# LUNAR POLAR VOLATILES: EVALUATION OF EXISTING DATA SETS.

D. M. Hurley[1]; [1]Applied Physics Laboratory, Johns Hopkins University, Laurel, MD (dana.hurley@jhuapl.edu)

**Introduction:** Human exploration is facilitated by in situ resource utilization (ISRU) because the production of consumables on site reduces the amount of material that must be launched from Earth's deep gravity well. Water is a valuable resource because it can be used to produce fuel and staples of life support. In order to make effective use of in situ resources, it is important to constrain the quantity, the form, and the distribution before the need to use them arises.

The abundance of water is the most important constraint on the viability of the resource for use. It defines the scale of the operations to produce the desired products. In addition, the abundance is related to the original abundance and the retention efficiency, and therefore can be used to infer the inventory of volatiles in the Inner Solar System over time. Data already indicate that volatiles have a heterogeneous distribution both in depth and lateral location. The size scale of the heterogeneity determines the amount of mobility and subsurface access needed to extract the volatiles. Relating the external conditions to the distribution will enable best application of remote sensing and reconnaissance data to predict the presence of the resource on operational scales. Understanding the processes that modify the distribution over time is indicative of the stability and renewability of the resource. At smaller scales, the physical form affects the distribution. There are multiple potential physical forms of water, including ice, frost, hydrated minerals, adsorbed monolayers, and ice-soil mixtures. Another factor of interest is the composition, including the molecular constituents and isotopic ratios. The collection of constituents and isotopic data provide clues as to the original source, and therefore the renewability of the resource. The presence of contaminants will be identified.

**Composition:** The composition of lunar polar volatiles is determined by spectroscopy. Spectral features provide an unambiguous identification of the molecular constituents. But spectral detection methods have limitations.

An illumination source is needed for reflectance spectroscopy. This is problematic in persistently shadowed regions, where direct sunlight cannot be used. The Lunar CRater Observation and Sensing Satellite (LCROSS) experiment provided the best window into the composition of lunar polar volatiles because the impact lofted material from the floor of the permanently shaded crater into sunlight where spectra can be observed. [1, 2] present the spectroscopic analysis of the ejecta from the LCROSS impact into Cabeus. They identified (with $> 3\sigma$ detection) the presence of water vapor and water ice. However, the impact introduces some ambiguities that must be considered. The impact may have induced chemistry that altered the molecular composition of the material that was released. Contributions from the impactor itself must be considered. Although most scientists agree that water was positively detected in the LCROSS plume, identification of some of the organic species is more tentative, and the spectrum is not well-modeled longward of 2.1 μm.

Using starlight to provide illumination in the ultraviolet, LAMP observes the water ice absorption edge at 165 nm within persistently shadowed regions. Although this is a spectral signature, the low levels of illumination make it such that the spectrum is binned only into broad wavelength ranges. [3, 4] present maps using this Far UV spectral signature. The spectral properties of lunar regolith mixed with water and ice are not well-studied in the UV. Given that and the poor spectral resolution possible using low lighting, this particular observation is better used to support other observations, rather than to be conclusive on its own.

Neutron spectroscopy is sensitive to the presence of hydrogen, although it cannot distinguish between various chemical forms. Neutron data from LPNS and LRO LEND both show a depression in neutron flux at high latitudes that is associated with an enhancement in hydrogen-bearing material at high latitudes [5], which supports an inferred thermal mechanism for retaining the material. Thus thermal studies offer an important constraint in that it provides information about the regions where certain volatiles are stable against sublimation [6]. The Diviner temperature measurements provide data for all times of day and seasons.

**Distribution:** The distribution of water in lunar polar regions is heterogeneous on many scales down to the limit of existing spatial resolution. Neutron data indicates that hydrogen is enhanced at high latitudes, both inside and outside of permanently shadowed regions. Surface reflectance data indicate that not all PSRs have uniformly low albedo within the crater, consistent with a diversity of surface processes.

Within an individual PSR, there is still heterogeneity. The abundance of water inferred from the LCROSS impact, 5%, was greater than the abundance of the surrounding region, 0.5% from neutrons [7], indicating the impact was into a subregion that was relatively rich. Alternatively, the high abundance of water could have originated at depth below the ~1 m depth probed by neutron spectroscopy. The crater formed by the LCROSS impact is expected to have excavated to a depth of 2-3 m. Indeed a temperature gradient is expected with depth that might influence the depth profile of trapped water ice. However in Cabeus, the temperature is so cold that ice is expected to be immobile at all depths given the present obliquity of the Moon.

Both radar data and neutron data are sensitive to the presence of volatiles within the top meter of regolith. Analyzing the flux of neutrons in multiple energy ranges provides information about the average depth distribution. One location, Shackleton crater, has high fast neutron flux consistent with hydrogen on the surface [8]. [9] found that although a depression in epithermal neutrons is the expected signature when hydrogen is buried, there may actually be excess epithermal neutrons if that hydrogen resides near the surface. Therefore, the differences in epithermal neutron flux from crater to crater may reflect differences in the depth of the hydrogen or may be caused by different abundances of hydrogen.

Laser reflectivity experiments demonstrate a correlation between lunar albedo at 1064 nm and locations with high potential for surface water frost. LOLA data [10] indicate higher reflectivity on poleward facing slopes than on equatorward facing slopes. LAMP and LEND data exhibit differences on poleward facing slopes that require further investigation.

**Abundance:** Measurement of the abundance conflates with the heterogeneous distribution of water ice owing to the spatial resolution of the data. Thus these values represent averages on size scales > 1 km.

Neutron spectroscopy provides the best integrated measure of the abundance of volatiles in lunar polar regions, although the ambiguity regarding the actual chemical composition exists. LPNS data are consistent with 1.5 ± 0.8% water equivalent hydrogen broadly distributed within the top 1 m of regolith in the polar regions [11]. Within PSRs 10° of the pole and 1 m of the surface, this integrates to on the order of $10^{11}$ kg of water [12]. More recent data from LEND yield similar values on average [7]. The measurements sensitive to the abundance on the extreme surface are consistent with concentrations < 2-3% in all PSRs, and < 1 % in most PSRs. However, there are many assumptions that go into these numbers and the systematic uncertainties are high.

**Physical Form:** Presently, there is very little known about the physical form of water ice in lunar polar regions. Radar data would reveal if coherent, pure ice blocks exist through the properties of the coherent backscatter. Unlike at the planet Mercury, radar evidence is not consistent with widespread, ice layers with thickness > 10 cm on the Moon. Two observations possibly support the presence of coherent ice blocks. One is an anomalous feature in the CPR observed in polar craters where only the insides of the craters have high CPR [13]. Elsewhere on the Moon, if the inside of the crater has high CPR, the outside of the crater does as well. This may indicate a subsequent deposition of ice in a crater in PSRs. However, this is controversial and has not been confirmed by a secondary technique. Secondly, bi-static observations using Mini-RF have revealed a phase effect in the CPR in Cabeus crater that is more consistent with ice than with rock [14]. This supports that there may be isolated regions with coherent ice blocks.

The LCROSS experiment also shed some light on the physical form of water in PSRs. The spectra were modeled using a combination of ice and water vapor. Both were needed to reproduce the spectra indicating that at least some of the water, if not all of it, is stored as ice in Cabeus. Additional studies of the time evolution of the plume indicate a shift in color that is attributed to a change in the size of the dust grains over time. The data are consistent with the sublimation of ice from the grains over time.

However, the lack of pervasive signature in radar is consistent with ice filling the pore space, adsorbed layers, hydrated minerals, or ice blocks < 10 cm in scale. It is unlikely that “skating rinks” of ice exist on the Moon.

**Next steps:** Many of the next steps to facilitate ISRU of lunar polar water are summarized in the 2014 Lunar Exploration Analysis Group (LEAG) Volatiles Strategic Action Team (VSAT) report. Multiple missions are in planning that would, if successful, enhance the understanding of the composition, distribution, and abundance of water in lunar polar regions. A multifaceted approach is necessary to effectively characterize the resource. Ground truth is essential to provide in situ confirmation of the composition and abundance. Subsurface access will resolve the depth distribution. Observations with lateral spatial resolution spanning 1 m – 100 m distance scales are most relevant. Monitoring the present day variability in the reservoir will provide data on durability and potential for renewal of water on timescales relevant for human exploitation. Further, the value of scientific understanding via laboratory experiments, theoretical work, and modeling cannot be overestimated.

**References:** [1] Colaprete et al. Science 330, 2010. [2] Gladstone et al. Science 330, 2010. [3] Gladstone et al. JGR 117, 2012. [4] Hayne et al. Icarus 255, 2015. [5] Feldman et al. Science 281, 1998. [6] Paige et al. Science 330, 2010. [7] Sanin et al. Submitted. [8] Miller et al. Icarus 233, 2014. [9] Lawrence et al. JGR 116, 2011. [10] Lucey et al. JGR 2014. [11] Feldman et al. JGR 106, 2001. [12] Eke et al. Icarus 200, 2009. [13] Spudis et al. JGR 118, 2013. [14] Patterson et al Icarus 2016.