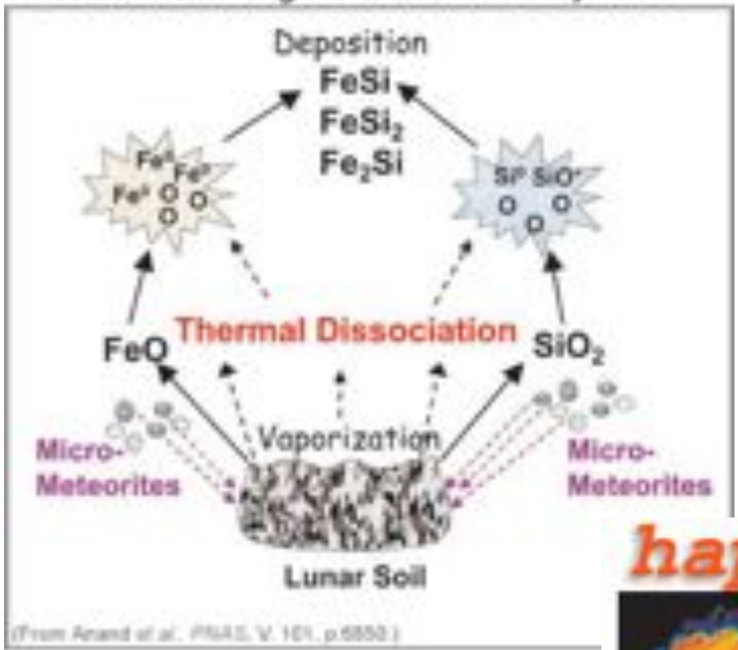


Space Weathering

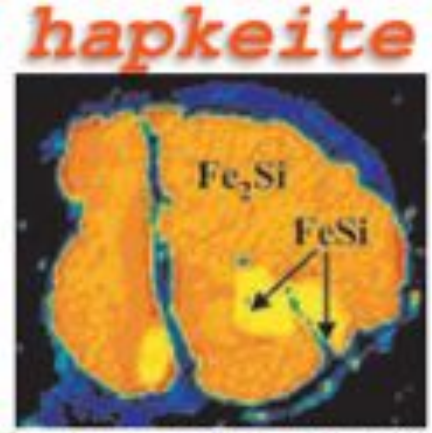
- Impact heating
  - melting
  - vaporization
  - dissociation
  - deposition

- Fe, O, H, Si

Cartoon showing formation of Fe-Si phases



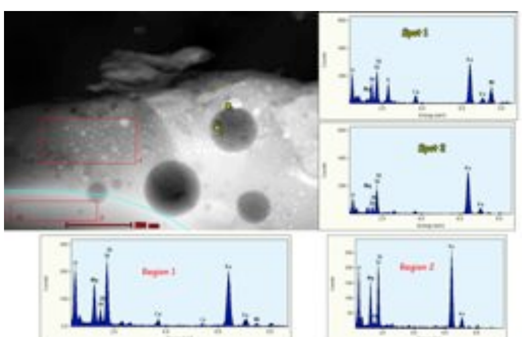
(From Anand et al., PNAS, V. 101, p.6850.)

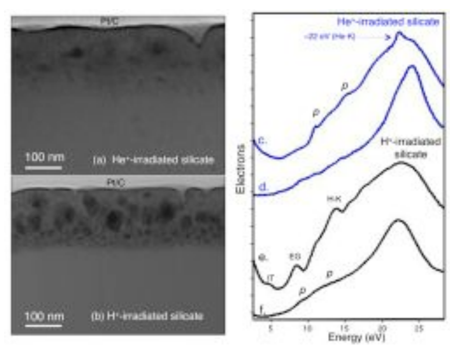


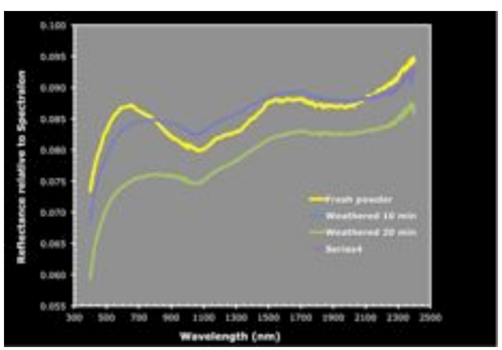
(From Anand, et al., PNAS, v. 101, p.6848.)

Space Weathering

- Micrometeorite bombardment, simulated by pulse laser irradiation
- Proton (H^{+}) implantation
- Interactions between the two studied as a function chemistry/mineralogy/petrologic type

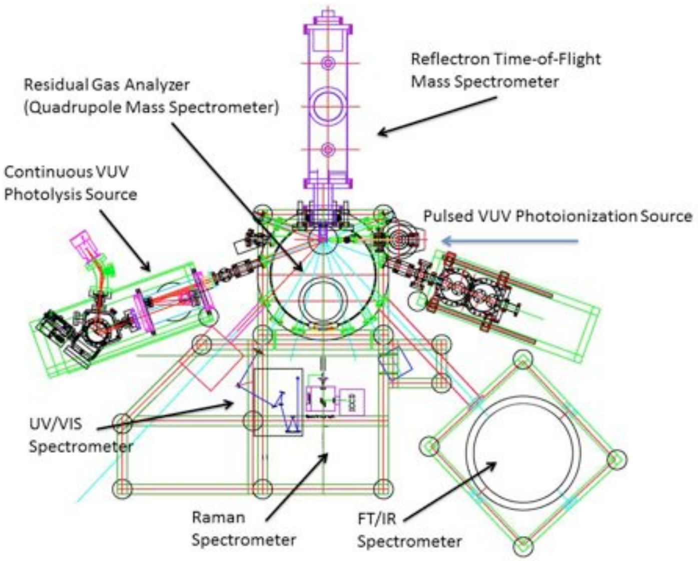






Space Weathering

- Spectroscopic measurement from UV through thermal IR
- Scanning Transmission Electron Microscopy and Energy Dispersive X-rays
- Valence Electron Energy-Loss Spectroscopy (VEELS) will be used to detect chemically bound water and OH- produced in simulations.
- Raman, infrared spectra and mass spectrometers will be used to measure water released during irradiation and heating.
- *Results of this task provide a framework for Task 5, and feed into to Task 9.*



Top view of the chamber including main recipient, target, analytical instruments, and charged particle and photolysis modules. The irradiation sources are aligned along the centerline with respect to the target to allow a simultaneous exposure of samples to mono energetic charged particles and photons

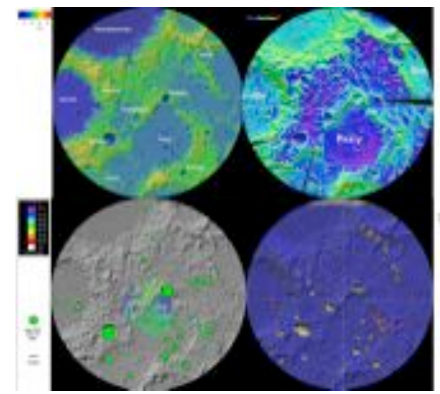
Exploration

- Although the previous tasks are “science driven” they will supply data of use to HEOMD
- We have several tasks that are “Exploration-driven”
- Flexibility to ensure we acquire results which are of the most use to you
- Two Themes
  1. Resources: Identification & Exploitation
  2. Closing SKGs

Search for Resources

Use multiple data sets to devise models of the distribution of volatiles and available sunlight in areas near the poles of the Moon

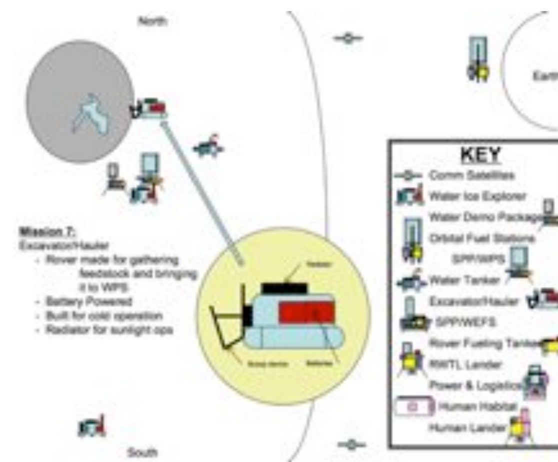
- Collate neutron Pixon models, Mini-RF radar, LAMP, LEND, LOLA and WAC data to locate cold traps and probably ice deposits
- Backscatter modeling of Mini-RF data to predict locations of water ice deposits
- Incorporate and coordinate with results of polar lighting studies



Resource maps - North pole

Devise scenarios for the harvesting of polar volatiles, including determination of mining locales, traverse distances, energy requirements, and likely production rates

- Architecture studies of lunar surface operations scenarios
- Required elements, masses, power, duty cycles
- Predicted yield of product as function of ice concentration levels, distances, deposit heterogeneity

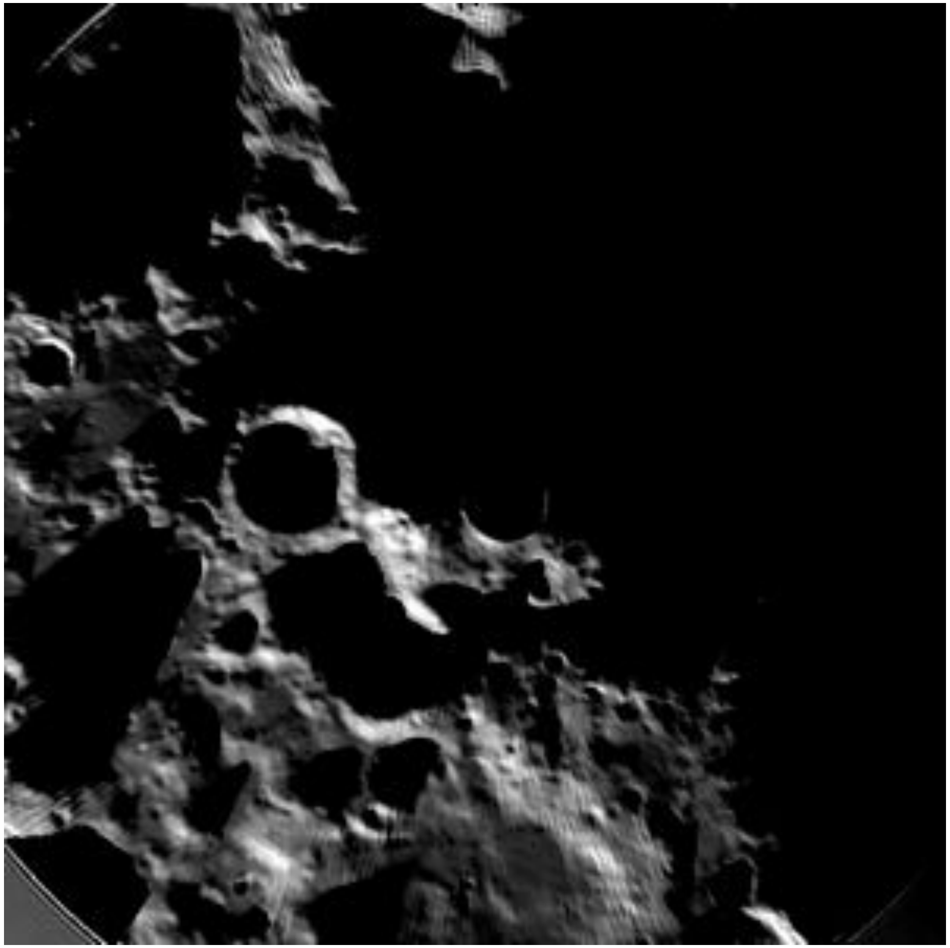


Resource development scenarios

Illumination Characterization for Surface Operations

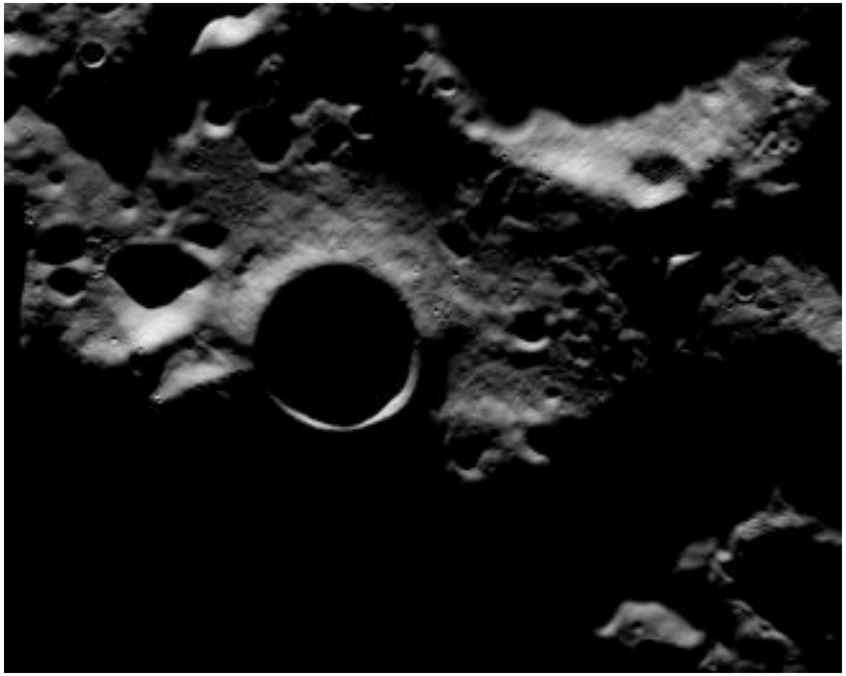
- **High-Resolution Illumination Studies**
  - Current best is 20m DEMs, goal is to incorporate 2m NAC DEMs
  - Conduct analysis of permanent shadow on NEAs as a function of spin axis
  - Generate high-res NEA topography using photoclinometry

- **Rover Traverse Planning Tool**
  - Determine route that minimizes exposure to shadows
  - Also consider communication requirements



LROC / Simulation Comparison

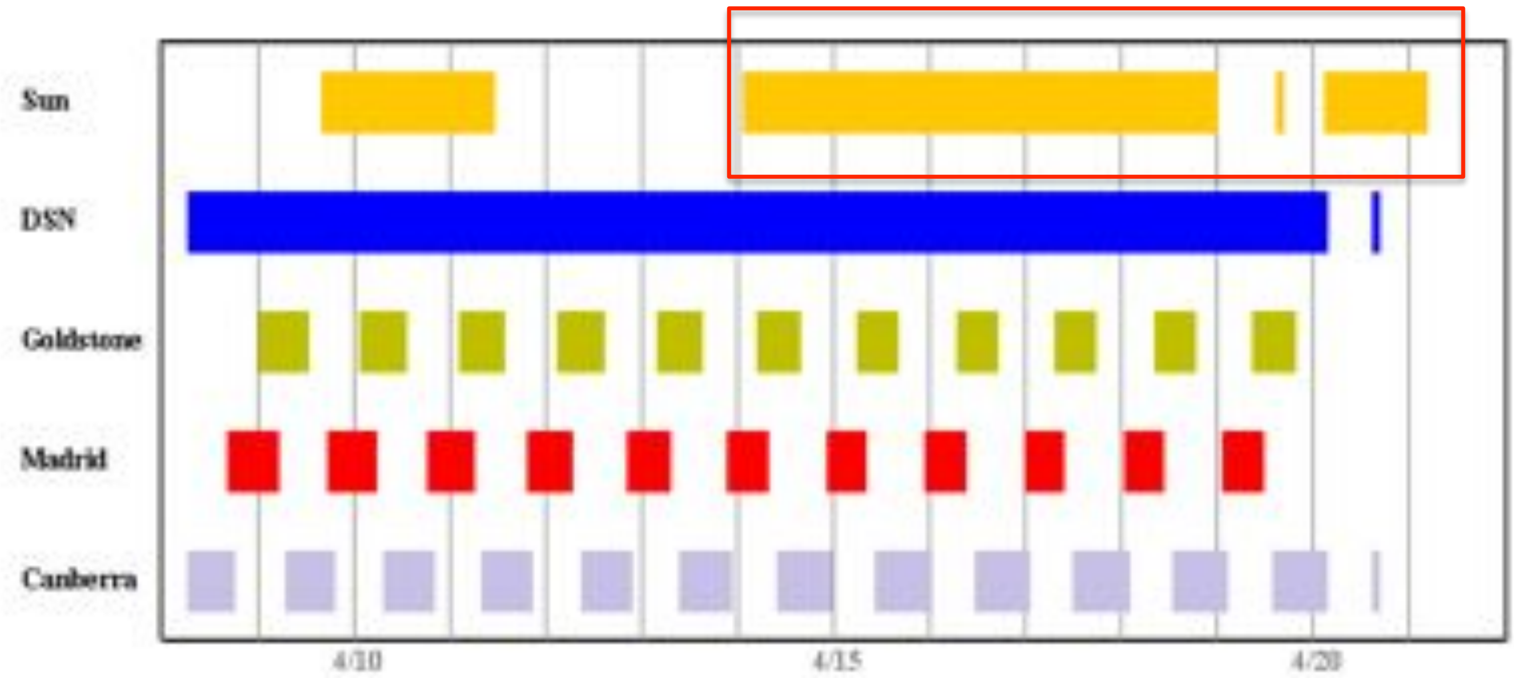
- One is generated from a 100 m LOLA grid and the other is a raw LROC image
- LOLA-based image generated with ray traced extended source shadows plus Gaskell's fits to the McEwen Lunar-Lambert photometric function



April 2017 Opportunity

20 m/pix LOLA DTM, 80°S to 90°S

85.75°S, 315.0°E, 1 m Mast



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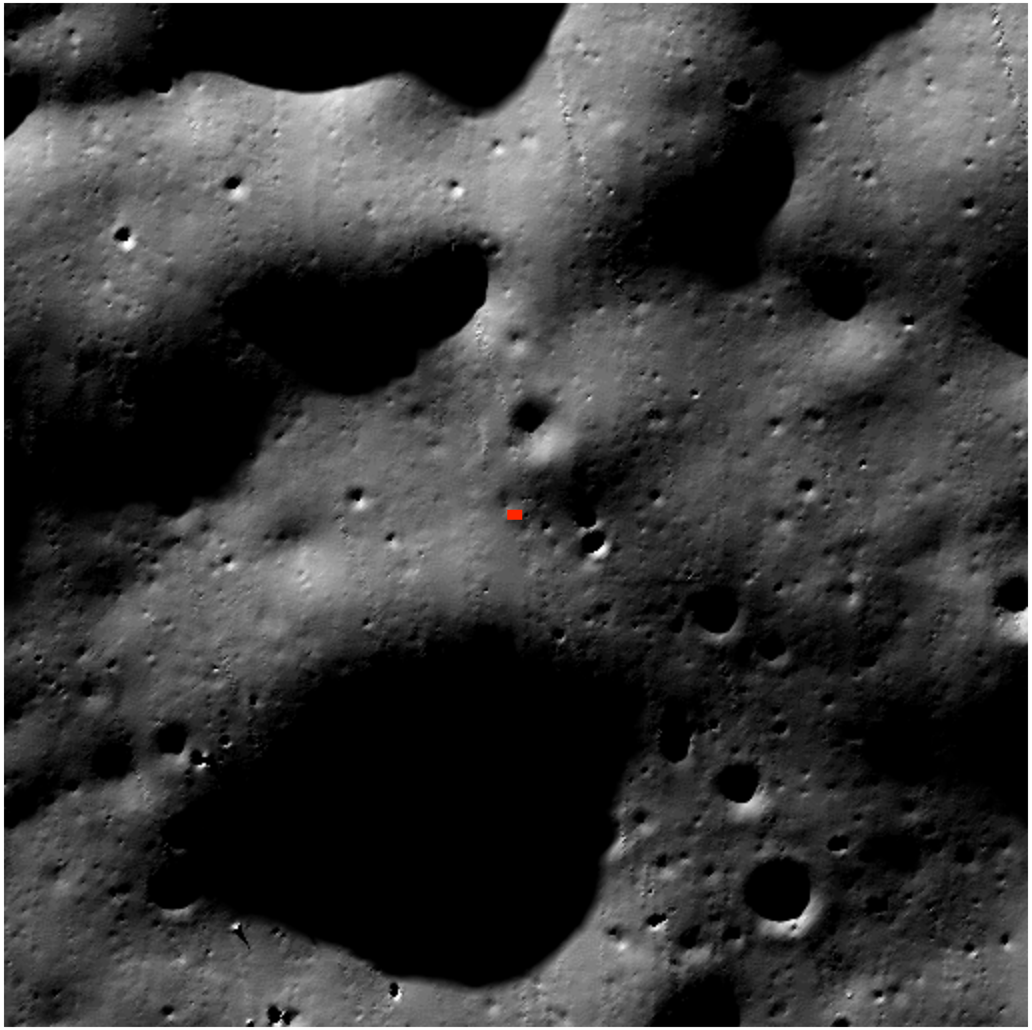
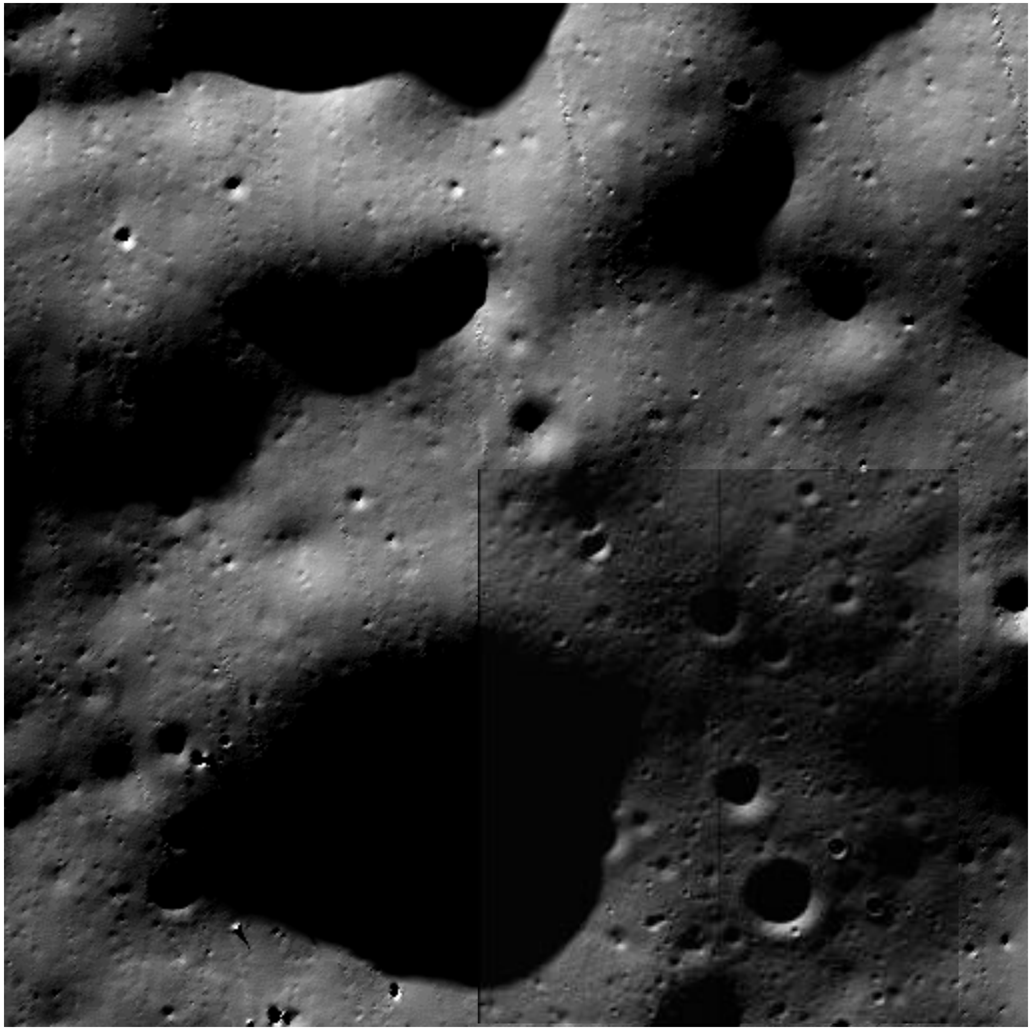
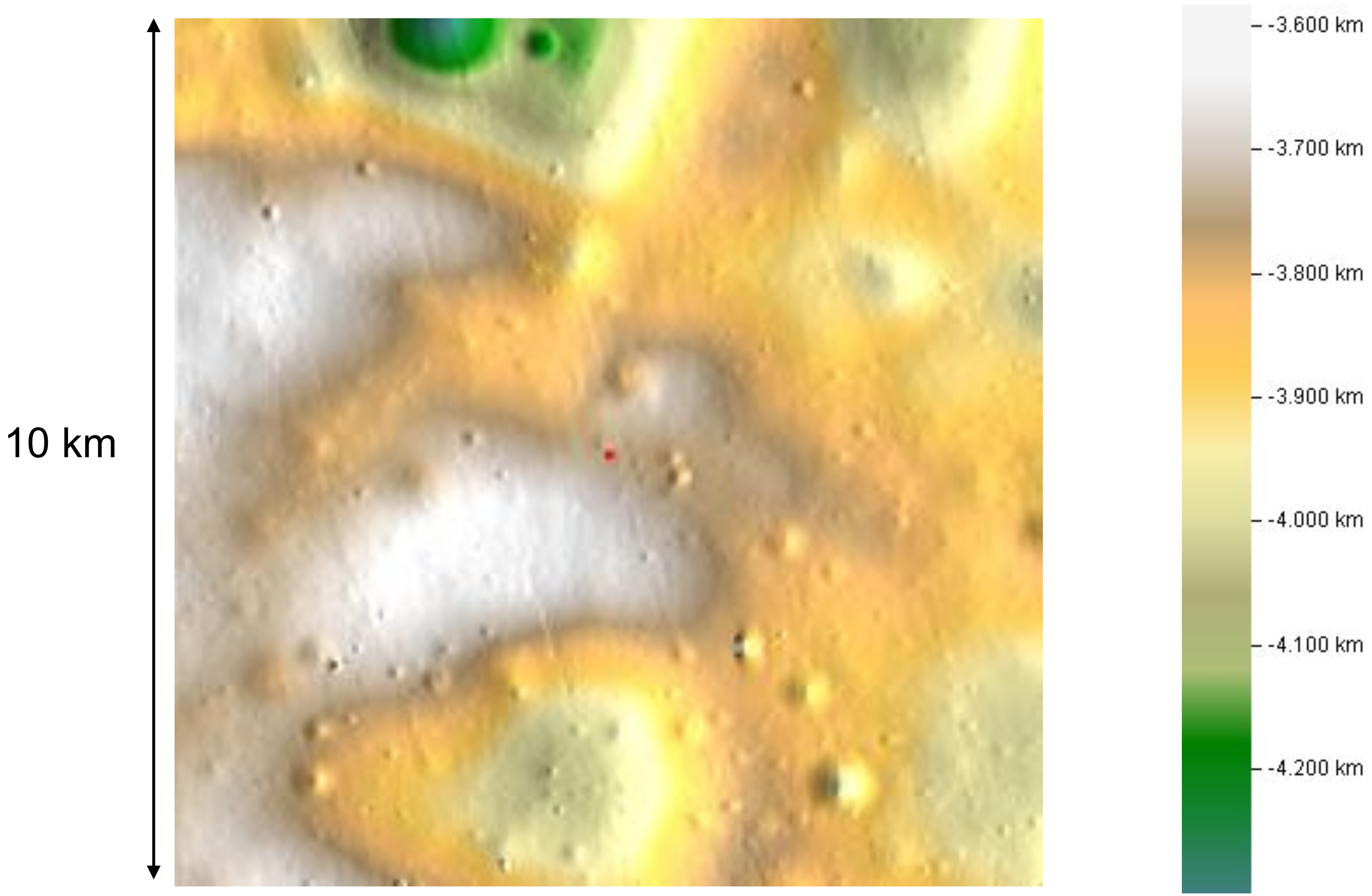




Oblique Stereographic Shaded Relief DTM Centered on A1
20 m/pix, 500x500 pixels (10 km x 10 km)



Oblique Stereographic Shaded Relief DTM Centered on A1
20 m/pix, 500x500 pixels (10 km x 10 km)
1 m Transmitter (A1), 1 m receiver
Darkened areas do NOT have line of sight with transmitter

Oblique Stereographic Shaded Relief DTM Centered on A1
20 m/pix, 500x500 pixels (10 km x 10 km)
1 m Transmitter (A1), 2 m receiver
Darkened areas do NOT have line of sight with transmitter

Oblique Stereographic Shaded Relief DTM Centered on A1
20 m/pix, 500x500 pixels (10 km x 10 km)
2 m Transmitter (A1), 1 m receiver
Darkened areas do NOT have line of sight with transmitter

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Oblique Stereographic Shaded Relief DTM Centered on A1
20 m/pix, 500x500 pixels (10 km x 10 km)
2 m Transmitter (A1), 2 m receiver
Darkened areas do NOT have line of sight with transmitter

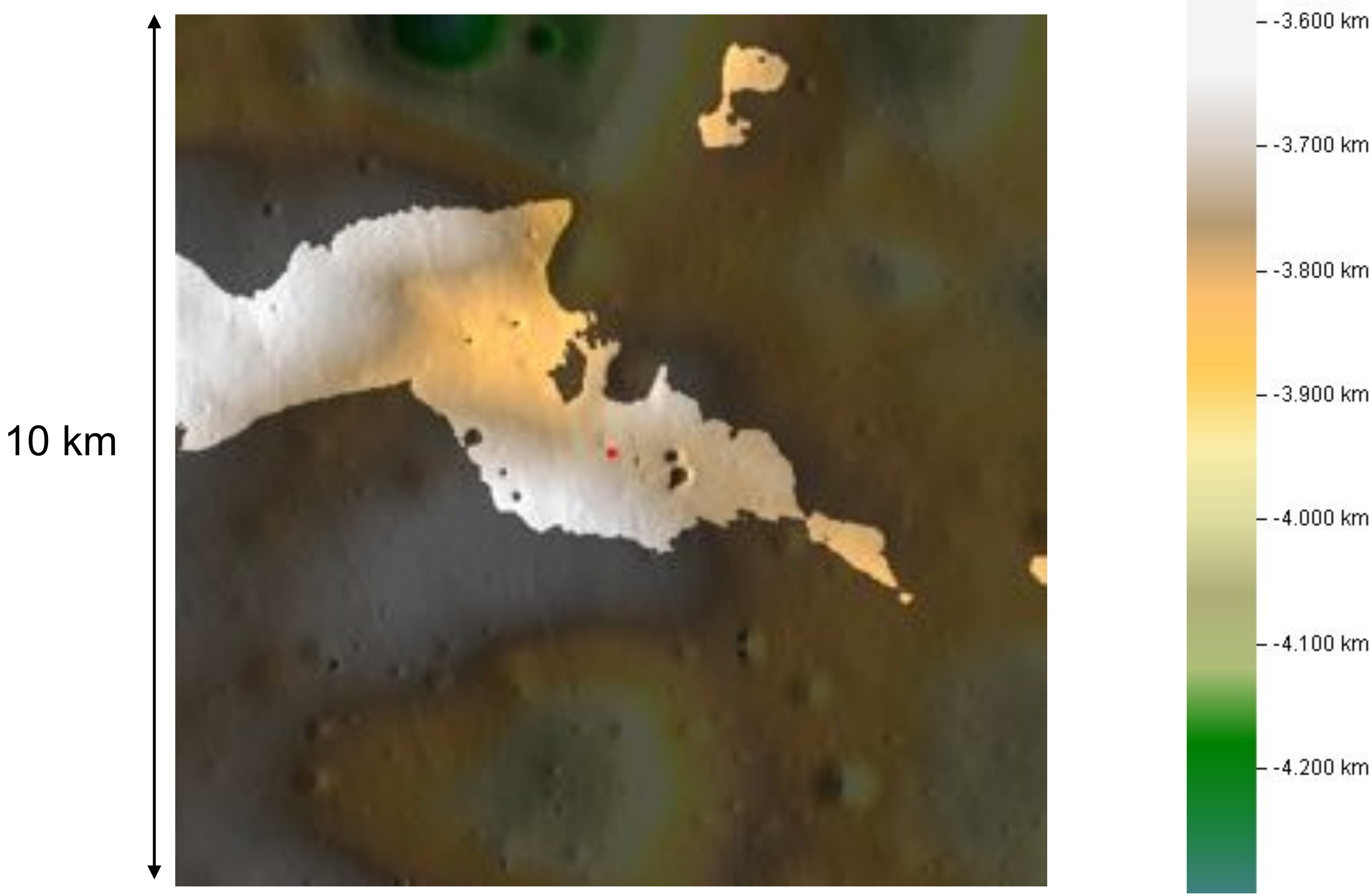
Oblique Stereographic Shaded Relief DTM Centered on A1
20 m/pix, 500x500 pixels (10 km x 10 km)
3 m Transmitter (A1), 1 m receiver
Darkened areas do NOT have line of sight with transmitter

Oblique Stereographic Shaded Relief DTM Centered on A1
20 m/pix, 500x500 pixels (10 km x 10 km)
3 m Transmitter (A1), 2 m receiver
Darkened areas do NOT have line of sight with transmitter

Oblique Stereographic Shaded Relief DTM Centered on A1
20 m/pix, 500x500 pixels (10 km x 10 km)
5 m Transmitter (A1), 3 m receiver
Darkened areas do NOT have line of sight with transmitter

Oblique Stereographic Shaded Relief DTM Centered on A1
20 m/pix, 500x500 pixels (10 km x 10 km)
10 m Transmitter (A1), 3 m receiver
Darkened areas do NOT have line of sight with transmitter

Oblique Stereographic Shaded Relief DTM Centered on A1
20 m/pix, 500x500 pixels (10 km x 10 km)
25 m Transmitter (A1), 3 m receiver
Darkened areas do NOT have line of sight with transmitter



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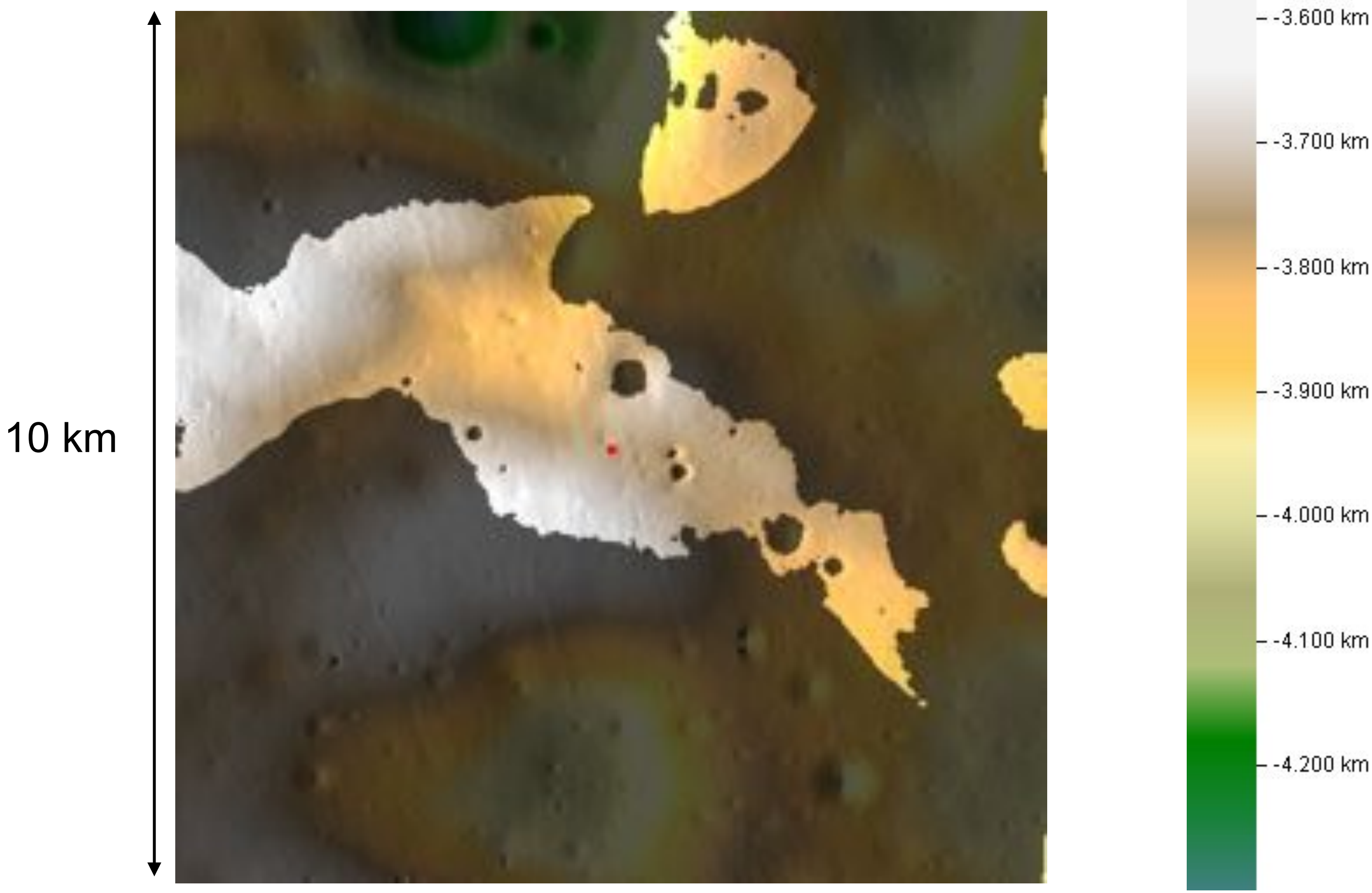
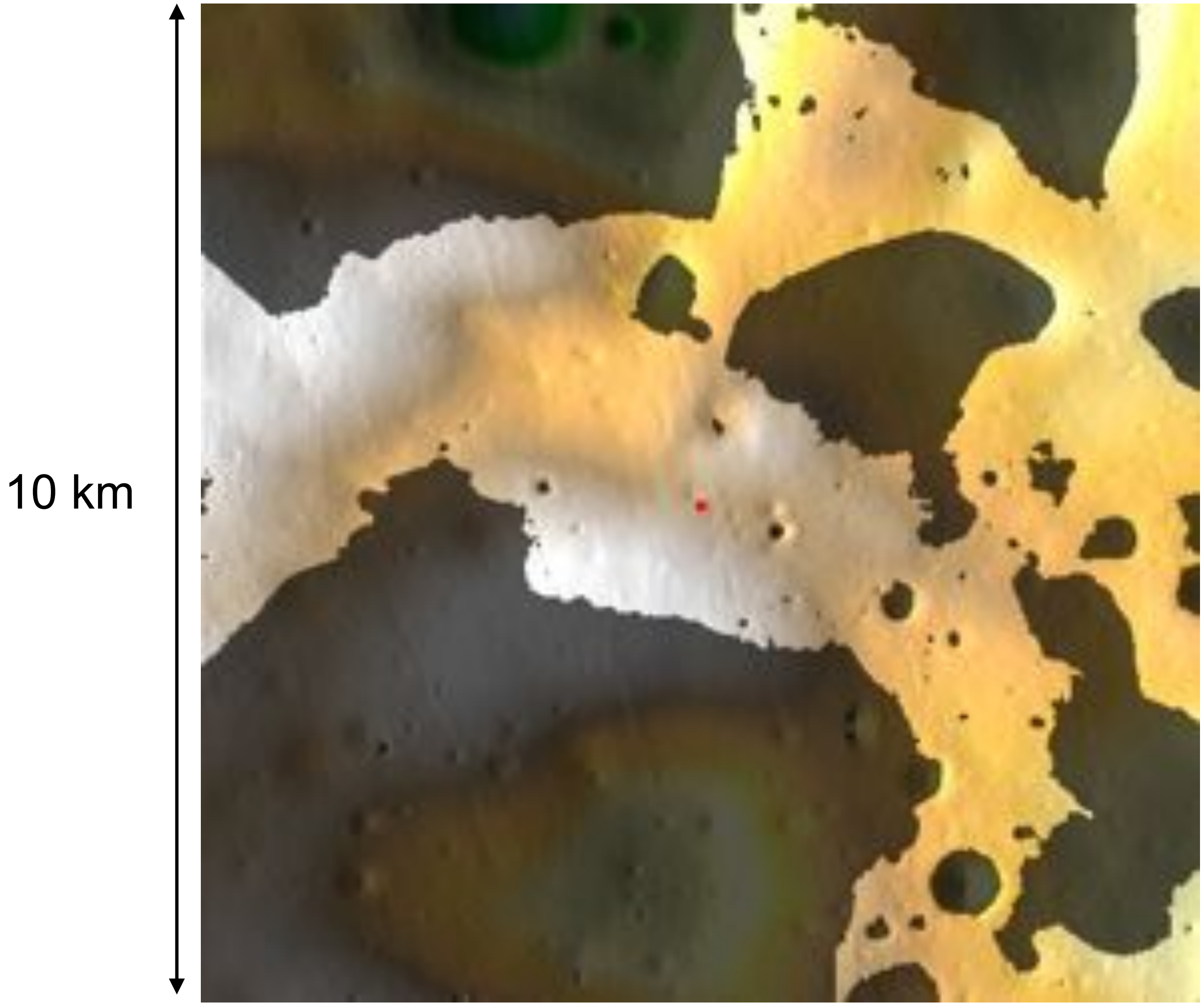
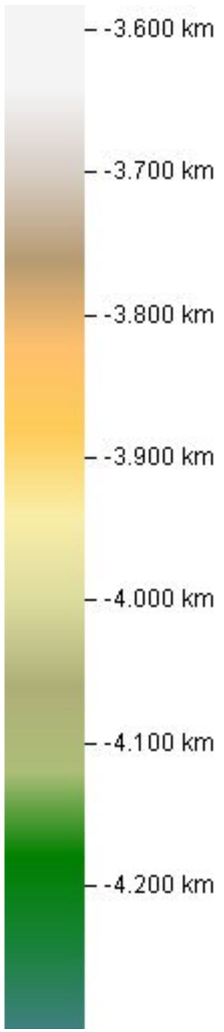
Oblique Stereographic Shaded Relief DTM Centered on A1
20 m/pix, 500x500 pixels (10 km x 10 km)
50 m Transmitter (A1), 3 m receiver
Darkened areas do NOT have line of sight with transmitter



Oblique Stereographic Shaded Relief DTM Centered on A1
20 m/pix, 500x500 pixels (10 km x 10 km)
100 m Transmitter (A1), 3 m receiver
Darkened areas do NOT have line of sight with transmitter





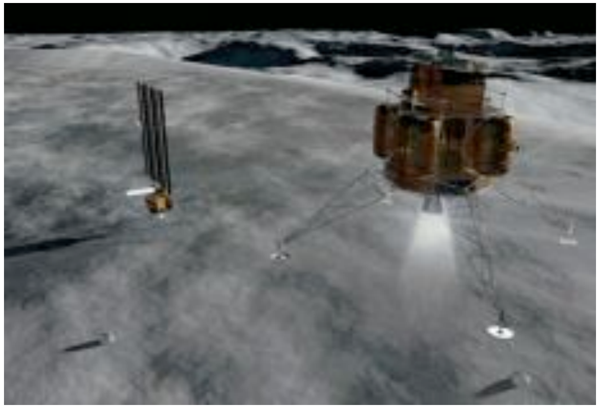
LunarShader Results

- Post the recent armada of international missions, we now have topography and image data with sufficient fidelity to fully characterize the polar illumination conditions
  - Maximum single period of illumination
  - Determine all eclipse periods
  - Exact shadow locations
  - Effect of mast height

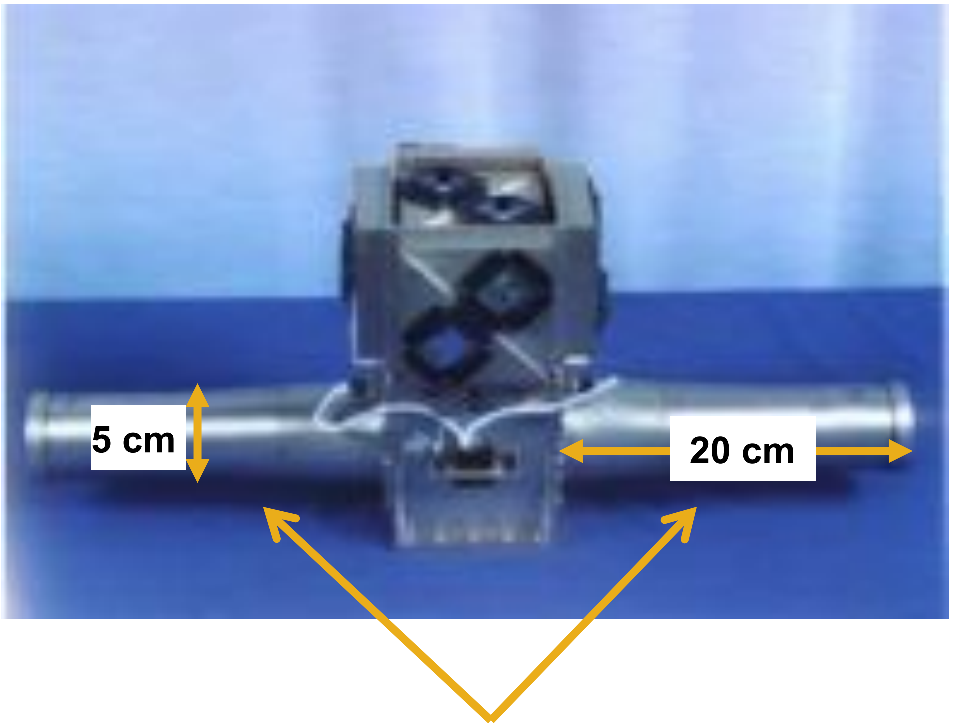
- Also discovered that permanent shadow can exist as far from the poles as 58°
  - Implications for easier access to volatiles

SKGs

- Which can be addressed using current data/research?
- For those that can't…..
  - What instruments/ missions are required to get the data needed



Lunar Polar Low-Altitude Neutron Experiment (PLANE)

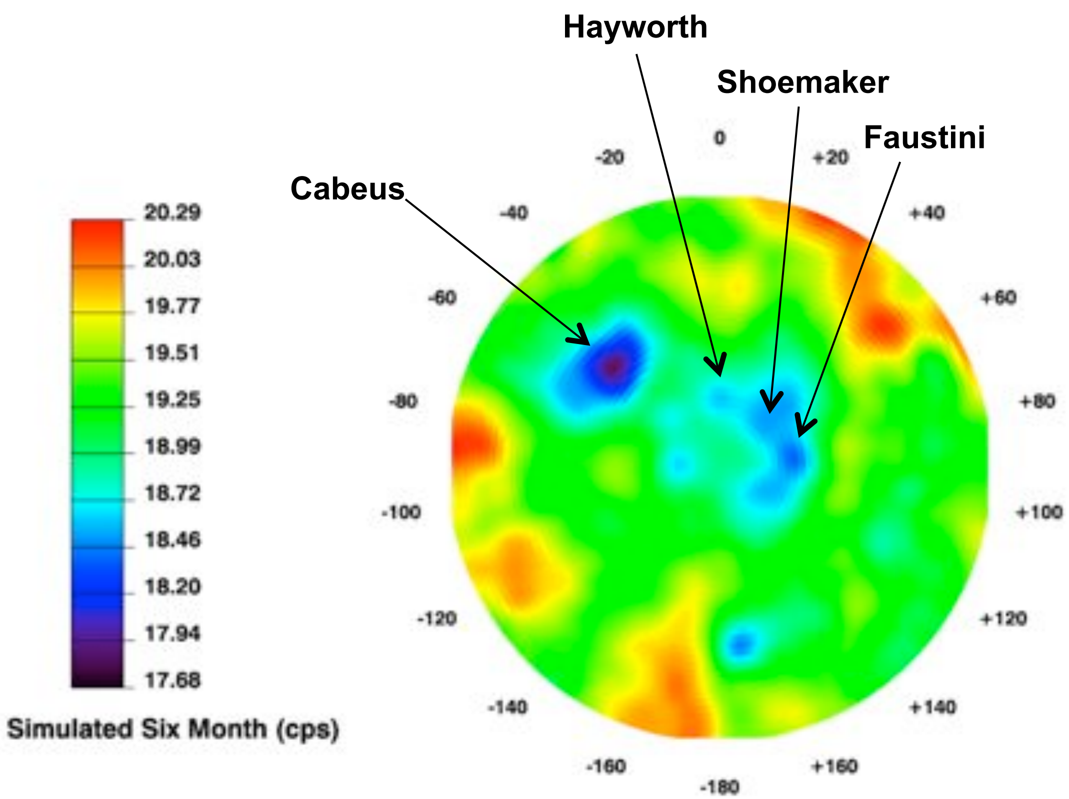


Lunar Prospector Neutron Spectrometer
(Two ^{3}He neutron sensors)

- Low altitude mission (<20 km) to obtain high spatial resolution
  - Elliptical orbit with periapsis at lunar south pole.
  - Mission duration: six months.
- Measure epithermal neutrons with two ^{3}He neutron sensors
  - Same as LP sensors
  - Total instrument mass <5 kg

Results: Lunar South Pole

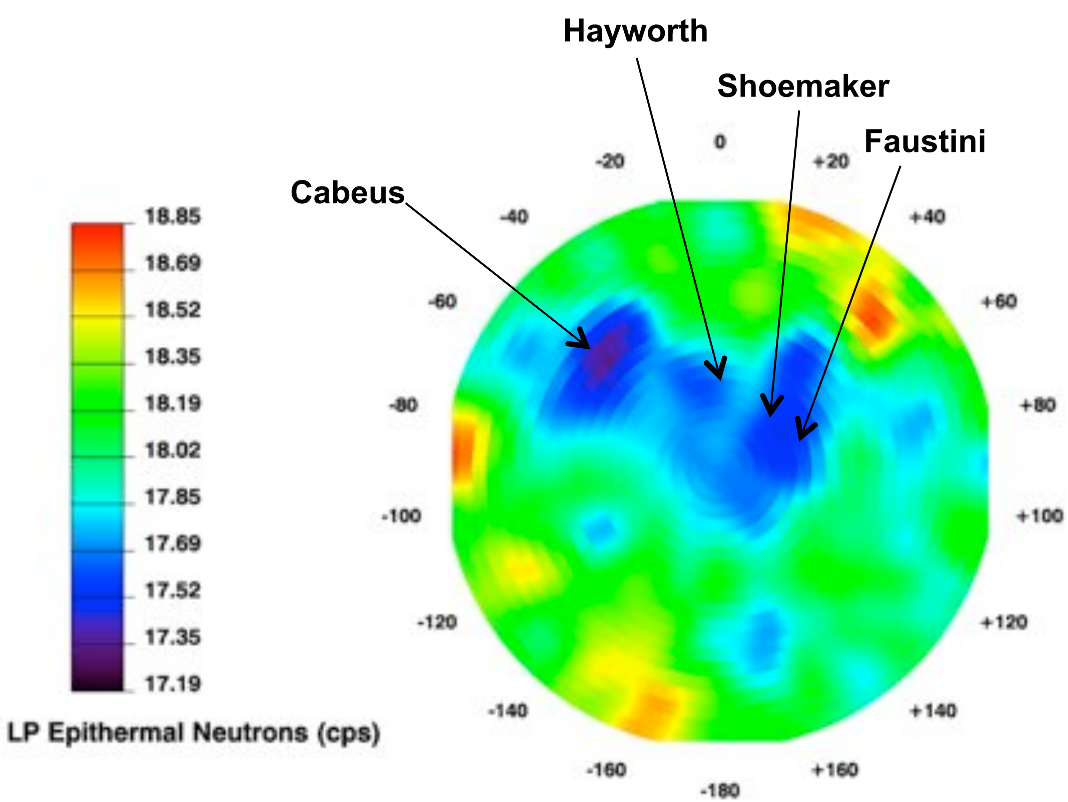
Lunar PLANE



- Use spatial reconstructed map as "ground truth".
  - Based on measured LP data.
  - Individual PSRs are resolved.
- Simulated Lunar PLANE data resolve individual PSRs.
- Compare with LP data that do not resolve PSRs.

Results: Lunar South Pole

LP Data



- Use spatial reconstructed map as “ground truth”.
  - Based on measured LP data.
  - Individual PSRs are resolved.
- Simulated Lunar PLANE data resolve individual PSRs.
- Compare with LP data that do not resolve PSRs.

PLANE Conclusions

- Investigated new mission concept to measure lunar polar hydrogen concentrations at high spatial resolution.
- Feasible mission design exists for low-altitude, polar measurements.
- Hydrogen concentrations within individual PSRs can be measured with a simple, six-month mission.

VORTICES E/PO Activities

- **NASA Education Outcome 1 – Training the Future Workforce**
- High school Mentor Program at APL
  - Internships for qualified high school students who are placed one-on-one with a Laboratory staff member to either complete a science project or gain work experience for school credit.
- NASA/APL Summer Internship Program
  - Hands-on research opportunities for undergraduate and graduate students, mentored by the VORTICES team at APL
- Support for Post-doctoral researchers

- **NASA Education Outcome 2 – Attract and Retain Students in STEM Disciplines**
- Middle school Science Pre-service Teacher Workshop (also aligns to NASA Outcome 1) – *Cornerstone Activity*
  - Partnering with Education Departments at Historically Black Colleges and Universities, Hispanic Serving Institutions, and Tribal Colleges.
  - Workshops will primarily be conducted in the Maryland and Texas regions; both have high percentages of underserved populations and a concentration of minority institutions; one workshop per year.

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VORTICES E/PO Activities (cont.)

NASA Education Outcome 2 – Attract and Retain Students in STEM Disciplines (cont.)

- Space Academy for Middle School Students – 1/year
  - One-day event that includes a question and answer session with VORTICES scientists and engineers, and tours of APL's facilities.

NASA Education Outcome 3 – Informal Education Strategic Partnerships

- Partnership with the Maryland Science Center for International Observe the Moon Nights.
- Partnerships with Museum Alliance for informal educator training by VORTICES team scientists.

VORTICES Take Aways

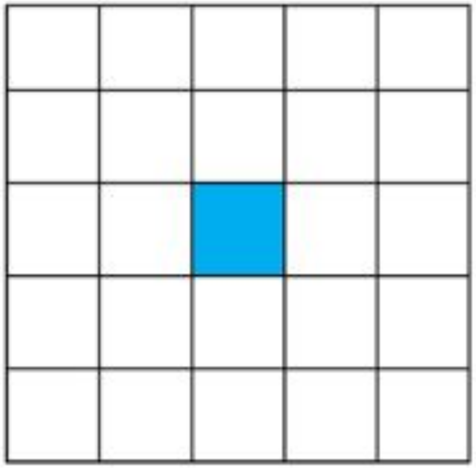
- Experienced team will conduct a strategic research project to better understand the life cycles of volatiles
- There is flexibility in the plan to ensure we target the areas of knowledge that are of the most interest to HEOMD

Remaining in sunlight

- Using LunarShader, create gridded lighting files over known DEM at known time intervals
  - 30 m/pixel LOLA DEM, 1 hr time intervals, 10/22/18 to 10/22/19

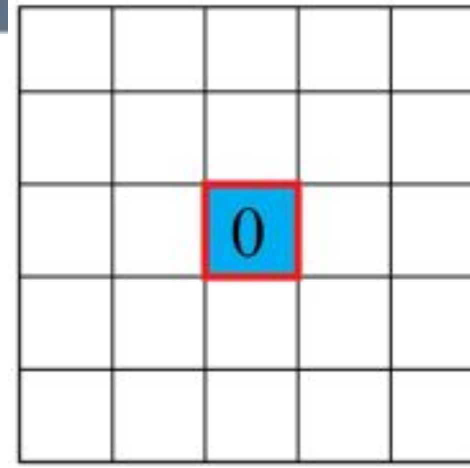
Current algorithm:

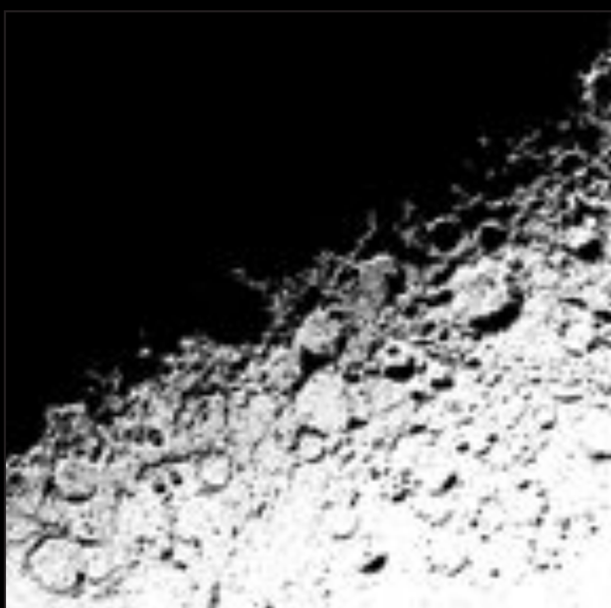
- Choose initial location, check lighting conditions at current and surrounding locations each time step
  - always know conditions for two future time
- Update current position as necessary to remain in sunlight
  - Moves at “average” rover speeds 30 m/hr (MER) to 90 m/hr (MSL)



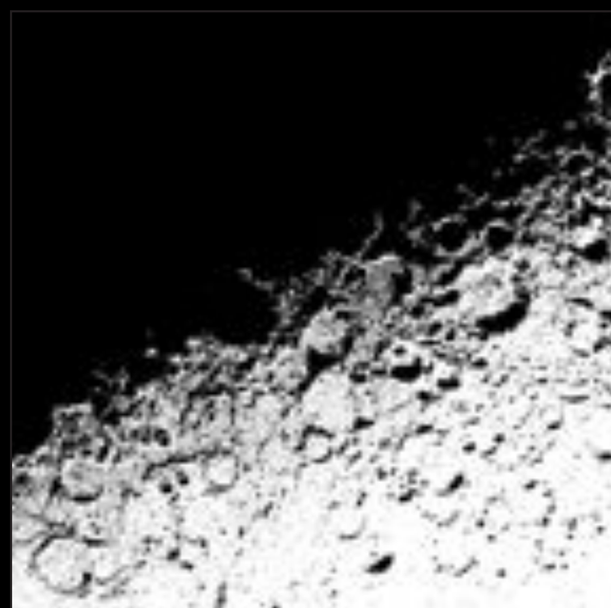
If, during the next two time steps, the pixel transitions to shadow, we search surrounding areas for light

The "rover" stays in the same location as long as it remains sunlit





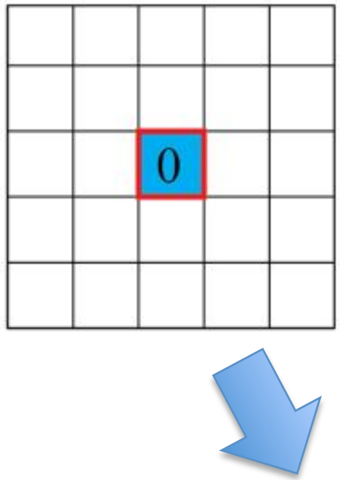
T=0



T= + 1 hr

T= + 2 hr

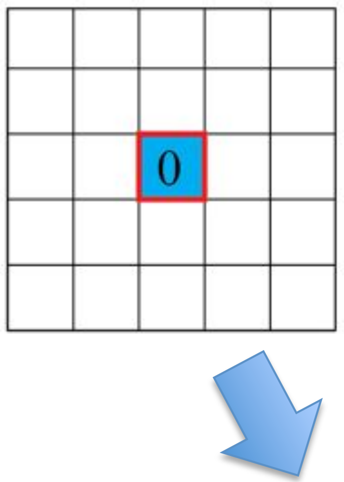
Algorithm for tracking sunlight



1/12	1/5	0	0	1/90
1/12	0	0	0	1/95
1/12	0		0	1/100
0	0	0	0	1/90
1/1	1/5	1/15	1/12	1/12

Step 1: Query the 8 surrounding pixels

- If one pixel is lit, move to that spot on next time step
- If more than one is lit, move to the spot that has the longest continuous illumination
- If none are lit, move to Step 2



Algorithm for tracking sunlight

1/12	1/5	0	0	1/90
1/12	0	0	0	1/95
1/12	0		0	1/100
0	0	0	0	1/90
1/1	1/5	1/15	1/12	1/12

Step 2: Query the 24 surrounding pixels

- If one pixel is lit, move to that spot on next time step
- If more than one is lit, move to the spot that has the longest continuous illumination