Lunar Surface Measurements to Inform Both Science and In Situ Resource Utilization

White Paper submitted to: The Artemis Science Definition Team

Author List: A. C. McAdam[1], D. M. H. Baker[1], E. H. Cardiff[1], J. B. Garvin[1], A. M. Parsons[1], D. P. Glavin[1], P. R. Mahaffy[1], D. M. Bower[1,2], R. D. Arevalo[3], K. C. Gendreau[1], Z. Arzoumanian[1], K. E. Young[1], J. Jones[1], R. Kent[1], J. E. Bleacher[1], M. Amato[1], M. L. Lupisella[1], P. A. Gerakines[1], C. I. Honniball[1,4], Z. R. Morse[1,5], C. N. Achilles[1,4], N. M. Curran[1,4], C. A. Knudson[1,2], and M. Benna[1,6].

[1]NASA GSFC, Greenbelt, MD (Amy.McAdam@nasa.gov), [2]CRESST, University of Maryland, College Park, MD, [3]University of Maryland, College Park, MD, [4]Universities Space Research Association at NASA GSFC, Greenbelt, MD, [5]Howard University, Washington, D.C., [6]University of Maryland Baltimore County, Baltimore, MD

Introduction: In 2019 NASA announced plans to resume crewed missions to the Moon by 2024 and achieve a sustainable human presence by 2028. Production of mission consumables from lunar materials, In Situ Resource Utilization (ISRU), is an important aspect of sustainable human surface operations. One key in situ resource will be water, sources of which have been identified in the lunar polar regions planned for crewed missions. This water would provide both fuel and oxygen for refueling vehicles as well as life support consumables. However, there are still important questions about the nature and extent of this resource. Additional resources include metals and metal oxides.

The measurements of lunar materials required for ISRU overlap in many cases with those desired to understand lunar science questions [e.g., 1], though they are not fully inclusive. Here we will: 1) Discuss in situ measurements of lunar materials that could be made in preparation for, and during, crewed missions to the lunar surface that would benefit both science and ISRU, 2) Indicate some differences between science and ISRU needs where they occur, and 3) Describe several capabilities and example technologies which can be used to obtain the measurements.

In situ survey-type measurements: Measurements of the vertical and lateral distribution of a resource, such as ice and/or other water sources, will inform both science questions which require an understanding of the distribution as well as the development of approaches to assess use of the material for ISRU purposes. For example, water ice has been inferred to be present at both the lunar south and north pole based on data from M^3, LOLA, Diviner, and LAMP [2-5]. However, more detailed knowledge of its abundance and distribution in the shallow subsurface on meter and smaller scales is highly desired to inform ideas about its origin for science purposes (e.g., comet or asteroid delivery [e.g., 6]), early volcanic outgassing [e.g., 7], or solar wind interaction with surface materials [e.g., 7,8]) and inform ideas about how to access and process it for ISRU.

Capabilities that can survey the ~10 cm scale distribution of ice to depths of at least one meter and spatial scales of 100s of m or more will be critical in and of themselves, and important for follow up approaches (see "Sampling" section below). Methods for these measurements can include neutron (NS) and gamma ray spectroscopy (GRS), ground penetrating radar (GPR), and electromagnetic sounding (E-M). For example, the Bulk Elemental Composition Analyzer (BECA) instrument concept [9], funded by NASA's Development and Advancement of Lunar Instrumentation (DALI) program, would reveal bulk subsurface elemental composition, including H, at relevant survey scales. While the next generation of orbital radars such as the Space Exploration Synthetic Aperture Radar (SESAR) instrument [10] can image and profile for subsurface ice across large regions of the lunar surface, analog field work using GPR [e.g., 11] demonstrates the utility of surface radar instruments for determining the detailed stratigraphy and quantity of ice in local areas of the shallow subsurface. Survey capabilities for other resources will also provide key ISRU and science inputs. For example, NS and GRS will also provide bulk chemistry relevant to potential metal extraction. GPR can measure regolith dielectric and radar scattering properties that can be used to infer bulk material properties such as titanium content, metals, and geotechnical properties (e.g., density, large boulders).

In situ measurements which involve samples: After the location of potential resources is constrained by survey techniques such as those described above, sampling and sample analysis will be needed to further inform science questions and ISRU needs. To continue with the key ice resource example, in addition to its local scale distribution inferred by survey techniques, finer scale distribution (in specific downhole looks after a drilling campaign, or observed in extracted drill cores), and detailed knowledge of the chemical and isotopic composition of the ice, has not yet been obtained. Isotopic composition, and elemental chemical composition, can inform the science goal of understanding the source of the water. For example, the D/H isotopic composition of water derived from comets/asteroids, lunar volcanic outgassing, and solar wind production will be different in each case, so the D/H composition of lunar ice can inform the ice source(s). The chemical composition of the ice may also inform the ice source, since ice largely associated with volcanic outgassing, for example, may tend to have more volatile impurities such as S and Cl [7, and references therein]. Understanding the source of the water is also relevant to ISRU because it can potentially assist with an extrapolation of the subsurface ice distribution measured at a mission landing site to broader areas. In addition, understanding the ice chemical composition will help ISRU planners consider what water treatment processes may be needed post extraction to prepare the water to spec for fuel or human consumption.

There is a wide array of approaches that could inform fine scale distribution, and also chemical and/or isotopic composition, of the ice. Some examples for downhole or intact drill core observations of fine scale distribution include reflectance spectroscopy, Raman spectroscopy and laser induced breakdown spectroscopy. One concept that would combine reflectance and Raman spectroscopy is the Rapid Optical Characterization Suite for in situ Target Analysis (ROCSTAR) [12]. Some examples for extracted water abundance and water/ice chemistry and isotopic composition include sample processing techniques (such as sample heating) coupled with mass spectrometer (MS) or tunable laser spectrometer (TLS) instruments. One concept for pyrolysis MS of lunar samples to measure water and other evolved sample volatiles, as well as constrain several volatile isotope ratios is the Volatile Analysis by Pyrolysis of Regolith (VAPoR) (Figure 1) [13]. This instrument is based on the evolved gas analysis (EGA) mode of the Sample Analysis at Mars (SAM) instrument on the Mars Curiosity rover, which has characterized volatiles evolved during heating of a variety of martian samples. The EGA-MS technique is simpler to implement than GCMS (e.g., no carrier gas is needed, the gas processing system is less complex, etc.) making it well suited to the first in situ pyrolysis analysis of a lunar sample. The VAPoR concept does not incorporate a TLS but could be adapted to do so based on experience with pyrolysis-TLS that has been performed by SAM. Overall, experience with extraction of volatiles with heating and measurement of those volatiles can be directly applied to planning of ISRU volatile extraction reactors.

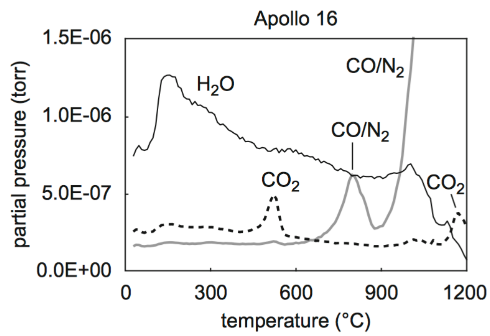

Fig. 3. VAPoR breadboard data from Apollo 16 sample [13].

Sample analysis capabilities for other materials that can be resources will also inform lunar science questions and ISRU requirements. For example, locating metals within, and assessing the internal structure of, rocks and other samples could be done with non-destructive techniques such as x-ray computed tomography (xCT) [14]. Assessing metals and metal oxides in samples could also be carried out with the CRaTER (Characterization of Regolith and Trace Economic Resources) laser ablation MS concept currently under development under the DALI program [15]. In addition, XRF and XRD instrument concepts such as the Chromatic Mineral Identification and Surface Texture (CMIST) [16] and DALI-funded eXTraterrestrial Regolith Analyzer (XTRA) [17] could constrain material elemental chemistry and mineralogy. Detailed understanding of structure and chemistry of lunar materials can inform models of lunar geologic history, as well as constrain possible metal and other resources of use to ISRU goals. These types of technologies could also be used to evaluate mission hardware for structural damage or contamination.

Summary: The example approaches and instrument concepts discussed here could, in most cases, be implemented either as part of CLPS payloads or other non-crewed in situ mission operations or set up and utilized by crew during human surface operations. Many of the approaches discussed are multi-purpose, with applications to important science measurements, several different aspects of ISRU (resource prospecting, assessment of extracted and processed resources), and in some cases possible assessment of mission hardware health. Multi-use analyses such as these can improve science return from both crewed and non-crewed missions while also simultaneously helping lay the groundwork for a sustained scientific investigation of the Moon by humans.

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