LEAG
Volatiles Specific Action Team

Final Report

12/31/14

Executive Summary

The lunar volatiles special action team (VSAT) found that there are three lunar polar areas of significant extent that fulfill the VSAT charter to identify regions "where NASA and international / commercial partners could operate on the lunar surface in a cooperative manner to further understand the size, distribution, form, and resource potential of deposits of water ice and other volatiles." These three areas, two near the south pole and one near the north pole, have combinations of hydrogen abundance and other relevant parameters that make them attractive candidates for detailed mission studies. This finding is based on our conclusion that existing orbital data are sufficient to support near term landings. However, significant uncertainties remain with regarding to the distribution of volatiles at the 10 to 100m scales accessible to near-term missions. Data and models are clear that volatiles are distributed unevenly at this scale and mission success scenarios should accommodate this likelihood. We also found that a range of new orbital missions and science support activities could reduce this risk by improving both the empirical data upon which site selections are based upon, and the scientific understanding of polar volatile evolution. Regarding landed experiments, there are several key measurements--such as compositional variation and soil geotechnical and thermal properties--within the capabilities of small near-term missions that would greatly improve the understanding of polar volatiles; obtaining any of the needed quantities would benefit subsequent missions.

Motivation and Execution

- NASA HEOMD requested LEAG form a Specific Action Team (SAT) to support international coordination of lunar activities associated with the Global Exploration Roadmap, including supporting non-traditional participants such as emerging space-faring nations and commercial and academic entities that may field lunar missions specifically aimed at polar missions
- The LEAG established the Lunar Polar Volatiles SAT to consider two principal tasks:
  - To assess if additional orbital remote sensing measurements are required to support landed missions
  - To conduct an assessment of the current state of knowledge, select and prioritize regions of interest with the potential of accessible volatiles that may support a synergistic approach of multiple missions, including measurements needed on the surface
- VSAT team membership included representatives of Government, national laboratories, universities and industry, and comprised levels of experience from graduate students though senior members of the lunar science and engineering communities
- The SAT conducted multiple telecons with briefings from relevant groups, a face to face meeting coincident with the LEAG annual meeting, and closeout telecons prior to submission of the report on December 31 2014

VSAT Membership

- Benjamin Bussey, The Johns Hopkins University Applied Physics Laboratory
- Richard Elphic, NASA Ames Research Center
- Terry Fong, NASA Ames Research Center
- Randy Gladstone, Southwest Research Institute
- John Gruener, NASA Johnson Space Center
- Myriam Lemelin, University of Hawaii
- Paul Lucey, University of Hawaii, VSAT Chair
- Clive Neal, University of Notre Dame
- Jeffrey Plescia, The Johns Hopkins University Applied Physics Laboratory, LEAG Chair
- Katharine Robinson, University of Hawaii
- Mark Robinson, Arizona State University
- Kurt Sacksteder, NASA Glenn Research Center
- Gerald Sanders, NASA Johnson Space Center
- Red Whittaker, Carnegie Mellon University
- Kris Zacny, Honeybee Robotics
- *Sponsor: Nantel Suzuki, NASA HEOMD*

Orbital Measurements Finding #1

There are sufficient data to support near-term landing site selections

- Enhanced hydrogen is widespread across the polar regions and and is sometimes concentrated in permanently shadowed regions (PSRs)
- Data show that average annual surface temperatures below 110K are also widespread, including both PSRs and areas sometimes illuminated. This characteristic allows preservation of shallow buried ice for geologic time
- LCROSS demonstrated hydrogen and water do occur at shallow depths at the LCROSS target site PSR
- However
  - Arguments derived from lunar surface processes suggest volatiles will be distributed irregularly
  - High water abundance observed by LCROSS was not consistent with the regional H abundance indicating sampling of a local concentration

Orbital Measurements Finding #2

Mapping of subsurface hydrogen with sufficient precision and resolution to resolve many individual PSRs (<5 km after any required signal averaging) is the most important orbital measurement

- Hydrogen distribution and concentration is currently the parameter of highest value in site selection studies
- Uncollimated LEND and LP neutron data have detection footprints much larger than the limited mobility ranges of near-term surface missions, and the size of many PSRs
  - The expected patchy nature of hydrogen distributions (See Orbital Measurements, Finding 1) constitutes significant risk to missions requiring detection and sampling of hydrogen
  - Higher resolution definitive hydrogen data would reduce this risk
- LEND collimated data are uncertain owing in part to the lack of consensus regarding its merits in the subject matter expert community

Orbital Measurements Finding #3

Testable hypotheses for volatile distribution should be formulated with the goal of developing a model that exceeds the attainable spatial resolution of orbital neutron measurements.

- Such a model could guide future missions and possibly reduce the risk for missions with limited mobility that require moderate or high volatile abundances--such as ISRU demonstrations

Orbital Measurements Finding #4

Missions that include early ISRU demonstrations should be aimed at sites with environmental conditions that are consistent with more extensive subsequent surface operations

- Sites similar to the LCROSS impact site feature extreme temperatures and limited access to sunlight making them challenging candidates for extended surface operations by follow-on missions
- ISRU demonstrations should be targeted to sites with more clement conditions

Orbital Measurements Finding #5

LCROSS-like impact experiments should be encouraged

- LCROSS and GRAIL impacts demonstrated the utility of using spacecraft impacts to sample subsurface volatiles
- Impact investigations of areas very different than the LCROSS site, including outside the polar regions, would increase understanding of the spatial variability of volatiles
- Impactor mass and velocity properties very different than the LCROSS experiment would sample different depths and improve understanding of the LCROSS experiment results
- The WMAP and Herschel observatory end-of-mission disposals that were not directed at the Moon represent lost opportunities to understand lunar volatiles
    - Lunar disposal of spacecraft, including spacecraft in high Earth orbits such as communication satellites at the end of their lifetimes, provide new opportunities for polar volatile investigations

Orbital Measurements Finding #6

Restarting the LRO bistatic radar capability should be a priority

- Bistatic radar measurements are the only mapping method other than neutron spectroscopy that offers direct depth sensing of volatiles
  - The LRO bistatic radar capability is the lowest cost polar volatile experiment now available
- Dual spacecraft or LRO-like combination of lunar orbit and ground-based radar should be pursued for future missions

Orbital Measurements Finding #7

New orbital remote sensing can characterize the distribution of surface volatiles, provide some insight into buried volatiles and aid understanding the cycling of polar volatiles

- New methods that directly or indirectly detect surface frost and subsurface ice can support understanding the contemporary migration of volatiles
  - Low light imaging within PSRs with much higher spatial resolution than provided by LROC NAC could reveal subsurface ice deposits by detection of anomalous fields of bright ejecta of very small (~ 1-m) craters associated with other volatile indicators
  - Active spectroscopy using orbital reflectors (i.e. Lunar Flashlight) or multispectral lasers in the 3um region would directly detect surface frost and have ancillary science benefits in understanding the lunar water cycle
  - Low light imaging spectroscopy exploiting indirect lighting such as innovative application of an M3-like instrument may also provide maps of surface frost in PSRs

Landed Measurements Finding #1

Small near term missions can provide critical data to resolve important unknowns regarding polar volatile science and resource utilization

- Lateral and vertical distribution of volatiles
- Chemical phases that contain volatile elements
- Geotechnical and thermal properties of polar soils

- Landed experiments obtaining <u>any</u> of the important quantities are of great science and exploration value

Landed Measurements Finding #2

Early characterization of the variation in volatile abundance at ISRU and scientifically relevant spatial scales would greatly benefit all future missions

- Current understanding of the spatial variation of volatile abundance at the scale of landers and small rovers is a major uncertainty. This ignorance is a strong inhibitor for the use of static landers
- Several studies suggest that near surface volatiles will be very unevenly distributed due to the impact process and other mechanisms
- A small rover traversing several hundred meters can characterize the variation in volatiles at this scale with simple instrumentation
- This would provide ground-truth for orbital volatile measurements by beginning to close the gap in scales

Landed Measurements Finding #3

The physical and chemical forms of abundant volatile elements are critical to understanding the resource and its origins

- Early measurements should include unambiguous determination of the chemical phase of volatiles present to a depth of one or more meters
- Measurements should not be restricted to the detection of water, but include other volatile species
- Profiling is desirable, but a bulk analysis would be of very high value

Landed Measurements Finding #4

Successful exploitation of *in situ* resources requires knowledge of the physical (geotechnical) and thermal properties of polar regolith in addition to the volatile abundance

- The utility of a resource is highly dependent on the cost of extraction that is in turn dependent on the physical and chemical state of the volatile and its refractory matrix
- The ISRU community should develop specific measurement objectives for geotechnical and temperature dependent properties
- Thermal analysis of polar soils such as differential scanning calorimetry would greatly enhance the ability to develop ISRU regolith processing strategies, even in a volatile poor polar target

- Thermal analysis can also be made sensitive to volatiles found in the LCROSS plume that could cause significant concerns for contamination and degradation of ISRU hardware including H_2S, Hg, and Na

Landed Measurements Finding #5

On-going development of polar rovers should include the ability to negotiate terrain and environmental conditions defined by measurement requirements (e.g. *LExSWG Lunar Surface Exploration Strategy (1995)*)

- Lunar polar regolith properties, particularly in permanent shadow, may be sufficiently different than equatorial regolith properties characterized by Apollo and Lunokhod that those measurements have uncertain applicability. Near term polar landers and rovers should include measurements relevant to trafficability (See also finding #4)
- Rover development should address sustained operations associated with acquiring measurements in extreme polar conditions. These conditions may be unique to locations associated with lunar volatiles (i.e., properties significantly different that terrestrial and Mars rover sites).
- Surface power systems development is essential to enable sustained operations

Landed Measurements Finding #6

Polar missions should leverage persistent lighting at the lunar poles

- Locations have been identified that include sunlit (long duration and temporary) areas near permanently shadowed regions
- Locations with long duration sunlit areas near permanently shadowed regions can enable establishment of infrastructure for navigation, communication, infrastructure for thermal protection during dark periods, rechargeable mobile power and power beaming

Landed Measurements Finding #7

Solar powered roving missions should take advantage of mobility to extend mission lifetime by "chasing the light"

- Preliminary engineering studies show that mission lifetimes can be drastically increased using rovers with currently available rates of advance that can stay within illuminated terrain for much longer periods than static landers
- These studies show that missions can include frequent and lengthy stops for scientific measurements enabling the extension of the scientifically useful lifetime of the missions

Landed Measurements Finding #8

In addition to ISRU goals, landed experiments should include measurements of current volatile flux to aid understanding volatile transport mechanism

- Apollo surface experiments revealed a dynamic exosphere and produced a lengthy list of potential volatile atmospheric species
- Measurements might include:
  - Pressure
  - Atmospheric species
  - Flux directions
  - Measurements at PSR contacts to measure the volatile flux into cold traps

Regions of Interest: Background

- International efforts to explore the polar regions may leverage discoveries and infrastructure from multiple landings if a single or small number of sites are agreed upon having the potential of accessible volatiles
- This builds upon the LEAG Robotic Precursor Campaign document of 2011 (http://www.lpi.usra.edu/leag/reports/RoboticAnalysisLetter.pdf)
- VSAT was tasked with identifying or constraining potential regions of interest
- Two approaches were used to reveal widespread regions of interest
    1. Optimizing a number of volatile relevant and environmental parameters: H abundance, temperature, slope, proximity to PSR and Earth visibility for direct communications
    2. Identifying regions similar to the LCROSS impact site based on H abundance and annual average temperature
- These were supplemented by examining
    - Visibility from Earth for line of sight communication
    - Total lighting over a lunar diurnal cycle
    - Proximity to PSR < 1 km (allowing small rovers to access)

Regions of Interest: Finding #1

At both poles there are regions that are generally suitable for a common landing region

1. **Cabeus vicinity (south pole)**
2. **Shoemaker/Nobile vicinities (south pole)**
3. **Peary vicinity (north pole)**

- **These are:**
  - Volatile rich (H > 150 ppm)
  - Can maintain subsurface ice (average annual surface temperature < 110K),
  - Modest slopes (10 degrees)
  - Adjacent to locations similar to the LCROSS impact site in terms of H abundance and temperature
  - Availability of PSR from lit areas
- When including Earth visibility and lighting explicitly, the north polar Peary vicinity is slightly favored owing to somewhat more persistent lighting, with the Cabeus vicinity showing the least persistent lighting

Regions of Interest: Finding #2

Specific landing sites for individual missions are critically dependent on mission goals and capabilities

- However, a study by NASA Ames Research Center in support of the RESOLVE polar resource mission demonstrated that within general regions of interest, many acceptable landing sites were available

Criteria For Site Identification

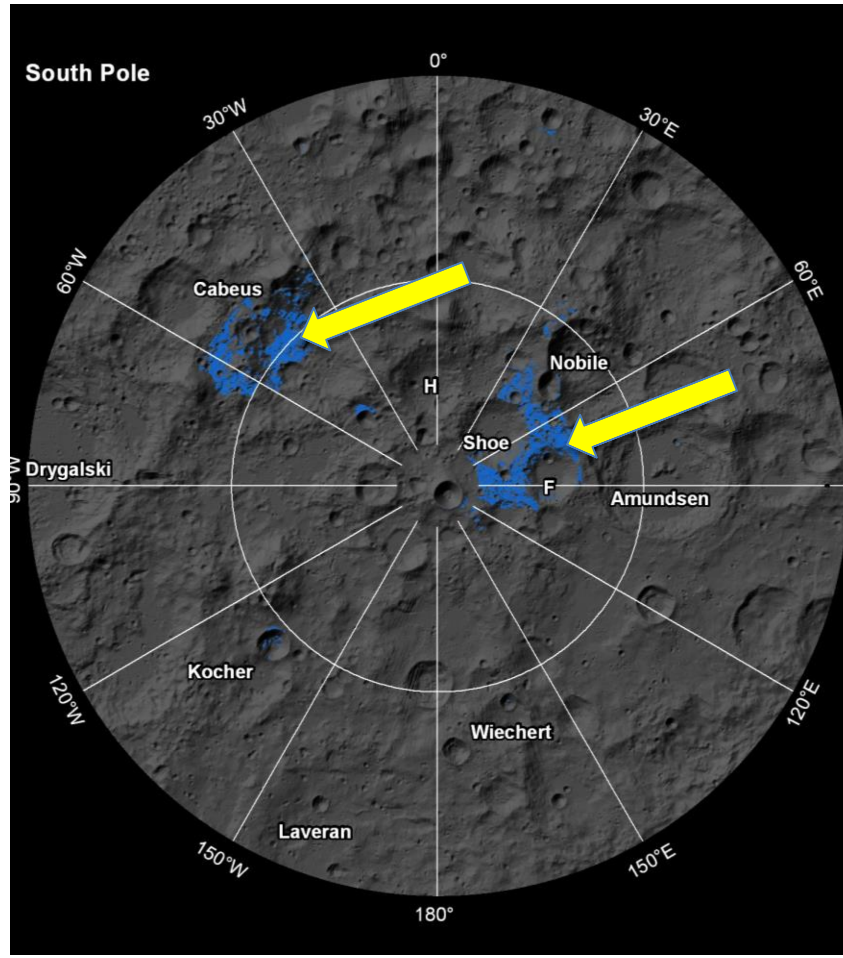
- Temperature
  - Average, minimum and maximum surface temperatures
- H concentration
  - LRO/LEND and Lunar Prospector
- Slope
- Lighting conditions
  - Duration of illumination
  - Permanent shadow
- Direct to Earth communication potential

Regions of Interest: Multi-parameter analysis

South Pole

- H>150 ppm
- Average T < 110K
  - Preserves subsurface ice for geologic time
- Slope < 10 degrees
  - Navigable by current rovers
- Outside and adjacent to PSR
  - Lighting available

Cabeus and Shoemaker/Nobile vicinities meet general criteria and have some Earth visibility



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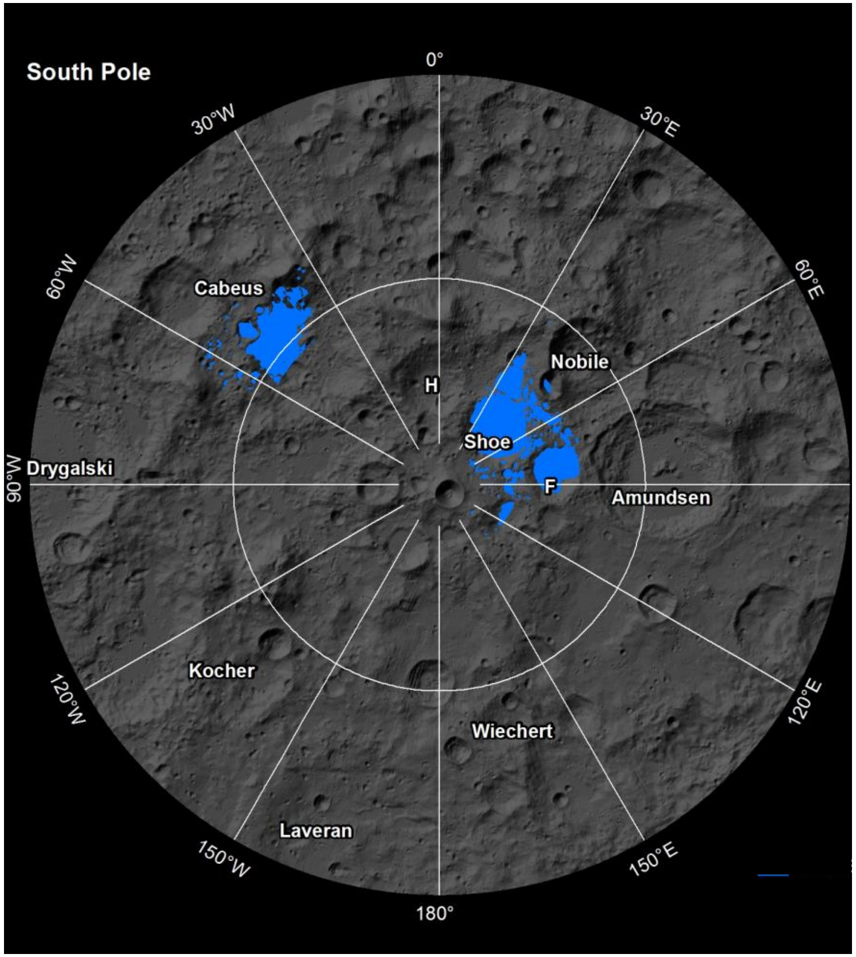
Regions of Interest: Similarity to LCROSS site

South Pole

- Regions similar to LCROSS Cabeus site in H and annual average temperature
  - "Likeness" is Euclidean distance from Cabeus H and T value

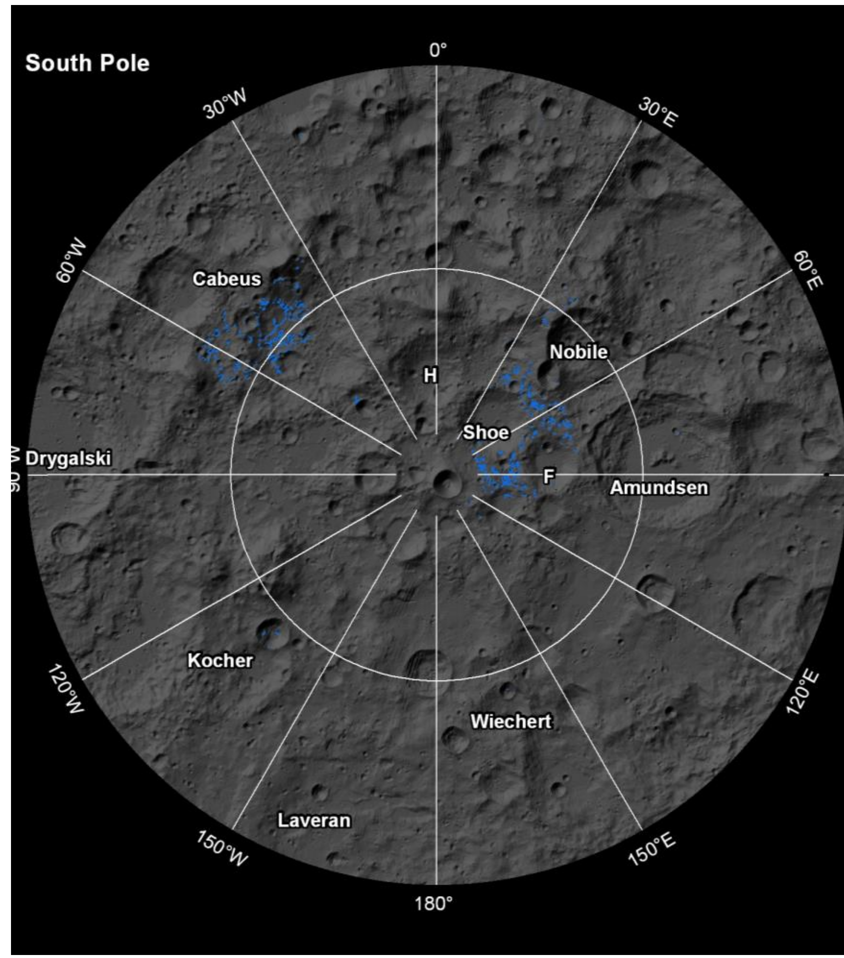
$$"Likeness" = \sqrt{(H - H_{Cabeus})^2 + (T - T_{Cabeus})^2}$$

Cabeus and Shoemaker/Nobile vicinities contain locations most similar to LCROSS site in H and temperature



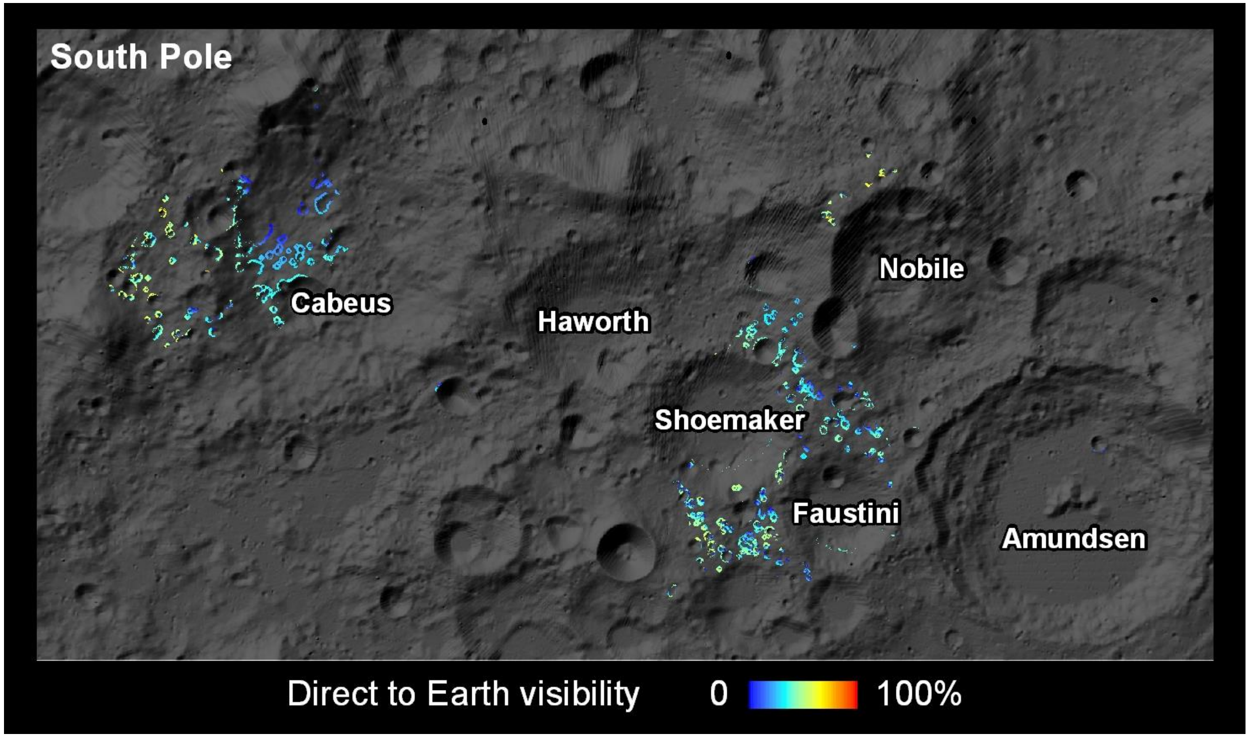
Regions of Interest: Proximity to PSR < 1 km

- South Pole
  - Sites meeting multiparameter analysis criteria and having PSR within 1 km
  - Distribution is patchy but shows access to PSR from lit areas is available



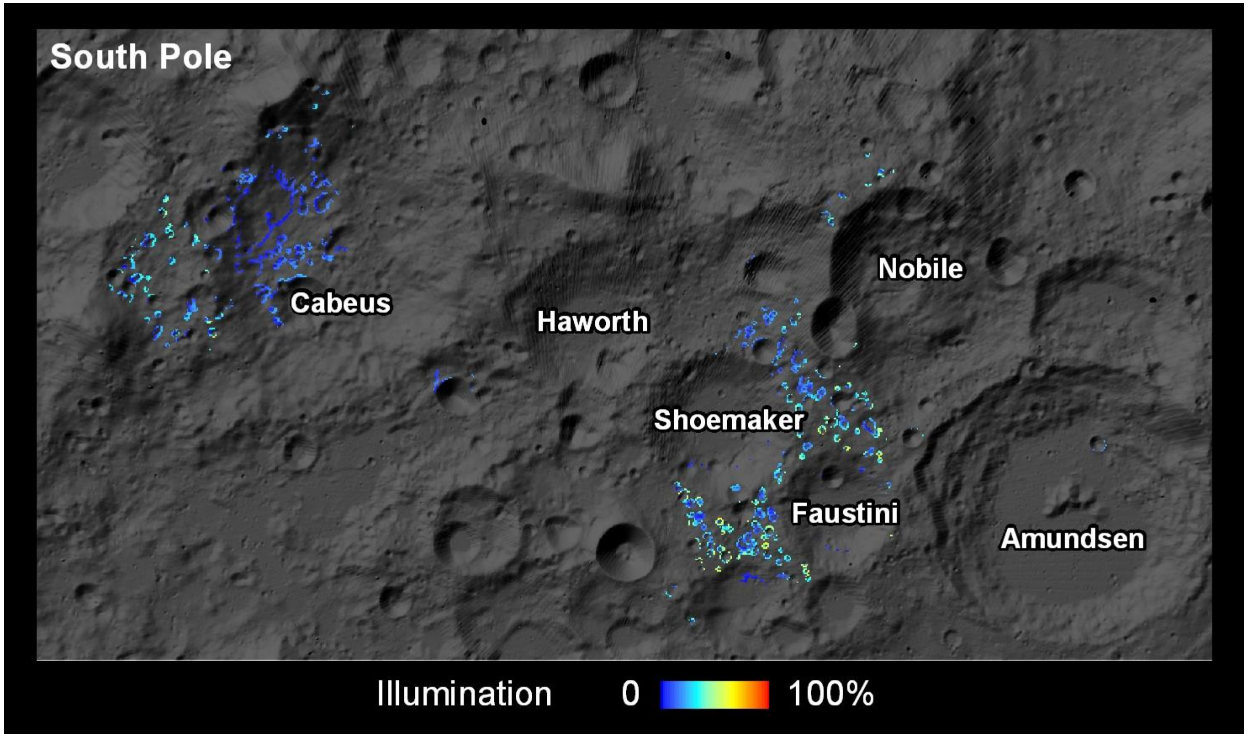
Regions of Interest: Proximity to PSR < 1 km and Earth Visibility

- **South Pole**
- These areas meet the H, T, and slope criteria, and are within 1 km of a PSR
- **Colors indicate earth visibility**



Regions of Interest: Proximity to PSR < 1 km and Persistent Lighting

- South Pole
- These areas meet the H, T, and slope criteria, and are within 1 km of a PSR.
- **Colors represent percent lighting per month**
- Availability of illumination is generally low with restricted regions having ~50% available lighting



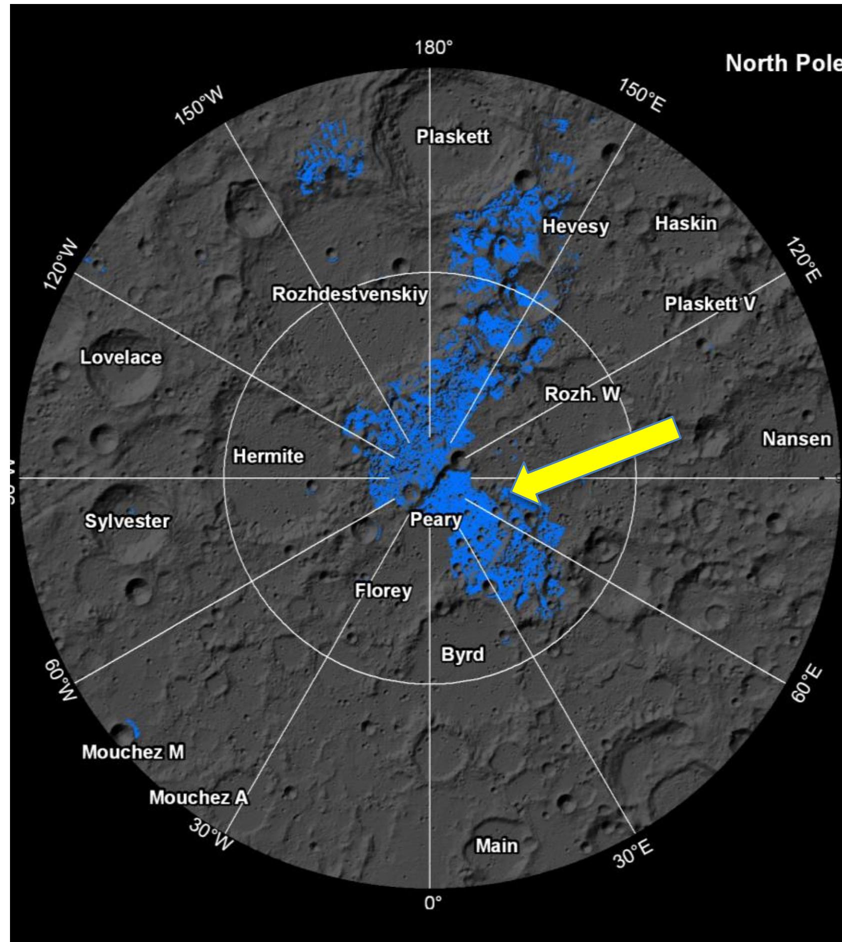
Regions of Interest: Multi-parameter analysis

North Pole

- H>150 ppm
- Average T < 110K
  - Preserves subsurface ice for geologic time
- Slope < 10 degrees
  - Navigable by current rovers
- Outside PSR
  - Lighting available

Peary vicinity meets general criteria and has Earth visibility

Substantial area of farside also meet general criteria



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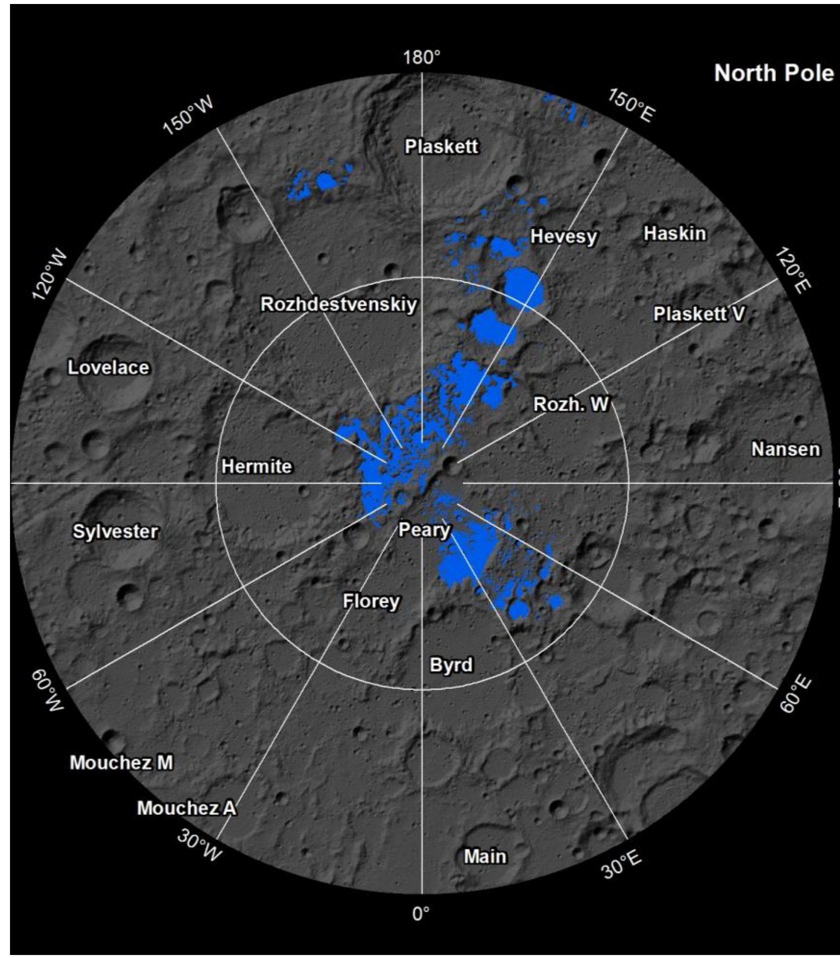
Regions of Interest: Similarity to LCROSS site

North Pole

- Regions similar to LCROSS Cabeus site in H and temperature
  - “Likeness” value threshold at <30

Peary and the north rim of Hermite vicinities contain locations most similar to LCROSS site in H and temperature with Earth visibility



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- North Pole
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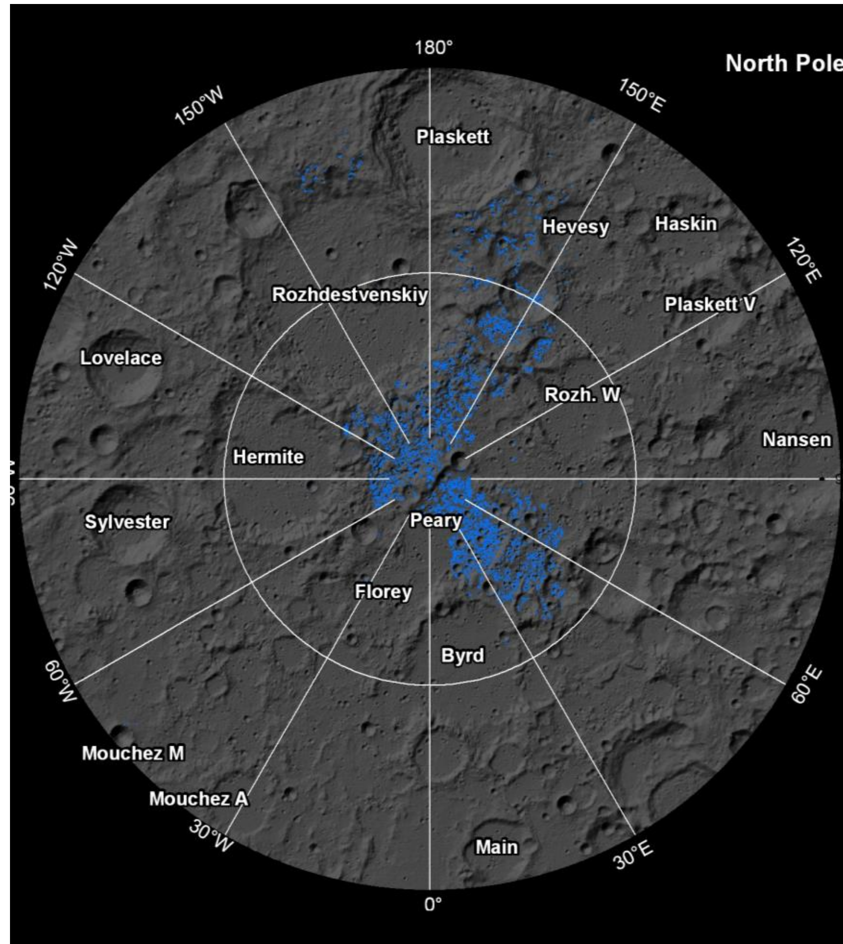
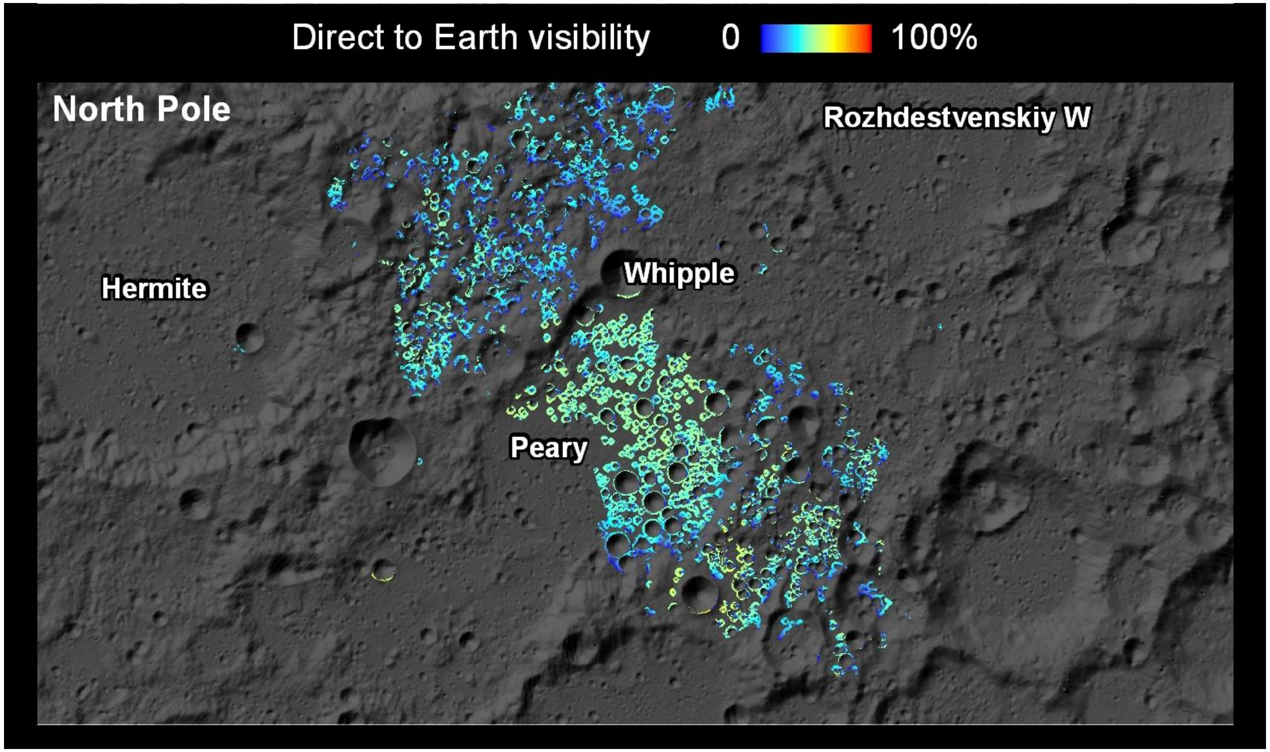
  - Distribution is patchy but shows access to PSR from lit areas is extensive



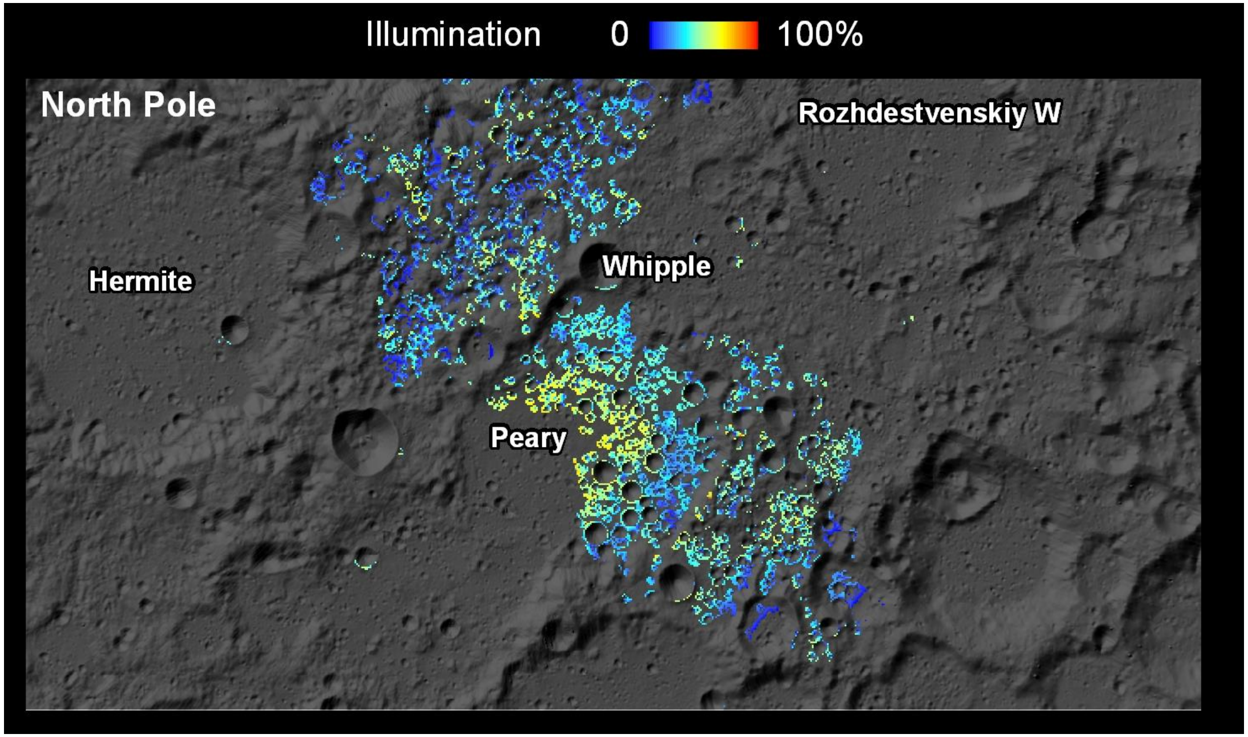
Regions of Interest: Proximity to PSR < 1 km and Earth Visibility

- **North Pole**
- These areas meet the H, T, and slope criteria, and are within 1 km of a PSR
- **Colors indicate earth visibility**



Regions of Interest: Proximity to PSR < 1 km and Persistent Lighting

- **North Pole**
- These areas meet the H, T, and slope criteria, and are within 1 km of a PSR.
- **Colors represent percent lighting per month**
- Availability of illumination in the Peary region is more favorable than the south polar site, or the farside north polar sites



Compatibility of platforms with priority measurements

	Static lander with limited subsurface access	Static Lander with drill	Rover		
			Surface sampling only	Limited subsurface access (<20 cm)	drill (>1 m)
Variability of volatile distribution	1	2			
Chemical Phase of Volatile Elements	3		4	5	
Chemical and physical behavior of polar soil with temperature			6		
Geotechnical properties			7		
Current volatile flux					

1,2) Lack of mobility excludes sampling 100-m horizontal scale
3, 4, 5) Limited subsurface access may not reach volatiles
6,7) surface soil may not be representative of properties relevant to mobility or ISRU