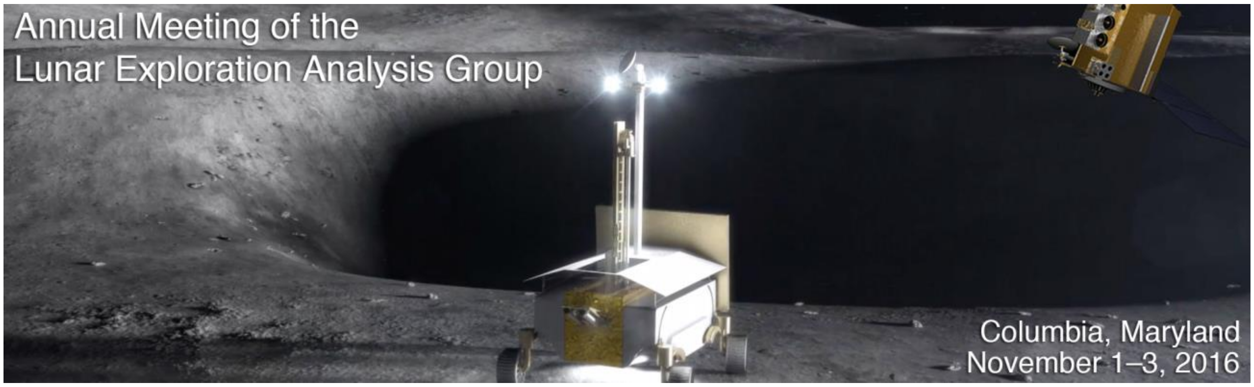

Annual Meeting of the Lunar Exploration Analysis Group

November 1–3, 2016

Meeting Program

LUNAR AND PLANETARY INSTITUTE

USRA

Annual Meeting of the Lunar Exploration Analysis Group

November 1–3, 2016 • Columbia, Maryland

Institutional Support

NASA Lunar Exploration Analysis Group (LEAG)
Lunar and Planetary Institute (LPI)
Universities Space Research Association (USRA)
National Aeronautics and Space Administration (NASA)
NASA Solar System Exploration Research Virtual Institute (SSERVI)

Organizing Committee

Clive Neal, Convener
University of Notre Dame

Stephen Mackwell, Convener
Universities Space Research Association

James Carpenter
European Space Agency-ESTEC

Ryan Clegg-Watkins
Washington University, St. Louis

Jasper Halekas
University of Iowa

Dana Hurley
Johns Hopkins University/Applied Physics Laboratory

Samuel Lawrence, Program Chair
NASA Johnson Space Center

Noah Petro
NASA Goddard Space Flight Center

Jeffrey Plescia
Johns Hopkins University/Applied Physics Laboratory

Jerry Sanders
NASA Johnson Space Center

Abstracts for this workshop are available in electronic format via the workshop website at **www.hou.usra.edu/meetings/leag2016/** and can be cited as Author A. B. and Author C. D. (2016) Title of abstract. In *Annual Meeting of the Lunar Exploration Analysis Group,* Abstract #XXXX. LPI Contribution No. 1960, Lunar and Planetary Institute, Houston.

Guest Speaker

Wednesday, November 2
7:00 p.m.

Congressman Jim Bridenstine (R-OK)
Update on the American Space Renaissance Act

The Congressman's remarks will touch on how NASA can leverage the private sector when conducting lunar missions, as well as the policies needed to ensure free enterprise can occur on the Moon and in cislunar space.

LEAG Bernard Ray Hawke Next Lunar Generation Career Development Awards

Sponsored by:

Recipients

Prasun Mahanti, *Arizona State University, Tempe*

Nathan Otten, *Carnegie Mellon University, Pittsburgh*

Angeliki Kapoglou, *International Lunar Exploration Working Group, Cupertino, California*

LRO Data Training

Do you have questions about how to access data from LRO?

Are you interested in learning more about what data LRO has collected?

Stop by the LRO booth to get your questions answered!

Noah Petro
NASA Goddard Space Flight Center
Universities Conference Room
Tuesday and Wednesday
During LEAG Meeting Breaks

Thank you USRA Headquarters for hosting LEAG 2016

Poster Session/Reception sponsored by:

MOON EXPRESS

Technical Guide to Sessions

Tuesday, November 1, 2016

7:30 a.m.	USRA Education Gallery	Registration
8:30 a.m.	USRA Conference Center	Lunar Community Updates
1:45 p.m.	USRA Conference Center	Building a Moon Village

Wednesday, November 2, 2016

8:30 a.m.	USRA Conference Center	Impact of Commerce on Science and Exploration
10:15 a.m.	USRA Conference Center	Recent Lunar Science and Exploration Results
1:15 p.m.	USRA Conference Center	New Views of Lunar Regolith
4:15 p.m.	USRA Conference Center	Resource Prospector: Exploring the Most Valuable Real Estate in the Solar System
6:00–8:00 p.m.	USRA Education Gallery	Poster Session/Reception
7:00 p.m.	USRA Conference Center	Guest Speaker — Congressman Jim Bridenstine *Update on the American Space Renaissance Act*

Thursday, November 3, 2016

8:30 a.m.	USRA Conference Center	New Missions to the Most Exciting, Accessible, and Affordable Planet in the Solar System
1:00 p.m.	USRA Conference Center	LEAG 2016 Findings and Conclusions

Program

Tuesday, November 1, 2016
LUNAR COMMUNITY UPDATES
8:30 a.m. USRA Conference Center

Chairs: **Samuel Lawrence**
Clive Neal

8:30 a.m. Lawrence S. J. *
Welcome, LEAG Meeting Logistics, and Hawke Awards

8:40 a.m. Neal C. R. *
LEAG Update

8:50 a.m. Foing B. * (for ESA Director General J. Woerner)
The European Space Agency's Vision for a Moon Village
ESA is elaborating the concept of a Moon Village with the goal of a sustainable human presence and activity on the lunar surface as an ensemble where multiple users can carry out multiple activities.

9:20 a.m. Williams G. *
Human Exploration and Operations Mission Directorate Update

9:40 a.m. Cruzan J. *
HEOMD AES Update

10:00 a.m. Bussey B. *
ISECG Update

10:15 a.m. Gruener J. E. * Suzuki N. H. Carpenter J. D.
International Coordination of Exploring and Using Lunar Polar Volatiles **[#5080]**
This abstract discusses the efforts of an International Space Exploration Coordination Group (ISECG) study team to coordinate the worldwide exploration of lunar polar volatiles. This effort includes the development of a website and conducting virtual workshops.

10:30 a.m. BREAK

10:45 a.m. Keller J. W. * Petro N. E.
The Lunar Reconnaissance Orbiter Cornerstone Mission: A Synergistic Study of Fundamental Solar System Processes **[#5036]**
LRO has been granted a two-year extension to study the fundamental processes recorded on the Moon. This Cornerstone Mission employs all seven instruments to constrain the science questions, creating an integrated study of the Moon and its environment.

11:00 a.m. Halekas J. *
ARTEMIS Mission Update

11:15 a.m. Gaddis L. *
New Views of the Moon 2 Update

11:30 a.m. Shearer C. K. * Eppler D. Farrell W. Gruener J. Lawrence S. Pellis N. Spudis P. D. Stopar J. Zeigler R. Neal C. Bussey B.
Results of the Lunar Exploration Analysis Group (LEAG) GAP REVIEW Specific Action Team (SAT). Examination of Strategic Knowledge Gaps (SKGs) for Human Exploration of the Moon. **[#5025]**
We review the activities of the LEAG GAP-REVIEW SAT that examined retired and current Strategic Knowledge GAPS for human exploration of the Moon.

11:45 a.m. Kramer G. Y. * Lawrence D. J. Neal C. R. Clark P. E. Green R. O. Horanyi M. Johnson M. D. Kelso R. M. Sultana M. Thompson D. R.
Lunar Capabilities Roadmap **[#5041]**
A Lunar Capabilities Roadmap (LCR) is required to highlight capabilities critical for science and exploration of the Moon as well as beyond. The LCR will focus mainly on capabilities with examples of specific technologies to satisfy those needs.

12:00 p.m. Schmidt G. *
SSERVI Update

12:10 p.m. Abbud-Madrid A. *
Space Resources Roundtable Update

12:20 p.m. LUNCH

Tuesday, November 1, 2016
BUILDING A MOON VILLAGE
1:45 p.m. USRA Conference Center

Chairs: **James Carpenter**
Clive Neal

1:45 p.m. Green J. G. *
Planetary Science Division Update

2:15 p.m. Vijendran S. Carpenter J. D. * Houdou B. De Rosa D. Fisackerly R. Laurini D. Aziz S. Schroeven-Deceuninck H. Landgraf M. Hufenbach B.
Forthcoming Lunar Exploration Studies and Technology Development Activities at the European Space Agency **[#5052]**
We present an overview of lunar exploration mission study and technology development activities that are planned by ESA for the period 2017–2019.

2:35 p.m. Petro N. E. * Keller J. W.
Lunar Exploration Products Generated from LRO Data: Enabling Future Surface Exploration **[#5035]**
While LRO has been operated as a science mission, its initial objectives focused on enabling future surface exploration. The extended life of LRO has allowed the science teams to generate a range of products critical for future exploration.

2:50 p.m. Spudis P. D. * Lavoie T.
A New Architecture to Explore the Potential of Lunar Resource Utilization **[#5007]**
We present a revised architecture to build a human-tended lunar outpost and a permanent space-based cislunar transportation system for people and cargo, based on the extraction and use of the material and energy resources of the Moon.

3:10 p.m. Sowers G. Kutter B. F. *
Transportation Supporting a Self-Sustaining Space Economy **[#5083]**
We describe a liquid hydrogen, liquid oxygen based transportation system supporting a robust economy in cislunar space. Elements of this system are currently in development by United Launch Alliance.

3:30 p.m. Kapoglou A. *
Outcome of the 1st Silicon Valley Workshop on Lunar Commercialization to Support a Permanent Human Settlement on the Surface of the Moon **[#5031]**
Fifty Silicon Valley innovators, space leaders, VCs, and designers gathered at the Rainbow Mansion in Cupertino, California to discuss the future of lunar commercialization and create a Moon Village consortium with tangible next steps.

3:45 p.m. BREAK

4:00 p.m. Landgraf M. * Hufenbach B. Houdou B.
Building Strategic Capabilities for Sustained Lunar Exploration **[#5005]**
We discuss a lunar exploration architecture that addresses the strategic objective of providing access to the lunar surface. This access enables the most exciting part of the lunar exploration: building a sustained infrastructure on the lunar surface.

4:15 p.m. Cowley A. * Salter J. Gutsche K. Barad L. Pedrazanni M. Fateri M. Meurisse A.
In-Situ Resource-Driven Approaches to Additive Manufacturing Using Lunar Regolith Simulant **[#5038]**
We report on the uses of 3D printing for large scale fabrication of building elements using lunar regolith simulant via a number of sintering and melting approaches.

4:30 p.m. Pambaguian L. Makaya A. * Lafont U.
Utilization of In-Situ Resources and Transported Materials for Infrastructure and Hardware Manufacturing on the Moon – Ongoing Developments by ESA Materials Scientists **[#5040]**
This contribution presents a review of completed and ongoing activities led by the European Space Agency's Materials Scientist on the use of in-situ resources and transported materials to enable exploration and settlement activities on the Moon.

4:45 p.m. Zuniga A. F. * Rasky D. J. Pittman R. B.
Lunar COTS: Using the Moon's Resources to Enable an Economical and Sustainable Pathway to Mars and Beyond **[#5003]**
The Lunar Commercial Orbital Transfer Services (COTS) plan presents a cost-effective approach to partner with industry to establish low-cost cislunar capabilities and services, such as lunar transportation, lunar mining, and lunar ISRU operations.

5:00 p.m. DISCUSSION

Wednesday, November 2, 2016
IMPACT OF COMMERCE ON SCIENCE AND EXPLORATION
8:30 a.m. USRA Conference Center

Chairs: **Clive Neal**
Ryan Clegg-Watkins

8:30 a.m. Nadar G. * Shah U. B. Kothandhapani A. Singh N. K. Hegde N. S.
Cost Effective Mission Strategy for Lunar Sample Return Mission Probe **[#5076]**
A novel lunar sample return mission from south pole region is proposed where, after ascent and Trans-Geo Injection, the return module attains an Earth orbit and is de-orbited using aero-braking. Also includes a lander and an orbiter with payload.

8:45 a.m. Hendrickson D. B. *
Astrobotic: Payload Opportunities for Lunar Science and Exploration **[#5013]**
This paper describes the latest developments in Astrobotic's lunar payload delivery service, along with a proposed model for science and exploration participation on this service.

9:00 a.m. Acierno K. T. *
Scientific Opportunities with ispace, a Lunar Exploration Company **[#5059]**
This presentation introduces ispace, a Tokyo-based lunar exploration company. Technology applied to the Team Hakuto Google Lunar XPRIZE mission will be described. Finally, it will discuss how developing low cost and mass efficient rovers can support scientific opportunities.

9:15 a.m. Hibbitts C. A. * Smith H. T.
Measurement Concept for Understanding the Water Cycle on the Moon Through Commercial Space Opportunities **[#5054]**
Existing commercial sub-orbital platforms enable multi-spectral IR imaging of the Moon for understanding the 'water cycle' on the illuminated Moon.

9:30 a.m. Kothandhapani A. Shah U. B. * Singh N. K. Nadar G. Hegde N. S.
Factors Affecting Commercial Delivery of Payload to the Moon **[#5075]**
Presents the technical and commercial factors that have to be considered by a private space transportation service in order to cater to the current needs to access the lunar surface.

9:45 a.m. Boucher D. S. * Chen N.
Planning the Mine and Mining the Plan **[#5034]**
Overview of best practices used in the terrestrial mining industry when developing a mine site towards production. The intent is to guide planners towards an effective and well constructed roadmap for the development of ISRU mining activities. A strawman scenario is presented as an illustration for lunar mining of water ice.

10:00 a.m. DISCUSSION

Wednesday, November 2, 2016
RECENT LUNAR SCIENCE AND EXPLORATION RESULTS
10:15 a.m. USRA Conference Center

Chairs: **Barbara Cohen**
Debra Needham

10:15 a.m. McClanahan T. P. * Mitrofanov I. G. Boynton W. V. Chin G. Livengood T. A. Starr R. D. Su J. J. Litvak M. Sanin A.
High Concentrations of Hydrogen-Bearing Volatiles at the Base of Poleward-Facing Slopes in the Large Southern Permanently Shadowed Regions **[#5012]**
Concentrations of hydrogen-bearing volatiles are non-uniform within the large permanently shadowed regions (PSR) at the lunar south pole. Volatiles in the PSR's, possibly water ice, are biased towards the base of the poleward-facing slopes.

10:30 a.m. Banks M. E. * Watters T. R.
Displacement-Length Relationship of Thrust Faults Associated with Lobate Scarps on the Moon **[#5029]**
A linear fit to plotted displacement-length data yields a γ value of $\sim 1.8 \times 10^{-2}$ ($\theta = 30°$) for the lunar lobate scarps. This result is higher than estimates of γ for scarps on Mars and Mercury but lower than that for thrust faults on earth.

10:45 a.m. Head J. W. * Wilson L. Qiao L. Xiao L.
Eruption of Magmatic Foams and Unusual Regolith Properties: Anomalously Young Crater Retention Ages and the Case of Ina **[#5069]**
Shield-building eruption models predict that waning-stage summit activity involved magmatic foam extrusion to produce mounds; this could explain Ina-like mounds and ages.

11:00 a.m. Needham D. H. * Hamilton C. W. Bleacher J. E. Whelley P. L. Young K. E. Scheidt S. P. Richardson J. A. Sutton S. S.
Lava Eruption and Emplacement: Using Clues from Hawaii and Iceland to Probe the Lunar Past **[#5039]**
We investigate the 2014/15 Holuhraun, Iceland and December 1974 Kilauea, Hawaii eruptions to improve understanding of relationships between eruption dynamics and final lava flow morphology. Insights are used to deduce the origin of Rima Bode on the Moon.

11:15 a.m. Clegg-Watkins R. N. * Jolliff B. L. Lawrence S. J.
Frequency-Range Distribution of Boulders Around Cone Crater: Relevance to Landing Site Hazard Avoidance **[#5017]**
Boulders are hazards / to future landing spacecraft / we must count them all.

11:30 a.m. Stopar J. D. * Lawrence S. J. Jolliff B. L. Speyerer E. J. Robinson M. S.
Defining Long-Duration Traverses of Lunar Volcanic Complexes with LROC NAC Images **[#5074]**
We compared a notional Marius Hills traverse to the slopes encountered during the Apollo 15 EVAs using LROC NAC DTMs. The similar slope distributions suggest that the Marius Hills are navigable for future roving.

11:45 a.m. DISCUSSION

12:00 p.m. LUNCH

Wednesday, November 2, 2016
NEW VIEWS OF LUNAR REGOLITH
1:15 p.m. USRA Conference Center

Chairs: **Jeff Plescia**
Brett Denevi

1:15 p.m. Plescia J. B. *
Lunar Regolith - Understanding for Science and Exploration **[#5057]**
Lunar regolith is the complex fragmental layer on the surface that is formed by mechanical and thermal processes, interacts with the space environment, and stores and processes volatiles.

1:30 p.m. Speyerer E. J. * Povilaitis R. Z. Robinson M. S. Thomas P. C. Wagner R. V.
Temporal Observations of Regolith Gardening Caused by Secondary Impacts **[#5071]**
LROC temporal observations reveal numerous, small (<30m) albedo changes across the Moon, including dense clusters near new impact craters. From this data, we modeled a regolith gardening rate and compared it to previous models and Apollo drive cores.

1:45 p.m. Domingue D. L. * Palmer E. Gaskell R. Staid M. Pieters C. M.
Characterization of the Lunar Surface Within Tsiolkovsky Crater: The Photometric, Albedo, and Thermal Properties of the Regolith **[#5023]**
Angles of moonlight / discovering albedos / temperatures found.

2:00 p.m. Stickle A. M. * Cahill J. T. S. Grier J. A. Greenhagen B. Patterson G. W.
Examining Lunar Surface Maturity from UV to Radar **[#5055]**
Lunar surface age / seen across the spectrum / does it age the same?

2:15 p.m. Farrell W. M. * Hurley D. M. Esposito V. J. McLain J. L. Zimmmerman M. I.
The Statistical Mechanics of Solar Wind Hydroxylation at the Moon **[#5011]**
We present a new formalism to describe the outgassing of hydrogen initially implanted by the solar wind protons into exposed soils on the Moon.

2:30 p.m. BREAK

2:45 p.m. Schwadron N. A. * Wilson J. K. Looper M. Jordan A. P. Spence H. E. Farrell W. M. Petro N. Stubbs T. J. Pieters C. Townsend L. W.
Diurnal Variation of Hydration from Lunar Soil Deduced from Albedo Proton Radiation **[#5014]**
We show first results from CRaTER comparing horizon to nadir observations in morning and evening sectors. Significant differences in the ratio of horizon to nadir protons suggests migration of volatiles may cause observed variations.

3:00 p.m. Jordan A. P. * Stubbs T. J. Wilson J. K. Hayne P. O. Schwadron N. A. Spence H. E. Izenberg N. R.
The Latitude Dependence of Dielectric Breakdown on the Moon **[#5004]**
Solar energetic particles may cause dielectric breakdown on the nightside of the Moon. We predict that breakdown weathering may have melted or vaporized about 4-11 wt% of impact gardened regolith on the Moon.

3:15 p.m. El Mir C. * Ramesh K. T. Delbo M. Plescia J. B.
The Contribution of Thermal Fatigue on Lunar Regolith Evolution **[#5073]**
Using an advanced thermomechanical model, we quantify the contribution of thermal fatigue on lunar regolith evolution and characterize the extent to which thermal fatigue can couple with other processes, such as breakdown by micrometeoritic impacts.

3:30 p.m. Mahanti P. * Denevi B. W. Robinson M. S.
On the Spatial and Age Based Variation of Optical Maturity for Copernican Craters **[#5064]**
We investigate the relationship of optical maturity values at different radial distances (from the crater center) to the absolute age (AMA) of the crater.

3:45 p.m. Schmitt H. H. *
North Massif Regolith at Taurus-Littrow May Contain Lithic-Clastic Volcanic Debris Erupted Prior to Mare Basalt **[#5008]**
Evidence of pre-mare basalt lithic-clastic eruptive events may exist in regolith developed on features that were not buried by basalt. Comparison of particle analyses of 76500 and 72500 provide evidence of the composition of the erupted debris.

4:00 p.m. DISCUSSION

Wednesday, November 2, 2016
RESOURCE PROSPECTOR:
EXPLORING THE MOST VALUABLE REAL ESTATE IN THE SOLAR SYSTEM
4:15 p.m. USRA Conference Center

Chairs: **Dana Hurley**
Georgiana Kramer

4:15 p.m. Colaprete A. * Elphic R. Andrews D. Trimble J. Bluethmann B. Quinn J. Chavers G.
Resource Prospector: An Update on the Lunar Volatiles Prospecting and ISRU Demonstration Mission **[#5047]**
This talk will provide an overview and status of the Resource Prospector mission.

4:30 p.m. Elphic R. C. * Colaprete A. Shirley M. McGovern A. Beyer R.
Resource Prospector Landing Site and Traverse Plan Development **[#5065]**
The Resource Prospector mission requires new tools for landing site selection and traverse planning. Initial results are presented that include mission operations and engineering constraints as well as realistic performance and activities.

4:45 p.m. Teodoro L. F. A. * Colaprete A. Roush T. Elphic R. C. Cook A. Kleinhenz J. Fritzler E. Smith J. T. Zacny K.
Modeling Volatile Loss During Resource Prospector Mission Sample Acquisition **[#5070]**
Here we present the modeling of volatile transport in lunar regolith in the context of the NASA's Resource Prospector.

5:00 p.m. DISCUSSION

Wednesday, November 2, 2016

LEAG 2016 POSTER SESSION/RECEPTION
6:00–8:00 p.m. USRA Education Gallery

GUEST SPEAKER
CONGRESSMAN JIM BRIDENSTINE
UPDATE ON THE AMERICAN SPACE RENAISSANCE ACT
7:00 p.m. USRA Conference Center

Sarkarati M. Reggestad V. Merri M.
Common Standards for Collaborative Inter-Agency Operations as Key Enabler for the Moon Village **[#5042]**
Our paper will provide an overview of standardization landscape for mission operations of a future Moon Village and elaborate on how existing standards, such as CCSDS Standards, can provide a solid basis for collaborative operations of Moon Village.

Kramer W. R.
Defining a Need for Assessing the Extraterrestrial Environmental Impacts of Lunar Activities **[#5006]**
Protocols guiding an extraterrestrial environmental impact assessment process are warranted. Industry-developed and -managed standards and an environmental code of conduct based, in part, on best management practices are proposed.

Amoroso E. Jones H. Otten N. Wettergreen D. Whittaker W.
Quantitative Evaluation of a Planetary Renderer for Terrain Relative Navigation **[#5037]**
A ray-tracing computer renderer tool is presented based on LOLA and LROC elevation models and is quantitatively compared to LRO WAC and NAC images for photometric accuracy. We investigated using rendered images for terrain relative navigation.

Cash T. J. Blair B. R.
Selective Heating of Regolith Grains Using Dynamic Phase and Frequency **[#5078]**
This paper will present concepts for heating lunar granular media using a dynamic strategy that varies phase and frequency to maximize the coupling efficiency of inbound radiation to a hypothetical work zone.

Blair B. R. Dula A. M.
IAA-SMR Propellant Demand Forecasting for Lunar Mineral Resources **[#5077]**
Access to the exponential mineral wealth of space begins with lunar resources, where commercial technologies can be developed, tested, and debugged. A custom-developed economic forecast is presented.

Elvis M. Milligan T. Krolikowski A.
The Peaks of Eternal Light: A Near-Term Property Issue on the Moon **[#5001]**
The Peaks of Eternal Light at the lunar poles are an example of rare, valuable lunar real estate. They can be effectively appropriated quite easily under the Outer Space Treaty. We consider the resulting legal, policy, and ethics issues.

Cunningham C. Jones H. Amato J. Horchler A. Holst I. Otten N. Kitchell F. Whittaker W.
Route Planning Software for Lunar Polar Missions **[#5062]**
Rover mission planning on the lunar poles is challenging due to the long, time-varying shadows. This abstract presents software for efficiently planning traverses while balancing competing demands of science goals, rover energy constraints, and risk.

Otten N. D. Amoroso E. Jones H. L. Kitchell F. Wettergreen D. S. Whittaker W. L.
Mission to Malapert **[#5066]**
This work presents methodology for evaluating lunar landing site amenability and identifies promising sites for landing on Malapert Mountain, which features shallow slopes, uninterrupted Earth visibility, and ten-plus days of uninterrupted sunlight.

Carpenter J. D.   Fisackerly R.   Houdou B.   Landgraf M.
Establishing Lunar Resource Viability **[#5051]**
We describe an approach to assessing the viability of lunar resources, emphasizing water ice, and the transition from prospecting to utilization.

Fisackerly R.   Carpenter J.   Landgraf M.
A Lunar ISRU Pilot Plant: An Anchor for Driving PreCursor Mission Planning and Human Architecture Preparation **[#5053]**
We propose a pilot plant as the transition step from resource prospecting to resource utilization.

Wilson J. K.   Schwadron N. A.   Spence H. E.   Jordan A. P.   Stubbs T. J.   Hurley D. M.   Farrell W. M.   Petro N. E.   McClanahan T. P.   Looper M. D.   Pieters C.   Townsend L. W.
Extracting Lunar Albedo Protons from Sparse Particle Data **[#5018]**
A new and robust method for extracting high energy protons from CRaTER data works well even for small data intervals and sparse particle counts.

Lucey P. G.   Fisher E. A.   Greenhagen B. T.   Lemelin M.   McClanahan T. P.   Mazarico E.   Neumann G. A.   Siegler M. A.   Smith D. E.   Zuber M. T.   Paige D. A.
Search for Transient Surface Water Ice at the Lunar South Pole: Results from LOLA and Diviner **[#5048]**
Frost that accumulates during the lunar night and is lost during the day is sought using LRO LOLA reflectance data and Diviner temperature measurements.

Day B. H.   Law E. S.
Moon Trek: NASA's New Online Portal for Lunar Mapping and Modeling **[#5015]**
This presentation introduces Moon Trek, a new name for a major new release of NASA's Lunar Mapping and Modeling Portal (LMMP). The new Trek interface provides greatly improved navigation, 3D visualization, performance, and reliability.

Archinal B.   Lee E.   Weller L.   Richie J.   Edmundson K.   Laura J.   Robinson M.   Speyerer E.   Boyd A.   Bowman-Cisneros E.   Wagner R.   Nefian A.
Controlling High-Resolution LROC NAC Polar Mosaics to LOLA Track Data **[#5044]**
We describe our progress on completing 1 m resolution geodetically controlled LROC NAC illumination mosaics of both lunar poles out to 85 degrees latitude, constrained using matching to LOLA track data.

Ogasawara K.   Ehresmann B.   Retherford K. D.   Mandt K. E.   Livi S. A.   Schwadron N.   Bloser P.   Legere J. S.   McConnell M.   McClanahan T. P.   Okada T.
Required Performances for Future Lunar and Asteroid Neutron Spectroscopy **[#5028]**
Future neutron spectroscopy requires better spatial resolution than the conventional omni-directional observations. The current issues for lunar and asteroid mission and possible solutions will be discussed in this presentation.

Williams D.   Taylor P.   Nagihara S.   Nakamura Y.   Kiefer W.
The Search for Apollo Era ALSEP Data and Its Restoration and Archiving **[#5033]**
Not all of the Apollo ALSEP data have been accounted for nor archived. We are searching for acquiring, restoring, and archiving as much of these data as we are able. In addition, we are including METADATA for several experiments.

Eubanks T. M.   Radley C. F.
Logistical Support of Lunar Exploration and Economic Activity with a Lunar Space Elevator **[#5058]**
An examination of proposed early deployments of a Lunar Space Elevator (LSE) and how these could be used for scientific research and to support a Moon Village on the farside.

Roux V. G.   Roth M.   Widdowson J.
"Test It Like You Fly It" — Developing a Large Lunar Surface Simulation Lab **[#5043]**
We are currently developing a large Lunar Surface Simulation Lab with high fidelity lunar highland regolith simulant that will allow researchers to "test it like you fly it."

Sarantos M.   Colaprete A.   Szalay J. R.   Halekas J. S.   Wooden D. H.   Horanyi M.   Janches D.
Generation and Migration of Potassium in the Lunar Exosphere **[#5063]**
We modeled what the recent LADEE measurements of potassium in the lunar exosphere imply about how gases are generated from and interact with the lunar surface.

Zimmerman M. I.   Farrell W. M.   Hartzell C. M.   Wang X.   Horanyi M.   Hurley D. M.   Hibbits K.
Grain-Scale Supercharging on the Moon **[#5061]**
Under lunar solar wind bombardment and photoemission levels, accumulated electric charge can produce grain-to-grain electric field strengths exceeding the dielectric breakdown limit, even away from the cold, relatively non-conductive lunar poles.

Shusterman M. L.   Izenberg N. R.   Wing B. R.   Irvin B. L.   Liang S. X.
Laboratory Simulation of Dielectric Breakdown of Lunar Regolith Simulant JSC-1A **[#5056]**
Laboratory simulations of dielectric breakdown of surface regolith in the lunar polar regions has shown that resulting alterations may provide an explanation for anomalous physical and optical features detected in permanently shadowed regions.

Guven U. G.
Utilization of Nuclear Power for Moon Missions: Nuclear Based Power and Propulsion Techniques for Spacecraft and Nuclear Power Generation Methods for Moon Habitats **[#5060]**
With a nuclear reactor, all of the power requirements in a Moon-based station with reduced gravity conditions can be met for several years without any difficulty. Nuclear reactor can be useful for Moon-bound spacecraft for the Moon and habitats.

Miller T. F.   Paul M. V.
A Power Source for Sunless Lunar Missions Using Lithium Combustion **[#5072]**
Some lunar exploration targets require non-solar power due to shading. Batteries provide very brief excursions into sunless areas. Undersea powerplants that burn metals have significantly higher specific energy than primary batteries and no exhaust.

Looper M. D.   Mazur J. E.   Blake J. B.   Schwadron N. A.   Wilson J. K.   Spence H. E.   Case A. W.   Kasper J. C.   Townsend L. W.
Differing Lunar Regolith Hydrogen Distributions as a Possible Source of Variations in Proton Albedo: Geant4 Simulations **[#5019]**
We use Geant4 to model the effect of varying mixing of hydrogen-bearing compounds with the near-surface regolith on the yield of upgoing lunar "albedo" protons produced by cosmic ray nuclear interactions, for comparison with LRO/CRaTER measurements.

Townsend L. W.   Zaman F.   Schwadron N. A.   Wilson J. K.   Spence H. E.   Case A. W.   Kasper J. C.   Mazur J. E.   Looper M. D.
Energy and Angular Spectra of Albedo Protons and Neutrons Emitted from Hydrated Layers of Lunar Regolith **[#5022]**
Energy and angular yields of albedo protons and neutrons emitted from the lunar surface as a function of hydration layer thickness in the lunar regolith using the MCNP computer code developed at Los Alamos National Laboratory are presented.

Petro N. E.   Cohen B. A.   Jolliff B. L.   Moriarty D. P.
Estimating the Contribution of Basins and Large Craters to the Regolith of the South Pole-Aitken Basin **[#5032]**
Here we revisit the question of how much non-SPA material may have been introduced to SPA. Data from recent lunar missions provides new insight into the composition and geologic evolution of the Moon. We assess the resurfacing effects of large impacts.

Fang E.   Suresh S.   Whittaker W.
Camera-Only Kinematics for Small Lunar Rovers **[#5026]**
Knowledge of the kinematic state of rovers is critical. Existing methods add sensors and wiring to moving parts, which can fail and adds mass and volume. This research presents a method to optically determine kinematic state using a single camera.

Visscher P.   Edmundson P.   Ghafoor N.   Jones H.   Kleinhenz J.   Picard M.
Results of Lunar Rover Drivetrain TRL-6 Environmental Testing **[#5027]**
Latest results of work performed by Ontario Drive and Gear Ltd., Canadensys Aerospace Corporation, and partners on Canadian lunar rover development activities for the Canadian Space Agency, including "dirty" thermal vacuum testing of drivetrain unit.

Cataldo R. L.
A Concept for a Radioisotope Powered Lunar CubeSat **[#5081]**
Presented is a concept for a small lander or CubeSat lunar mission that would benefit from a low-power milli-watt radioisotope power source (RPS). A RPS would provide long-lived electrical and thermal power enabling a long-lived lunar mission.

Ethridge E. C.
Proposed Experiment for Prospecting and Mining Water from Lunar Permafrost from Boreholes Using RF Energy **[#5024]**
The extraction of water from planetary permafrost has been demonstrated with experiments using RF heating and capture of water in a cold trap. We will describe an experiment to demonstrate the process at the lunar poles.

Indyk S.
Structural Members Produced from Unrefined Lunar Regolith **[#5082]**
Manufacturing structural components directly from unrefined lunar regolith would be advantageous compared to refining the lunar regolith for its raw elements. Quantification of sintered JSC-1A mechanical material properties was performed through compression testing of sintered samples.

Thursday, November 3, 2016
NEW MISSIONS TO THE MOST EXCITING, ACCESSIBLE, AND AFFORDABLE PLANET IN THE SOLAR SYSTEM
8:30 a.m. USRA Conference Center

Chairs: **Julie Stopar**
Lisa Gaddis

8:30 a.m. Jackman A. L. * Smith D. A.
Space Launch System Trans Lunar Payload Delivery Capability **[#5016]**
NASA's SLS will fly Orion crew missions with a co-manifested payload to a lunar vicinity every year after the first two flights in the early 2020's. This presentation will provide an overview of co-manifested payload accommodations available.

8:45 a.m. Kring D. A. *
Potential Exploration Mission Objectives for Crew on Orion **[#5020]**
Instrumentation for Orion and mission concepts for crew are proposed that will help fulfill the objectives of the Global Exploration Roadmap.

9:00 a.m. Clark P. E. * Malphrus B. Brown K. Brambora C. Hurford T. MacDowall R. Reuter D. Farrell W. Banks S. Tsay M. Brandon C. Folta D.
Lunar Ice Cube: Progress and Implications for Building Lunar Orbiting CubeSats **[#5030]**
We are developing a compact broadband IR instrument that will fly on a 6U CubeSat bus for a high priority science application: understanding volatile origin, distribution, and ongoing processes in the inner solar system.

9:15 a.m. Carpenter J. D. * Houdou B. Fisackerly R. De Rosa D. Schiemann J. Huesing J.
Robotic Precursors to Human Explorers: ESA Mission Activities and Studies **[#5050]**
We describe ESA's current lunar exploration mission activities and studies for future robotic missions, including both international and commercial partnerships.

9:30 a.m. Kerber L. * Nesnas I. Ashley J. W. Malaska M. J. Parcheta C. Mitchell K. L. Anderson R. C.
Moon Diver: A Mission Concept for Exploring the History of Lunar Mare Deposits with the Axel Extreme Terrain Rover **[#5068]**
Moon Diver is a lunar exploration concept that would access a mare pit, allowing thorough exploration of a cross sectional exposure of both regolith and bedrock on the Moon, including stratigraphy, textures, chemistry, and mineralogy.

9:45 a.m. BREAK

10:00 a.m. Blewett D. T. * Hurley D. M. Denevi B. W. Cahill J. T. S. Klima R. L. Plescia J. B. Paranicas C. P. Greenhagen B. T. Anderson B. A. Korth H. Ho G. C. Nunez J. I. Zimmerman M. I. Brandt P. C.
Lunar Compass: A Rover Mission for Exploration of a Lunar Crustal Magnetic Anomaly **[#5010]**
We suggest that a rover mission to a lunar magnetic anomaly could answer key questions in several major fields of planetary science: planetary magnetism, space plasma physics, lunar geology, and space weathering.

10:15 a.m. Lucey P. G. * Sun X. Petro N. Farrell W. Abshire J. B. Mazarico E. Neumann G. A. Green R. Thompson D. E. Greenberger R. Hurley D. McClanahan T. P. Smith D. E. Zuber M. T.
The Lunar Volatiles Orbiter: A Discovery Class Lunar Water Mission **[#5049]**
The Lunar Volatiles Orbiter is a Discovery Class mission concept aimed at characterizing the nature and mobility of water on the Moon. Its instruments include a laser spectrometer, an infrared hyperspectral imager, and a neutral mass spectrometer.

10:30 a.m. Zacny K. Indyk S. * Luczek K. Paz A.
Planetary Volatiles Extractor (PVEX) for In Situ Resource Utilization (ISRU) on the Moon **[#5021]**
We present test results from various approaches to extracting volatiles from frozen and water-saturated JSC-1a lunar soil simulant in vacuum. We also present ISRU mission architecture that would employ the most promising water extraction approach.

10:45 a.m. Cohen B. A. * Coker R. F. Petro N. E.
Prospects for Dating the South Pole-Aitken Basin Through Impact-Melt Rock Samples **[#5046]**
Radiometric dating of a few hundred impact-melt fragments will yield the age of the SPA basin from a regolith scoop sample, as well as the ages of nearby craters and basins.

11:00 a.m. Lawrence S. J. * Jolliff B. L. Draper D. Stopar J. D. Petro N. E. Cohen B. A. Speyerer E. J. Gruener J. E.
Building on the Cornerstone: Destinations for Nearside Sample Return **[#5045]**
Feasible destinations for lunar sample returns are presented in the context of beginning the discussion for future Discovery missions to address vital planetary science issues.

11:15 a.m. DISCUSSION

11:35 a.m. LUNCH

Thursday, November 3, 2016
LEAG 2016 FINDINGS AND CONCLUSIONS
1:00 p.m. USRA Conference Center

Moderator: **Clive Neal**

Panel Members: **Samuel Lawrence**
Dana Hurley

The community findings from the Annual Meeting of the Lunar Exploration Analysis Group will be fully developed.

Scientific Opportunities with ispace, a Lunar Exploration Company K. T Acierno, ispace inc, 1-3-6 Azabudai, Minato-ku, Tokyo, 106-0041 k-acierno@ispace-inc.com

Introduction: This presentation will introduce ispace, a lunar exploration company headquartered in Tokyo, Japan, and Team Hakuto, a front-running team participating in the Google Lunar XPRIZE (GLXP) competition. The presentation will begin by introducing the technology that ispace is developing, along with its three-step plan to utilize resources on the lunar surface. Next, the presentation will explain Team Hakuto mission plans and rover capabilities. The presentation will conclude by explaining how ispace can support the scientific community in expanding our understanding of the Moon with low-cost mission opportunities.

ispace & Water on the Moon: ispace technologies is the commercial arm that manages Team Hakuto in the GLXP Mission. Founded in 2013, its mission is to find the resources necessary to extend human life into outer space. ispace's primary goal is to locate and utilize water on the lunar surface. Observations from the Moon Mineralogy Mapper aboard India's Chandrayaan-1, and measurements from NASA's Lunar Reconnaissance Orbiter, each provide strong evidence for the presence of water ice on the Moon [1]. The water may originate from endogenous sources, delivery by comets or asteroids, or implantation by solar wind [2]. While extracting hydrogen and oxygen from lunar regolith will require significant amounts of energy and infrastructure, the higher concentrations of lunar ice recently discovered at the Southern Lunar Pole could offer an energy-efficient alternative. In 2009, LCROSS impacted the permanently shadowed crater Cabeus and measured a water ice concentration of 5.6-2.9 wt% [3]. Ground truthing missions are needed in order to further verify the distribution of lunar ice in permanently shadowed and other regions.

ispace has a three-step plan that will demonstrate its technology, locate, map and measure resources, and finally utilize those resources on the lunar surface. ispace will have its first attempt to demonstrate its rover technology during the GLXP mission. Once proven successful, ispace will develop a tethered dual rover crater exploration vehicle, as well as rover with a drilling mechanism, which will give the company access to the permanently shawdowed lunar surface and the resources that lay beneath it. In this phase ispace plans to partner with space agencies and the scientific community for sensor and technology development to better detect and understand water ice deposits. Finally, depending on the location, distribution, quality and quantity of the lunar ice, ispace will develop extraction, processing, and utilization techniques with interested industrial partners. An ultimate goal is to convert the ice to fuel and deliver it to private companies such as the United Launch Alliance, who recently offered to purchase fuel on the lunar surface for $500/kg [4].

Team Hakuto: ispace owns and operates Team Hakuto, the only Japanese Team competing for the $30M GLXP competition. During this first mission to Lactus Mortis, the 4kg rover will attempt to survive one lunar day. The rover has a hybrid communication system, with both 900 MHz and 2.4 GHz capabilities, enabling both long distance and high speed communication. The rover will travel at least 500m and downlink high-definition video at 100 kbits/sec to Earth via the lander to achieve the required objectives of the GLXP. In order to further test and demonstrate new technologies, the rover will attempt a total traverse distance of up to 10 km. The traverse will be executed in a flower petal pattern, repeatedly circling back toward the host lander to be photographed. The mission will provide a low cost opportunity to obtain ground truth data for the numerous remote sensing missions. In the future this technology can be further used to investigate promising regions for potential resource deposits. This mission is the first of many missions planned by ispace technologies.

Supporting Science: 2017 is the beginning of a new era of exploration with cost-efficient opportunities for scientists on commercial missions. Japan Aerospace Exploration Agency is partnering with ispace and Team Hakuto to send a dosimeter to measure cosmic rays and solar wind for future human missions. Another GLXP team, Astrobotic, is carrying a university payload funded by the Mexican Space Agency [4]. By decreasing the overall mass of the rover, ispace is able to accommodate future opportunities for scientific payloads and offer the scientific and space technology community unprecedented economical opportunities to gather data and test instruments, algorithms, and equipment during our missions.

References: [1] Delory et al., (2010) The LADDE Mission: The Next Step After the Discovery of Water on the Moon. [2] Hauri et al., (2011) High Pre-Eruptive Water Contents Preserved in Lunar Melt Inclusions, Science 333, 213-215 [3] Colaprete et al., (2010) Detection of Water in the LCROSS Ejecta Plume, Science 330, 463-468 [4] David, L (2015) Inside ULA's Plan to have 1,000 People Working in Space by 2045. Space.com [5] Azer, N (2015) Mexico to the Moon – With Astrobotic, Google Lunar XPRIZE

QUANTITATIVE EVALUATION OF A PLANETARY RENDERER FOR TERRAIN RELATIVE NAVIGATION.

E. Amoroso[1], H. Jones[2], N. Otten[2], D. Wettergreen[2], and W. Whittaker[12] [1]Astrobotic Technology, Inc. 2515 Liberty Ave, Pittsburgh, PA 15222. eric.amoroso@astrobotic.com, [2]Carnegie Mellon University Robotics Institute. 5000 Forbes Ave, Pittsburgh, PA 15213, red@cmu.edu.

Introduction: New missions in planetary research require a spacecraft to autonomously land with a precision that is difficult to achieve with traditional space sensors. Visual navigation techniques have been developed, specifically terrain relative navigation (TRN), to achieve low landing dispersions [1][2]. TRN achieves an absolute pose measurement by registering a visual image to a georeferenced image database. This database can be compromised of previous spacecraft images of planetary terrain or can be simulated renderings. One advantage of using renderings as the georeferenced database is that renderings can be generated at the specific date and time the spacecraft will expect to use TRN [3]. Thus, illumination angles and planetary and solar ephemeris will be very similar to the spacecraft's visual imagery. Our work presents a ray-tracing lunar map generator based on the Mitsuba renderer[4] that uses graphical textures and stochastic path-tracing algorithms to generate realistic, map-projected lunar images at multiple spatial resolutions.

Methods: The renderer uses a combination of LOLA digital elevation models (DEMs), NAC stereo DEMs, the SLDEM2013 dataset, and Clementine albedo maps as data inputs to achieve its precision at multiple scales [5][6]. We then quantitatively compare ray-traced renderings using DEMs at various spatial resolutions to LRO NAC and WAC images. Pixel-by-pixel comparisons are made to the radiance simulated and received by the WAC and NAC instruments. Multiple locations are compared, including polar regions as seen by Figure 1, and previous Apollo landing sites as shown in Figure 2. Next, a preliminary investigation in the use of this renderer for TRN applications is presented. We generate a rendered lunar map of high resolution images of the Lacus Mortis region and register images capture by LRO WAC, NAC, and Apollo's Metric Camera instruments. Registration is performed using an a priori position estimate to rectify camera images to the database projection, from which a homography is estimated using visual correspondences. Using the respective instrument's camera model, a pose measurement is obtained. Position measurement error is then quantified using spacecraft ephemeris data as ground truth. Limitations and sensitivity to image spatial resolutions, illumination angles, and a priori estimates are presented.

Acknowledgement: This work was supported in part by NASA contract NNX13AR25G.

References: [1] Johnson, A., et al. (2016) AIAA Guidance, Navigation, and Control Conference. [2] Johnson, A., et al. (2015) Proc. AIAA Guidance, Navigation, and Control Conference. [3] Peterson, K., et al. (2012) i-SAIRAS. [4] Jakob, W. Mitsuba Renderer. (2010) http://www.mitsuba-renderer.org. [5] Mazarico, E., et al (2011) Icarus 211.2: 1066–1081. [6] Gläser, P., et al. (2014) Icarus 243: 78–90.

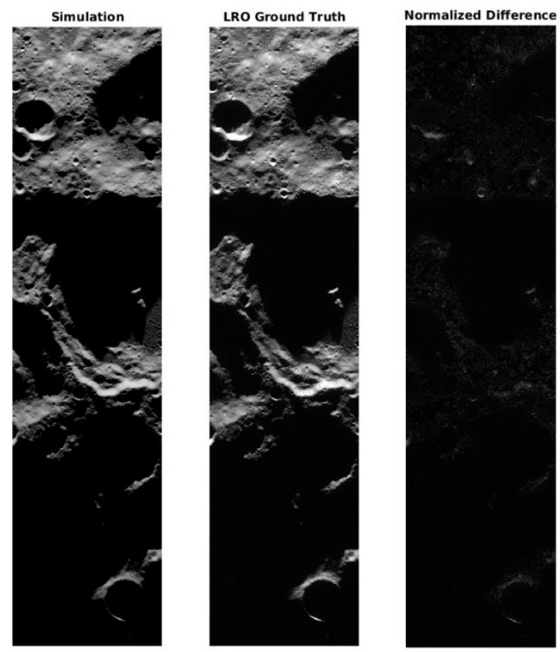

Figure 1. Quantitative comparison of a ray-traced simulation (left) and an image from LRO's WAC instrument (middle). The pixel-by-pixel normalized difference in radiance (right) shows that 98% of rendered pixels are within 15% of the radiance values measured in the LRO image.

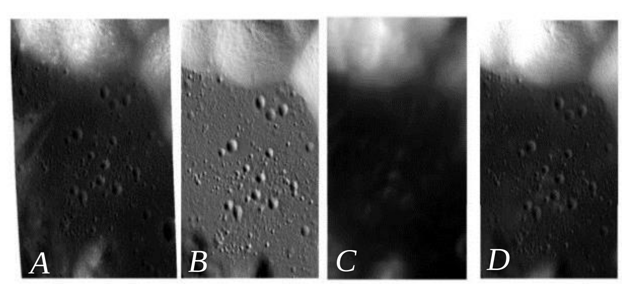

Figure 2. High resolution (1.2m/pixel) rendering enhancements of the Apollo 17 landing site from using a Clementine albedo map vs. assuming constant albedo. *A*: LRO NAC image M1190504960L. *B*: Rendered image without albedo map. *C*: Clementine albedo map. *D*: Rendered image with albedo map. Without an albedo map, the render was measured to be 72% similar. With an albedo map, a 91% similarity was achieved.

CONTROLLING HIGH-RESOLUTION LROC NAC POLAR MOSAICS TO LOLA TRACK DATA. B. Archinal[1], E. Lee[1,2], L. Weller[1], J. Richie[1], K. Edmundson[1], J. Laura[1], M. Robinson[3], E. Speyerer[3], A. Boyd[3], E. Bowman-Cisneros[3], R. Wagner[3], A. Nefian[4], [1]USGS, Astrogeology Science Center (2255 N. Gemini Drive, Flagstaff, AZ 86004; barchinal@usgs.gov); [2]Retired; [3]School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287; [4]NASA Ames Research Center, Moffett Field, Mountain View, CA 94035.

Introduction: We are continuing our effort to create geodetically controlled 1 m/pixel LRO LROC narrow angle camera (NAC) lunar polar cap mosaics, poleward from 85° latitude [1,2]. The final products of this effort will include controlled mosaics of all useful images and "illumination" controlled mosaics made every 10° of solar longitude. We highlight here progress since last year's report [3], which also covered the many benefits and possible uses of this work.

Control solutions are being performed with the USGS ISIS software package *jigsaw* application [4]. We have completed preliminary control network solutions for both poles.

Ground Control: We are using a NASA Ames application [5] to match illuminated LRO Lunar Orbiter Laser Altimeter (LOLA) track data to images in order to provide absolute constraints on position. We are redoing our solutions using constraints appropriate to the accuracy of the LOLA track data and checking cases of high measurement residuals. Currently the north pole includes 18,908 constrained points over 233 images, and the south pole 12,535 constrained points over 228 images. A plot of the north pole images and points used is given in Figure 1. During FY17 we will complete final solutions tied to LOLA points, create the mosaics, archive products to the PDS, and document the work with a journal article.

Other Benefits: This work will help improve capabilities for the development of further large controlled mosaics, as well as provide information on what critical tools will need to be developed in advance of such work [6]. The products will facilitate characterizing the precision and accuracy of LRO SPICE data and possibly to provide further geometric calibration of the LRO instruments. The updated SPICE data could also be used to improve LOLA [7] results.

Acknowledgements: This effort is funded by the NASA Lunar Advanced Science and Exploration Research program, and builds on early funded efforts by the LRO Participating Scientist Program and LMMP. We also acknowledge the tremendous work and effort by LRO mission and the LROC and LOLA personnel, without which this work would not be possible.

References: [1] Vondrak et al. (2010) *Space Sci. Rev.* 150, 7. [2] Robinson et al. (2010) *Space Sci. Rev.* 150, 81. [3] Archinal et al. (2015) *LEAG*, #2040. [4] Edmundson et al. (2012) *Int. Ann. Photog., Rem. Sens. & Spatial Inf. Sci.*, I-4, 203. [5] Nefian et al. (2014) *LPS XLVI*, #1679. [6] Archinal et al. (2012) *LPS XLIII*, #2394; http://tinyurl.com/cartoplanning. [7] Archinal et al. (2010) *LPS XLI*, #2609.

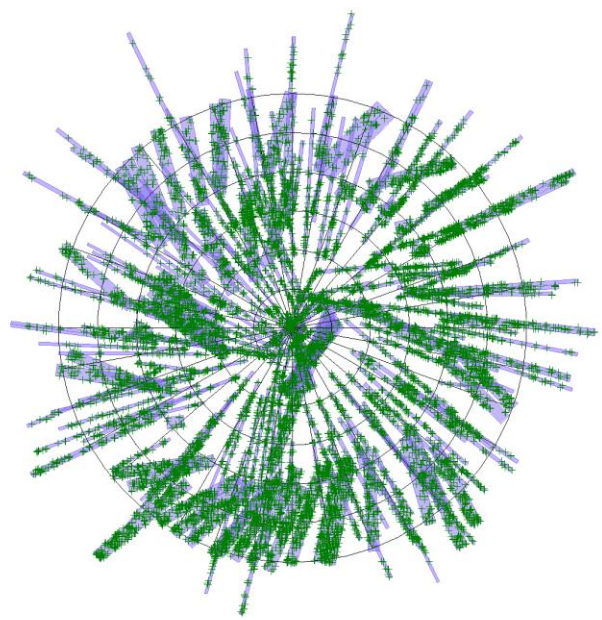

Figure 1: North pole area image showing LROC images (purple) and points (green) constrained to LOLA. Covers 84° latitude and poleward, 1° lat. x 10° long. grid spacing, 0° longitude (toward Earth) at bottom.

DISPLACEMENT-LENGTH RELATIONSHIP OF THRUST FAULTS ASSOCIATED WITH LOBATE SCARPS ON THE MOON. Maria E. Banks[1, 2] and Thomas R. Watters[2], [1]Planetary Science Institute, Tucson, AZ, 85719 USA, banks@psi.edu,, [2]Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, DC 20560 USA.

Introduction: Lunar lobate scarps, relatively small-scale thrust fault scarps, are observed predominantly in highland material [1-4] and are the most common tectonic landform on the farside [1-4]. Images acquired by the Lunar Reconnaissance Orbiter Camera (LROC) [5] and LROC stereo-derived digital terrain models (DTMs) enable widespread detection and detailed morphometric analysis of lobate scarps [6-7]. Over 3200 globally distributed lunar scarps have now been identified and mapped [6-8].

Data and Methods: DTMs derived from LROC Narrow Angle Camera (NAC) stereo pairs are used to measure the maximum relief (h) and horizontal length (L) of >40 individual lobate scarps. Measurements of h are used to estimate the maximum displacement (D_{max}) using the relationship $D = h/\sin\theta$, where θ is the dip of the surface-breaking fault-plane [e.g., 9]. This assumes that h expresses the total displacement from cumulative slip on the thrust fault. Populations of terrestrial faults, formed in uniform rock types, indicate that the maximum D on a fault scales with L as a linear function such that $D = \gamma L$, where γ is a constant determined by tectonic setting and mechanical properties of the near-surface crustal materials [e.g., 10]. When the displacement-length (D-L) relationship of a certain fault population is known, it can be used to estimate contractional strain using fault lengths alone [e.g., 11] and to provide insight into differences in tectonic setting, and mechanical properties, particularly strength, of faulted materials.

Results and Discussion: Maximum relief of scarp segments ranges from ~4 to 165 m with lengths ranging from ~0.3 to 14 km. The value of γ for the lunar lobate thrust fault scarp population, obtained by a linear fit to the D-L data (Fig. 1), ranges from ~2.1×10^{-2} to ~1.4×10^{-2} assuming a range in θ of 25° to 40° (~1.8×10^{-2} for $\theta = 30°$).

The values for lunar thrust faults are higher than estimates of γ for lobate scarp populations on Mars (~6.2×10^{-3} for $\theta = 30°$) [e.g., 12] and the large-scale scarps on Mercury (~8.2×10^{-3} for $\theta = 30°$; scarps on both planets may have >1 km of relief; Fig. 1) [13]. However the values for lunar thrust faults are lower than the γ for typical thrust faults on Earth (~8.0×10^{-2} for $\theta = 30°$) [9] and similar to the γ for recently discovered small (<100 m relief) scarps on Mercury [13]. The differences in γ for thrust faults on these bodies likely reflects differences in both tectonic setting and the mechanical properties of the near-surface rock. For example, terrestrial thrust faults localized at convergent plate margins accumulate large amounts of strain. On the Moon, Mars, and Mercury, lobate scarps indicate more distributed deformation [9]. Abundant water on Earth also reduces the residual frictional stress on faults resulting in higher γ values compared to faults where water is absent [1]. In addition, the lower γ values estimated for the larger-scaled scarps on Mars and Mercury may indicate that these faults extend into a deeper and more mechanically strong rock compared to the smaller-scaled scarps on the Moon and Mercury, which extend to depths of ≤1 km and are likely confined to mechanically weaker megaregoliths [1,9,19]. For further comparison, displacement and length for lobate scarp segments on asteroid 433 Eros [e.g., 6] are included in Fig. 1 and plot within the cluster of data points for the small-scale lunar scarps. It has been suggested that γ scales with the acceleration due to gravity [14]. Our results suggest the principle influence on γ is the accumulated strain.

References: [1] Watters T. R. and Johnson C. L. (2010) in *Planetary Tectonics*, Cambridge Univ. Press, 121–182. [2] Binder A. B. (1982) *Earth, Moon, and Planets, 26*, 117–133. [3] Binder A. B. and Gunga H.-C. (1985) *Icarus, 63*, 421-441. [4] Schultz P. H. (1976) University of Texas Press, Austin, TX. [5] Robinson M. S. et al. (2010) *Space Sci. Rev.*, *150*, 81-124. [6] Banks M. E. et al. (2011) *LPS*, *XLII*, 2736. [7] Banks et al. (2012) *JGR*, 117, doi:10.1029/2011JE003907. [8] Watters T. R., et al. (2015) *Geology*, 43, 851–854. [9] Watters T. R., et al. (2000), *GRL*, *27*, 22, 3659–3662. [10] Cowie P. A. and Scholz C. H. (1992) *J. Struct. Geol.*, 14, 1133–1148. [11] Scholtz C. H. and Cowie P. A. (1990) *Nature*, 346, 837–839. [12] Watters T. R. and Nimmo F. (2010) in *Planetary Tectonics*, Cambridge Univ. Press, 15–80. [13] Watters T. R. et al. (2016) *Nature Geoscience*, in press. [14] Schultz R. A. et al. (2006) *J. Struct. Geol.*, 28, 2182–2193.

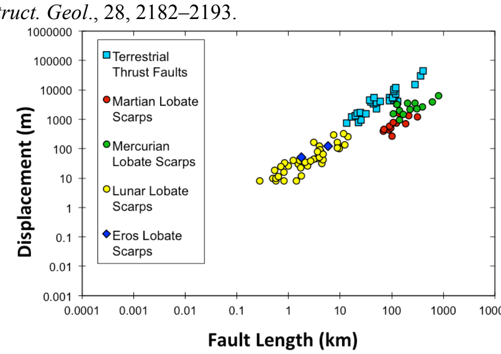

Fig. 1. Log-log plot of maximum displacement as a function of fault length for faults on the Moon, Earth, Mars, Mercury, and Eros.

IAA-SMR PROPELLANT DEMAND FORECASTING FOR LUNAR MINERAL RESOURCES. Brad R. Blair[1], and Arthur M. Dula[2], [1]NewSpace Analytics LLC, PO Box 7, Idaho Springs, CO, 80452, <planetminer@gmail.com>, [2]The Law Office of Art Dula, 3106 Beauchamp Street, Houston, TX 77009, <art@dula.com>.

Abstract: A recently published study[1] by the International Academy of Astronautics (IAA) found that space mineral resources (SMR) can serve as an economic game-changer, opening a vast new source of wealth to benefit humanity.

Access to the exponential mineral wealth of space begins with lunar resources, where commercial technologies can be developed, tested and debugged. A custom-developed economic forecast starts with the industrial utilization of lunar resources, and later adding the minerals of near-Earth asteroids, Phobos and Mars to a growing sphere of economic expansion into space. The study examined technical, economic, legal, and policy-related requirements to enable SMR, and offered specific recommendations to international space agencies and commercial enterprise for moving humanity forward into a new era of space settlement and commercial resource development.

A critical element of the IAA-SMR study is a chapter devoted to systems modeling and analysis, which presents a quantitative model of future space infrastructure and a propellant demand forecast based on published goals to put thousands of people on Mars for commercial settlement. The forecast was used to translate unit technical requirements for life support and transportation into water consumption based upon the ultimate consumer: the future space colonist. A per-capita modeling approach offers a simple and upgradeable point of departure that can easilty be translated into financial and policy goals as well as technical milestones and objectives.

In principle, the agreement by both entrepreneurs and international space agencies on a future baseline human space settlement scenarios can serve to underwrite private business plans as well as facilitate the timing of key technology investments and policy actions. Advisory groups such as LEAG can serve as a focal point in developing this important new consensus.

References:

[1] Arthur Dula (Editor), and Zhang Zhenjun (Editor), *Space Mineral Resources: A Global Assessment of the Challenges and Opportunities*, IAA Cosmic Study 3.17, Virginia Edition Publishing Company, 27 November 2015, 472 pages, http://www.amazon.com.au/Space-Mineral-Resources-Assessment-Opportunities-ebook/dp/B018OJD95Q

LUNAR COMPASS: A ROVER MISSION FOR EXPLORATION OF A LUNAR CRUSTAL MAGNETIC ANOMALY. David T. Blewett[1], Dana M. Hurley[1], Brett W. Denevi[1], Joshua T.S. Cahill[1], Rachel L. Klima[1], Jeffrey B. Plescia[1], Christopher P. Paranicas[1], Benjamin T. Greenhagen[1], Brian A. Anderson[1], Haje Korth[1], George C. Ho[1], Jorge I. Núñez[1], Michael I. Zimmerman[1], and Pontus C. Brandt[1]. [1]Space Science Branch, Space Exploration Sector, Johns Hopkins University Applied Physics Laboratory, Laurel, Md., USA. (david.blewett@jhuapl.edu).

Introduction: The Moon does not possess a global, internally generated magnetic field, but the lunar crust does contain areas of magnetized rocks ("magnetic anomalies" [e.g., 1]). Magnetized basin ejecta may be the source of some of the magnetic anomalies [2]. Another hypothesis contends that the magnetic anomalies were created by plasma interactions during impact of a cometary coma with the lunar surface [3, 4].

The crustal fields at the magnetic anomalies produce disturbances in the interaction of the solar wind with the Moon [e.g., 5, 6]. Described as "mini-magnetospheres", the disturbances have been detected through analysis of the flux of neutral atoms [7], electrons [8], and solar-wind protons [9].

The crustal magnetic anomalies are often correlated with unusual, sinuous, high-reflectance markings called lunar swirls [10, 3, 11, 12]. Several hypotheses for the origin of the swirls have been put forward. One states that the magnetic anomaly stands off the solar wind [1], and thus inhibits the normal soil darkening process (space weathering) to which unshielded areas are subjected. Other workers suggest that impact of a cometary nucleus/coma [3, 13, 4] or meteoroid swarm [14] could disturb the surface to produce the bright swirl markings by changing the structure and particle-size distribution of the uppermost regolith. Alternatively, the electromagnetics of these regions could alter the trajectories of levitated, charged dust. These grain motions might lead to accumulation of high-reflectance dust in the swirls [15], or could disturb the uppermost regolith structure and thus produce high reflectance [16].

The magnetic anomalies present a natural laboratory for at least four major areas in planetary science:

a) Planetary magnetism: What is the strength and structure of the field on the surface? What is the depth of the magnetic source: surficial (comet impact), or deep (magnetized intrusion or basin ejecta)? What are the implications for an ancient dynamo?

b) Space plasma physics: How does the magnetic anomaly interact with the incident plasma to form a stand-off region? How important are electric fields? What are the fluxes of the particles that actually reach the surface by energy and species?

c) Lunar geology: What are the nature and origin of the lunar swirls? Are they ancient or recent? Has levitated dust or cometary material modified the surface?

d) Space weathering: What is the role of ion vs. micrometeoroid bombardment? The lunar magnetic anomalies offer some control on one of the key variables, solar wind exposure.

A Rover Mission: An instrument package traversing one of the major magnetic anomalies could help to provide answers to the important questions listed above [17]. Two elements of the package characterize the magnetic and plasma environment on the lunar surface. Vector magnetometer measurements will help to constrain the depth and thickness of the magnetic source region [18]. A solar wind spectrometer will directly measure the solar-wind flux reaching the surface, testing the solar-wind shielding model for swirls.

A second group of instruments focuses on characterization of the regolith: an XRF/XRD to determine elemental abundance; a UV-VIS-NIR spectrometer to obtain mineralogy; a Mössbauer spectrometer to measure nanophase iron content; a mast-mounted multispectral imager to assess surface morphology and composition; and a microscopic spectral imager for particle size distribution, regolith texture, and spectral-compositional properties.

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Planning the Mine and Mining the Plan. Dale S. Boucher[1] and Norman Chen[2], [1]Deltion Innovations Ltd, 26 Meehan St, Capreol, Ontario, Canada, P0M1H0, dboucher@deltion.ca; [2]Hatch Ltd. - Sudbury Operations, Notre Dame Business Complex, 40 Elm Street, Unit ND255, Sudbury, Ontario, Canada, P3C1S8, norman.chen@hatch.com

Introduction: The development of a terrestrial mining operation follows a well understood planning cycle, designed to provide the mine operator with the means to evaluate and efficiently manage the build up of the mining operations to maximize the ore body's potential and to help the operator understand mine life cycle constraints. This paper will discuss the development of mine plans for the express purpose of lunar mining of water ice/volatiles in support of global exploration activities.

Overview: In general, planning a mine can be divided into a 4-step Stage Gate process. Each stage has clearly defined activities and goals unique to the project. The gate at the end of the stage is used to filter the stage results and determine if the plan can advance to the next stage, force a rework, or abandon the project.

Each stage is built upon the Client Requirements Specification, similar to a multi level System Requirements Document process. The CRS is a live document and will evolve throughout the project and must be carried through each of the stages and gates as a means to ensure the mine planning activity remains focused on the appropriate end goals. Unlike multi-level SRD's as used in mission planning, the CRS is somewhat flexible and must respond to changes in market and client conditions over time. The decision to proceed with any stage is based upon evaluations of: the expected benefit of the project end result, costing, and risk (technical and administrative).

Each Gate in the process is very similar to the Milestone Review process used in flight programs. The Gate provides a formalized means by which the Gate Review team can evaluate project viability, and provide an Authorization To Proceed for the next stage.

Concept Development: This is the primary stage of a mine development plan (similar to a Phase A Concept Study). It is focused upon definition of the requirements and a first look at the ore body capacity (quality, quantity). At least one option is proposed that will be evaluated in later stages as solutions to the mining plan. This stage will suggest a high level "functional" block diagram of mining operations that is improved in the following stages. This stage will generate the following evaluation results:

1) Basic assumptions underpinning the concept remain valid.
2) Context of the orebody (type of deposit, exploration work undertaken to date, reserve potential).
3) Project, resource and technology ownership.
4) Client Requirements, Specifications are valid.
5) Strategic case for the project; information for a preliminary economic assessment report.
6) Mine capacity and rate; waste disposal method.
7) Key Performance Criteria defined.
8) Alternative approaches defined.
9) Risks (technical, cost and management) defined and evaluated.
10) Plan for completion of the next stage is workable and realistic.

Technology Selection and Development: This evaluates the options proposed in the Concept Development with more rigor. A review of the discarded options is undertaken to determine if new knowledge would change the evaluation. One option proposed in Concept is selected and evaluated for viability. Evaluation of technologies and capabilities available (or may require development) is critical so that a detailed roadmap can be implemented. The focus is on the selected option (similar in nature to the Preliminary Design Stage of a flight program) and will generate:

1) Detailed validation of the project assumptions.
2) Most viable option for execution selected.
3) Risks eliminated/reduced.
4) Execution stage preliminary plan defined.
5) Evaluate the plan for completing the next stage.

Feasibility Evaluation: Produces the investment rationale (not the business case) for the mine plan. It is used to prepare the investment portfolio and can include completion of any legislated documentation regarding due diligence (ex. NI 43-101, JORC or SAMREC) for the purposes of financing the execution phase. The selected option is further defined and detailed designs are produced that support the solution in terms of cost, schedule, scope and client based requirements. This stage focuses on the execution planning, schedule alignment with other external factors (e.g., commodity pricing, demand, technology and capability readiness). The primary output is the development of a detailed expenditure programme, schedule and execution plan with all risks addressed, either retired or mitigated, and will yield the following:

1) Detailed validation of the underpinning assumptions of the project.
2) Detailed cost, schedule and risk analysis.
3) Client based opportunity validity remains defined.
4) Key Performance Criteria met or retired.

5) Risks identified for Execution Phase.
6) Evaluate the plan for completing the next stage.

Execution: This includes development and management of the actual capital investment, development of final design modifications (if required) to realize changes in scope, schedule, cost, quality, and other defined constraints/parameters. This stage is executed to deliver the defined outcomes and includes the actual start-up stage of the mine. It is considered a "live" exercise in that the mining activity begins with first shovel in the ground. Many items are considered energized at day one. Cost and schedule management is primary. Operational build up includes site preparation, support infrastructure build up, equipment purchase, deployment scheduling, logistics management (procurement, shipping, external support), subcontractor management, market and financing management, and overall project schedule management.

Strawman Scenario: A commercial water mining activity on the moon is envisioned. Some "typical" example results are shown for each of the stages to attempt to provide perspective. This plan is only intended to illustrate the overall process necessary to develop a workable mine on the lunar surface.

Basic Assumptions:

Client: Lunar Lager Brewing Company LTD.
Mine Site: Cabeus Crater
Production: 1000 tonnes purified water per year
Life Cycle: 10 year production
Delivery point: Lunar outpost Shackleton rim Clive's Bar and Grill, hamburger stand and refueling depot
Projected price point: $500 per kg

Stage 1: Concept Development:

1) Cost cap budget for project set at $1600 million
2) Early results indicate 7% water ice by weight average over mining site of 100 hectares. Average depth is 2 m; overburden is 40 cm desiccated material. Rubble field geology requiring handling of large (1 m) rubble as overburden and embedded waste. Estimates show that 40% of the available area is accessible; remainder is under excessive rubble or trapped by rock outcroppings.
3) Small ISRU-specific mobile platforms (500 kg) are reasonably mature and can be used to provide most mobile services. Sampling technologies well developed for detailed ore body definition. Refining systems are at early TRL stages. Storage of product can be evolved from known technologies.
4) Technology development plans include excavation systems, command and control with Direct To Earth (DTE) link or via specialized orbiter or crater rim emplaced links. Power systems to be RTG stacks and/or crater rim mounted solar voltaic cells.

Stage 2: Technology Selection and Development:

1) CRS revised to include Level 2 requirements.
2) Open pit mining process selected. Overburden dump site selected for ease of access at later date in support of habitat requirements.
3) Plan revised to incorporate new fusion power system development.
4) Technology development roadmap completed. Contact made with OEM's to begin development of target technologies in joint venture/ speculation style sub-projects.
5) Execution Stage (Stage 4) concept will rely upon robotic pre-cursors to develop infrastructure, roadways, maintenance sites. Overburden from mine site will be used as required for fill.

Stage 3: Feasibility Study:

1) CRS revised to include Level 3 Requirements.
2) Time-based technology deployment completed. Fleet make up of 2 roadway maintenance rovers, 2 construction robots, 1 mobile exploration drill, 2 Load Haul Dump machines, 4 haulage trucks deployed in order indicated over 3 years.
3) Refining process to be in situ thermal release of water ice from regolith with water filtration plant for 98% purity.
4) Bulk storage tank farm with auto loaders for pure water storage.
5) Technical risks 80% retired: remaining risks are in the area of long term machine availability
6) Management risks remain with long term financing and market volatility for end product.

Stage 4: Execution:

1) Establish project execution team.
2) Secure launch, cruise and lander contracts.
3) Secure OEM equipment procurement contracts and schedule.
4) Establish ground based command and control center.
5) Deploy road building systems to establish landing pads, basic infrastructure, mine pit roads.
6) Deploy construction robot team.
7) Deploy LHD robots.
8) Deploy long-haul trucks.
9) Commissioning of systems and ramp up to full production.
10) Hand-over to Operations.

ESTABLISHING LUNAR RESOURCE VIABILITY

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Introduction: Recent research has highlighted the potential of lunar resources as an important element of space exploration but their viability has not been demonstrated. Establishing whether or not they can be considered in future plans is a multidisciplinary effort, requiring scientific expertise and delivering scientific results.

To this end various space agencies and private entities are looking to lunar resources, extracted and processed in situ, as a potentially game changing element in future space architectures, with the potential to increase scale and reduce cost. However, before any decisions can be made on the inclusion of resources in exploration roadmaps or future scenarios some big questions need to be answered about the viability of different resource deposits and the processes for extraction and utilisation. The missions and measurements that will be required to answer these questions, and which are being prepared by agencies and others, can only be performed through the engagement and support of the science community.

In answering questions about resources, data and knowledge will be generated that is of fundamental scientific importance. In supporting resource prospecting missions the science community will de facto generate new scientific knowledge. Science enables exploration and exploration enables science.

Whether the resource in question is cold trapped polar ice or something else, there are a number of steps that need to be taken to establish their viability as a source of resources, that the capability exists to extract and store those resources, and that their utilisation will bring benefits over and above resupply from Earth. These steps can be summarised as:

- Find and characterise the resource deposits
- Validate the required technologies
- Demonstrate extraction and utilisation

Characterise the resource deposits: The first step in establishing the viability of a resource is to find where it is located and then to characterise the extent of a deposit and the physical and chemical properties of the ore or bulk material from which it is to be extracted. While comprehensive measurements have been made of the physical and chemical properties of lunar regolith in the past, and samples of lunar regolith are available from the Apollo missions, these samples may have limited direct applicability to previously unexplored landing sites such as those in the polar regions.

In the case of lunar polar ice deposits characterisation on both regional and local scales surface is required, which may be performed by different mission types with different strengths. For example:

- Comprehensive single point measurements as planned by PROSPECT on Luna-27 or sample return.
- Regionally distributed point measurements with small missions with limited but focussed measurement capabilities such as penetrators or impactors.
- Local deposit characterisation with mobile platforms as proposed for Resource Prospector and ESA's Lunar Volatile Prospector study.

Validate the required technologies: Having defined the extent and properties of a given deposit the specific challenges associated with extracting and processing the resource can be identified. These challenges may be associated with the environment in which those resources are located the mechanical properties of the feedstock to be extracted; the process by which the feedstock is to be converted into a resource or the process by which a resource is stored, preserved and later delivered for use. Each of these steps poses its own challenges and may require new developments, which may need to be tailored to the specific deposit or resource and may require demonstraiotn in the lunar environment.

Demonstrate extraction and utilisation: A final step is to demonstrate the end to end process associated with a resource using what may be termed as a pilot plant. In this scenario a feedstock must be extracted from its environment. The feedstock must then be processed and converted into a usable resource. The resource must then be made available and utilised directly or stored for future use. Waste products must also be handled appropriately. Ideally the resource should be used, in a demonstrative way, in an early human mission to show for the first time that lunar resources can be used and enabling a transition to resource dependency.

Reference:

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ROBOTIC PRECURSORS TO HUMAN EXPLORERS: ESA MISSION ACTIVITIES AND STUDIES.

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Introduction: Exploration of the Moon is the next step for human spaceflight, building on the experience of the International Space Station, which has seen human spaceflight restricted to Low Earth Orbit (LEO). This transition from LEO to Moon requires the development of new technologies, new capabilities and new knowledge across multiple domains and the progression of international partnerships exemplified through the ISS. The progression to lunar surface will be achieved through a combination of developments in robotic and human spaceflight systems and missions.

ESA's strategic approach to lunar exploration, the approach to technology development and synergies with other exploration destinaitons will be presented elsewhere in this meeting. Here we describe the current precursor robotic mission activities.

Contributions to the Russian lunar exploration programme: In advance of human surface missions robotic missions to the surface provide an opportunity to drive up the technology and system maturities of key elements for the future, to generate relevant operational experience, to build partnerships and to generate knowledge.

To this end ESA is investing in a series of robotic precursor missions that will be implemented as a collaborative effort with Russia. The first mission in this campaign is the Russian Luna-25 ('Luna-Glob Lander') lander mission in 2019. ESA will provide an imaging system for this mission as a precursor of a complete precision landing and hazard avoidance system, PILOT, which will be deployed on the Luna-27 lander mission in 2021. The Precise Intelligent Landing using On-board Technology system, PILOT, is a generic exploration product, which will be available as a European contribution to future missions to enable pinpoint and safe landing.

The Russian Luna-27 ('Luna-Resurs') mission also includes the "Package for Resource Observation and in-Situ Prospecting for Exploration Commercial exploitation and Transportation", PROSPECT. This system will be used to investigate the presence, provenance and viability of lunar resources at the Luna-27 landing site. This mission also provides the basis for future deployments of PROSPECT as a system for comprehensive resource evaluation across the lunar surface. PROSPECT emphasises cold trapped polar volatiles but is intended to provide a broader investigatory capability, which could be deployed more broadly across the lunar surface.

ESA will provide communications support across the sequence of Russian missions including both landers and the Luna-26 orbiter.

Mission studies: Following these flights ESA is looking to build on the demonstrated capabilities and further support the definition of Europe's path to the lunar surface. To this end a number of mission studies are on-going including sample return and mobile surface exploration. It is important that these next steps address key knowledge and capability gaps for human exploration, build strong partnerships and build the user base for the exploration missions that will follow.

Two mission robotioc mission concepts are being studied; a lunar polar sample return mission, in cooperation with Russia and a Lunar Volatile Prospecting rover missions. Both of these missions would investigate lunar polar volatiles.

Precursor missions integrating human and robotic caabiltities are also being investigated as potential future internaiotnal partnerships.

Partnerships: International partnerships have been and continue to be an essential element in ESA's approach to exploration. The ability to work and operate together in space also represents one of the key benefits delivered by exploration. In addition a new partnership model with the private sector is being explored, with initial pilot phases into commercially led activities to prepare robotic capabilties and infrastructure for the future.

Conclusions: We will present the current robotic precursor activities in ESA to prepare for future human exploration to the surface. Emphasis will be placed on the development activities for PILOT and PROSPECT, mission studies which are on-going with European industry, as part of a partnership between ESA and Russia, on the LPSR and LVP mission studies and on activities related to developing partnerships with the private sector.

SELECTIVE HEATING OF REGOLITH GRAINS USING DYNAMIC PHASE AND FREQUENCY. T. J. Cash[1] and B. R. Blair[2], [1] IEEE, EMC Society, Senior Member, 8 German Street, Annapolis, MD 21401; cash.tim@gmail.com; [2]NewSpace Analytics LLC, PO Box 7, Idaho Springs, CO, 80452, planetminer@gmail.com.

Introduction: Fine grained, uniformly mixed lunar soil is known to be semi-transparent at microwave frequencies, enabling penetration of inbound radiation as well as localized heating. Because the grains are typically coated with a thin patina of reduced iron, methods for melting together the surface of lunar granular materials are enabled, and indeed have been demonstrated to work in the laboratory. Indeed, unprocessed in-situ lunar regolith could make an excellent starting material for lunar base construction and manufacturing.[1]

Microwave Granular Heating: This paper will present concepts for heating lunar granular media using a dynamic strategy that varies phase and frequency to maximize the coupling efficiency of inbound radiation to a hypothetical work zone. It will present an overview of regions of transparency and opacity within and beyond the microwave frequency range for known terrestrial materials[2] and detail current theory of wave propagation and dispersion through granular media, with a specific focus on maximizing coupling parameters to match lunar regolith characteristics. The paper will then develop key metrics and decision criteria in order to search the feasible design space for local and global optima for in-situ lunar fabrication. Finally, it will explore using dynamic phase locking of microwave emitter sources in a manner that increases power density beyond the range of any single microwave source.

Prior and concurrent art will be reviewed, including solar concentrators, microwave sintering, inductive heating, Tungsten Inert Gas Welding, Metal Inert Gas Welding, hot pressing and thermal storage as well as recent designs for lunar habitats by the European Space Agency (ESA).[3,4]

Extended Applications: Methods described above could be utilized beyond the Moon, depending upon frequency propagation characteristics through other planetary granular media. Because lunar "nanophase iron" is a byproduct of space weathering, it could also exist on Phobos and asteroids, extending the utility of microwave heating and particle sintering farther into the solar system. Finally, the addition of ancillary processing methods could facilitate the localized melting, bonding and shaping of lunar materials in order to form a dynamic material stream used to manufacture any shape or matrix desired. Thus, the innovation described is envisioned to be one tool in a spectrum of options enabling commercial lunar development.

References: Use the brief numbered style common in many abstracts, e.g., [1], [2], etc. References should then appear in numerical order in the reference list, and should use the following abbreviated style:

[1] S. Lim, M. Anand and T. Rousek (2015), "Estimation Of Energy And Material Use Of Sintering-Based Construction For A Lunar Outpost – With The Example Of Sinterhab Module Design," 46th Lunar and Planetary Science Conference. [2] Ryan, P. L. "Radio frequency propagation differences through various transmissive materials," MSc Thesis, University of Northern Texas (UNT), Denton, Texas, UNT Digital Library, December 2002. [3] E.C. Eldridge, and W. Kaukler, (2009) "Extraction of Water from Polar Lunar Permafrost with Microwaves - Dielectric Property Measurements," 47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition Orlando, Florida. [4] NAS, *Microwave Processing of Materials*, National Academies Press, ISBN: 978-0-309-07475-9, 164 pages.

A Concept for a Radioisotope Powered Lunar CubeSat

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Radioisotope power systems have powered many highly successful missions to the far reaches of the solar system as well as the Moon and Mars. These systems, called Radioisotope Thermoelectric Generators (RTG) have relied on converting heat generated by the natural decay of Plutonium 238 to electric current via thermoelectric devices. The earliest unit developed supplied about 3 We and over the years developed into much higher powered units such as the ~290 We General Purpose Heat Source RTG (GPHS RTG) developed for Ulysses, Galileo and Cassini missions, and last flown on Pluto New Horizons. The RTG currently being produced is the ~110 We Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) and is powering the Curiosity rover and also planned for the Mars 2020 rover mission.

While these systems are obviously too large in power and mass to be practical for a cubesat type mission however, several concepts were developed during the 1980's that utilized the radioisotope heater unit (RHU). The RHU produces ~1.0 Wth that would produce ~40 mWe coupled with thermoelectric conversion devices, named the RHURPS.

Lunar missions have been discussed that would explore the permanently shadowed regions (PSR)/craters of the moon to validate abundance and homogeneity of deposits of volatiles and/or water ice. Since solar power is not available in these regions and batteries could only support hours of operation, a conceptual assessment of how a long life RHURPS system might fit into a cubesat structure was performed. Preliminary estimates show the 40 mWe RHURPS, controller electronics and a battery could fit within 2U. This 2U cube would be combined with other cube(s) devoted to science instrumentation, communications and other devoted subsystems to complete a lunar science station. These RHURPS systems were developed with a hard landing capability in the range of 2000 g. The objective of this assessment is to see if the lunar science community can envision science missions that are enabled by lower power, long life RPS. The RHURPS is certainly not confined to a cubesat platform, but viewed as a more restrictive configuration than other small lander options.

Lunar Ice Cube: Progress and Implications for Building Lunar Orbiting Cubesats. Pamela E. Clark[1], Ben Malphrus[2], Kevin Brown[2], Cliff Brambora[3], Robert MacDowall[3], David Folta[3], Terry Hurford[3], Dennis Reuter[3], Deepak Patel[3], Stuart Banks[3], William Farrell[3], Michael Tsay[4], Carl Brandon[5], [1]Jet Propulsion Laboratory, California Institute of Technology (pamela.e.clark@jpl.nasa.gov), [2]Morehead State University, [3]NASA/GSFC, [4]Busek, [5]Vermont Technical College.

Lunar Ice Cube, a science requirements-driven deep space exploration cubesat mission, was selected by the NASA HEOMD NextSTEP program to be deployed in cis-lunar space by NASA's EM1 mission. We are developing a compact broadband IR instrument that will fly on a 6U cubesat bus for a high priority science application: understanding volatile origin, distribution, and ongoing processes in the inner solar system. JPL's Lunar Flashlight, and Arizona State University's LunaH-Map, also lunar orbiters to be deployed by EM1, will provide complementary observations to be used in understanding volatile dynamics.

The Lunar Ice Cube team is led by Morehead State University, who will provide build, integrate and test the spacecraft, provide mission operations and ground communication. JPL provides the Science PI, Pamela Clark. Propulsion is provided by the Busek Iodine ion propulsion (BIT-3) engine. Attitude Control will be provided by the Blue Canyon Technology XB1, which also includes a C&DH 'bus'. C&DH will also be supported, redundantly, by the Proton 200k Lite and Honeywell DM microprocessor. Onboard communication will be provided by the X-band JPL Iris Radio and dual X-band patch antennas. Ground communication will be provided by the DSN X-band network, particularly the Morehead State University 21-meter substation. Flight Dynamics support, including trajectory design, is provided by GSFC.

Lunar Ice Cube utilizes a versatile GSFC-developed payload: BIRCHES, Broadband InfraRed Compact, High-resolution Exploration Spectrometer, a miniaturized version of OVIRS on OSIRIS-REx. BIRCHES is a compact (1.5U, 2 kg, 7-12 W including an AIM microcryocooler) point spectrometer with a compact cryocooled HgCdTe focal plane array for broadband (1 to 4 micron) measurements. The instrument will achieve sufficient SNR (>100) and spectral resolution (10 nm) through the use of a Linear Variable Filter to characterize and distinguish important volatiles (water, H_2S, NH_3, CO_2, CH_4, OH, organics) and mineral bands. Typical footprint size will be 10 x 10 km, but will be somewhat smaller at the equator and larger toward the poles. We are also developing compact instrument electronics which can be easily reconfigured to support future instruments with H1RG focal plane arrays in 'imager' mode, when the communication downlink bandwidth becomes available.

The Lunar Ice Cube mission science team will enable broadband spectral determination of composition and distribution of volatiles in lunar regolith as a function of time of day, latitude, regolith age and composition, and thus enable understanding of current dynamics of lunar volatile sources, sinks, and processes, with implications for evolutionary origin of volatiles.

Thermal design is critical for the instrument. The compact and efficient AIM microcryocooler with IRIS controller is designed to maintain the detector temperature below 115K. In order to maintain the optical system below 230K, a special radiator is dedicated to optics alone, in addition to a smaller radiator to maintain a nominal environment for spacecraft electronics.

Use of a micropropulsion system in a low energy trajectory will allow the spacecraft to achieve the science orbit within a year. The high inclination, equatorial periapsis orbit will allow coverage of overlapping swaths, with a 10 km along-track and cross-track footprint, once every lunar cycle at up to six different times of day (from dawn to dusk) as the mission progresses during its nominal six-month science mapping period.

FREQUENCY-RANGE DISTRIBUTION OF BOULDERS AROUND CONE CRATER: RELEVANCE TO LANDING SITE HAZARD AVOIDANCE. R. N. Clegg-Watkins[1,2], B. L. Jolliff[1], S. J. Lawrence[3], [1]Washington University in St. Louis and the McDonnell Center for the Space Sciences, Campus Box 1169, 1 Brookings Dr., Saint Louis, MO 63130, rclegg@levee.wustl.edu, [2]Planetary Science Institute, Tucson, AZ, [3]NASA Johnson Space Center, Houston, TX.

Introduction: Boulders represent a landing hazard that must be addressed in the planning of future landings on the Moon. A boulder under a landing leg can contribute to deck tilt and boulders can damage spacecraft during landing. Using orbital data to characterize boulder populations at locations where landers have safely touched down (Apollo, Luna, Surveyor, and Chang'e-3 sites) is important for determining landing hazard criteria for future missions. Additionally, assessing the distribution of boulders can address broader science issues, e.g., how far craters distribute boulders and how this distribution varies as a function of crater size and age.

The availability of new Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) images [1] enables the use of boulder size- and range-frequency distributions for a variety of purposes [2-6]. Boulders degrade over time and primarily occur around young or fresh craters that are large enough to excavate bedrock. Here we use NAC images to analyze boulder distributions around Cone crater (340 m diameter) at the Apollo 14 site. Cone crater (CC) was selected because it is the largest crater where astronaut surface photography is available for a radial traverse to the rim. Cone crater is young (~29 Ma [7]) relative to the time required to break down boulders [3,8], giving us a data point for boulder range-frequency distributions (BRFDs) as a function of crater age.

Methods: We used CraterTools [9] in ArcMap to visually identify and estimate the size of boulders in an ~7 km^2 count area centered on Cone Crater (Fig. 1a). CraterTools is designed to count craters, so boulder sizes are recorded in terms of a circular diameter to capture the long dimension. Using NAC images with a resolution of 0.5 m/pixel, the smallest boulders that can be identified with confidence are ~1 m. We then determine the BRFD at increasing distances (in units of crater radii) to find how the frequency of boulders varies as a function of distance from the crater rim.

Boulder Distributions: We counted 2441 boulders, 2011 of which are outside the crater. The boulders range in diameter up to ~8 m, with the majority of large (>4 m) boulders falling within 2 crater radii of the rim. About 25% of the boulders occur on or within 0.5 crater radii of the rim. The quantity (areal density) of boulders decreases with increasing distance from the crater rim (Fig. 1b), with a few clusters around 6-7 crater radii. The distribution is well fit by a power-law function. Only a few boulders occur near the Apollo 14 lander, ~8 crater radii from CC. Few boulders originating from CC are detected beyond 8 crater radii, providing a key data point for the distance that a crater of this size distributes boulders.

Ongoing work includes verifying LROC boulder counts with Apollo 14 surface photography and using LROC data with Diviner rock-abundance data to extrapolate to submeter boulder populations that may also pose a landing hazard. This information, coupled with counts at other spacecraft landing sites and verification using surface photography, can inform boulder populations at varying distances from craters and aid in establishing safe landing zones for future missions [10,11].

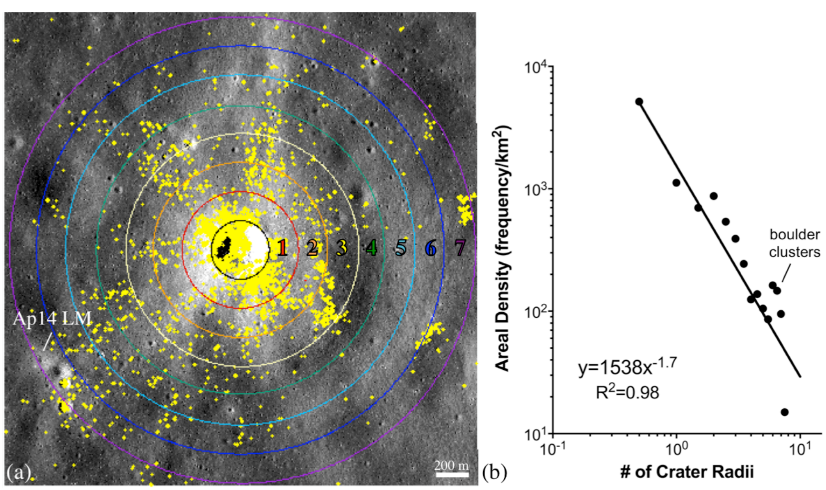

Figure 1: (a) Count area, centered on Cone Crater. Colored circles and numbers indicate distances from the rim (black circle) in crater radii. (b) The frequency of boulders falls off with increasing distance and can be fit with a power-law function.

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PROSPECTS FOR DATING THE SOUTH POLE-AITKEN BASIN THROUGH IMPACT-MELT ROCK SAMPLES. B. A. Cohen[1], R. F. Coker[1], and N. E. Petro[2]. [1]NASA Marshall Space Flight Center, Huntsville, AL, USA (Barbara.a.cohen@nasa.gov); [2]NASA Goddard Space Flight Center, Greenbelt, MD, USA.

Introduction: Much of the present debate about the ages of the nearside basins arises because of the difficulty in understanding the relationship of recovered samples to their parent basin. The Apollo breccias are from basin ejecta formations, which are ballistically-emplaced distal deposits that have mixed provenances. The Nectaris, Imbrium, and Serenitatis basins all have mare-basalt fill obscuring their original melt sheets, so geochemical ties are indirect.

Though the geological processes acting to vertically and laterally mix materials into regolith are the same as at the Apollo sites, the SPA interior is a fundamentally different geologic setting than the Apollo sites. The South Pole-Aitken basin was likely filled by a large impact melt sheet, possibly differentiated into cumulate horizons [1, 2]. It is on this distinctive melt sheet that the regolith has formed, somewhat diluting but not erasing the prominent geochemical signature seen from orbital assets [3].

By analogy to the Apollo 16 site, a zeroth-order expectation is that bulk samples taken from regolith within SPA will contain abundant samples gardened from the SPA melt sheet. However, questions persist as to whether the SPA melt sheet has been so extensively contaminated with foreign ejecta that a simple robotic scoop sample of such regolith would be unlikely to yield the age of the basin.

Modeling SPA regolith: We focused on four candidate landing sites within the SPA basin for more detailed modeling (Table 1). Modeling shows that the majority of sites within SPA have only a modest contribution to the regolith from foreign material [7]. Only two basins, Imbrium and Orientale, contribute a majority of the accumulated ejecta. We then added to the global basin dataset 90 craters contained within the boundaries of SPA [4-6]. These craters formed in the SPA terrain, so although their ejecta is “foreign” to each landing site, it is likely geochemically and petrologically within the SPA sample family. Including these craters increases the amount of “foreign” material at each site, but a competing effect is that as smaller craters churn the regolith, material that is directly derived from the SPA impact melt is reintroduced from depth [7, 8].

Impact-melt ages: Any given scoop sample retrieved from regolith that contains the SPA geochemical signature will contain fragments of SPA impact melt as well impact melt from large, distant basins and successive nearby craters, many of which may have impact-melt compositions similar to (indeed, derived from) the SPA melt sheet.

We assigned each crater and basin a reference age in order to compute statistics of sample abundance. We used this knowledge of impact-melt parentage to construct a simple, Monte-Carlo-like statistical model to understand how many randomly-selected impact-melt fragments would need to be dated, and with what accuracy, to confidently reproduce the impact history of a site.

Conclusions: Even if samples cannot be definitively recognized as SPA melt by other means, our modeling shows that dating of a few hundred impact-melt fragments will yield the age of the SPA basin from such a sample, as well as the ages of nearby craters and basins. The range of ages, intermediate spikes in the age distribution, and the oldest ages are all part of the definition of the absolute age and impact history recorded within the SPA basin region of the Moon.

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Table 1: Sites in SPA used for this study.

Site	Lat (N)	Lon (E)
Bhabha	-57	198
Bose NW	-51	186
Leibnitz-Oppenheimer	-33	183
Oresme Th	-49	163

Resource Prospector: An Update on the Lunar Volatiles Prospecting and ISRU Demonstration Mission
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Introduction: Over the last two decades a wealth of new observations of the moon have demonstrated a lunar water system dramatically more complex and rich than was deduced following the Apollo era. Lunar water, and other volatiles, have the potential to be a valuable or enabling resource for future exploration. The NASA Human Exploration and Operations Mission Directorate (HEOMD) have selected a lunar volatiles prospecting mission for a concept study and potential flight in CY2021. The mission includes a rover-borne payload that (1) can locate surface and near-subsurface volatiles, (2) excavate and analyze samples of the volatile-bearing regolith, and (3) demonstrate the form, extractability and usefulness of the materials.

Relevance and Goals: While it is now understood that lunar water and other volatiles have a much greater extent of distribution, possible forms, and concentrations than previously believed, to fully understand how viable these volatiles are as a resource, the distribution and form needs to be understood at a "human" scale. That is, the "ore body" must be better understood at the scales it would be worked before it can be evaluated as a potential architectural element within any evolvable lunar or Mars campaign. This next step in our evaluation of lunar resources has been captured as a list of Strategic Knowledge Gaps (SKGs). and provide the next step in evaluating the distribution and form of polar volatiles at scales that may be critical to robotic/human exploration (10s to 1000s of meters). RP's Level 2 mission requirements (paraphrased) are shown in Table 1.

Real-time Prospecting and Combined Instrument Measurements: Given the relatively short time period this lunar mission is being designed to, prospecting for sites of interest needs to occur near real-time. The two instruments which are being used for prospecting are the Neutron Spectrometer System (NSS) and the NIR Volatile Spectrometer System (NIRVSS). NSS will be used to sense hydrogen at concentrations as low as 0.5WT% to a depth of approximately 80-100 cm. This instrument is the principle instrument for identifying buried hydrogen bearing materials. NIRVSS, which includes its own calibrated light source, radiometer (for thermal correction) and context camera, will look at surface reflectance for signatures of bound H_2O/OH and general mineralogy. Once an area of interest is identified by the prospecting instruments the option to map the area in more detail (an Area of Interest activity) and/or subsurface extraction via drilling is considered. The RP drill is an auger which can sample from discrete depths using "biting" flutes, deep flutes with shallow pitch which hold material as the drill is extracted. As the drill is extracted a brush can deposit cuttings from the biting flutes to the surface in view of NIRVSS for a "quick assay" of the materials for water or volatiles. If this quick assay shows indications of water or other volatiles, a regolith sample may be identified extracted for processing. Processing of the sample if performed by the Oxygen and Volatile Extraction Node (OVEN). OVEN will heat the sample to first 150C, pause, then to 450C. Any gases evolved from the sample are analyzed by the Lunar Advanced Volatile Analysis (LAVA) system which includes a Gas Chromatograph / Mass Spectrometer system.

As part of efforts to mature mission design and reduce technical risk during fiscal year '15 RP designed, built and tested a RP rover/payload prototype, referred to as "RP15". This effort resembled a "mission in a year" in that initial RP15 requirements and specification were defined at the start of the fiscal year, with interface control documents and initial design review occurring a couple month later, The effort culminated in a demonstration of distributed operations of the rover/payload as it performed mission related tasks. These efforts worked to reduce a great number of technical risks as well as inform mission design going forward. In parallel to these hardware and operation development and test, lunar surface operation concepts, including further development of traverse planning tools and lunar site analysis has continued. Payload design maturation and testing has also continued, with evaluation of two mass spectrometer performance and testing of the drill, NRIVSS and mass spectometers in lunar-like conditions.

This talk will provide an overview of the RP mission and its current status.

In-situ Resource driven approaches to Additive Manufacturing using Lunar Regolith Simulant: A. Cowley[1], J. Salzer[1], K. Gutsche[1], M. Pedrazzani[1], L. Barad[1], M. Fateri2, A. Meurisse[2], [1]European Astronaut Centre, Linder Höhe, D-51147 Cologne, Germany, aidan.cowley@esa.int, [2]German Aerospace Centre (DLR), Institute of Materials Physics in Space, Linder Höhe, Building 21, D-51147 Cologne, Germany.

Introduction: In-situ-resource utilisation (ISRU) in combination with 3D printing may evolve into a key technology for future exploration. Realising the 'Moon Village' concept could be enabled by using additive manufacturing (AM) techniques to build elements from local materials – this would drastically reduce mission mass requirements (and thus cost) and act as an excellent demonstrator for ISRU on other planetary bodies (e.g. Mars). Such an approach is in line with the global vision of using the Moon as a proving grounds for essential exploration enabling technologies. Fabricating structures and components using Lunar regolith is an area of interest for ESA, as evidenced by the successful General Studies Program (GSP) conducted with Foster & Partners Architects [1].

At the Cologne DLR campus, a collaborative project known as Spaceship EAC is investigating various approaches to 3d printing for exploration activites. While classical polymer printing systems are also investigated, we work together with DLR on 'large scale' AM approaches using regolith simulants. In this collaboration, we are currently studying AM techniques for regolith via focused solar sintering, resistive heating, selective laser melting (SLM) and microwave heating. The concurrent investigation of these approaches will allow for increasd material utilisation potential, project synergy and experience sharing.

Herein, we report on early studies into utilizing these four approaches with a variety of simulant compositions.

SLM: this approach modifies a conventional Al/Ti SLM process to accommodate JSC2 simulant material as feedstock. A preparatory stage is detailed, in which the flowability of the material is improved to better fit within the acceptable parameter range for the tool. Samples procuded via this approach are shown to have comparable compressive strength to terrestrial concrete, though prone to thermally induced cracks during fabrication.

Microwave: a conventional 2.4 GHz microwave system has been modified to investigate the use of Illmenite as a weak susceptor for the melting of regolith. In compostions of simulant with increased Illmenite ($FeTiO_3$) concentrations, we observe improved regolith response to microwave heating, and the readily achieved formation of a glassy melt in ambient atmosphere. The improved response relative to untreated simulant is likely owing to the increased Fe/Magnetite content in the powder mix.

Resistive heating: conventional pressing of regolith and subsequent heating regimes (both *in vacuo* and at ambient atmosphere) have been shown to be an effective means of producing smaller sintered samples (fig. 1). We detail the process range and their characterization, as well as the microstructure of such sintered samples.

These approaches will be presented and discussed, as well as further planned activities in this area.

***Fig. 1** – Processed DNA sintered simulant via conventional resistive heating oven (vacuum).*

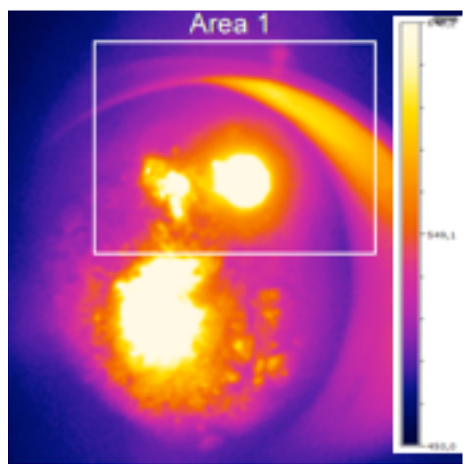

***Fig. 2** – IR image of 2.4 GHz Microwave heating of DNA regolith material (max temp shown here ~650° C)*

References:

[1] ESA GSP study on Lunar Base 3D printing: http://www.esa.int/Our_Activities/Space_Engineering_Technology/Building_a_lunar_base_with_3D_printing

ROUTE PLANNING SOFTWARE FOR LUNAR POLAR MISSIONS.

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Introduction: Traverse planning for robots operating on the lunar poles presents challenges not encountered in prior planetary rover missions. Route selection must account for hazards caused by precipitous slopes, lack of direct-to-Earth communication, and long, fast-moving shadows caused by the low sun angle.

Mission operators have a finite operating window during which they seek to accomplish as many scientific objectives as possible. However, planning while considering both rover energy and spatiotemporal variation in lighting and communication adds significant complexity for path planning algorithms. The problem becomes even more complex when considering that many different paths must be evaluated during waypoint sequencing, which is an NP-hard problem.

To address this challenge, Carnegie Mellon and Astrobotic have developed mission planning software that efficiently evaluates paths between waypoints and finds sequences of goals that maximize scientific return. The planner generates, analyzes, and optimizes routes between sequences of locations, balancing the competing demands of driving efficiency, scientific information gain (e.g., hydrogen content observed), and rover constraints (e.g., kinematics, communication, power, thermal, and terrain ability). The planner rapidly explores the space of feasible paths, constrains those paths to meet mission requirements, and returns a set of viable high-return paths to rover operators.

Methods: Our mission planning software has three components: (1) input of rover parameters, environmental data (e.g., area of interest, lighting, slope, line-of-sight for communications), and waypoints from the user, (2) computation of a set of viable paths, and (3) display of paths and statistics to the user (Fig. 1).

Defining mission goals can be difficult because it is not obvious which areas of the map are accessible from others as conditions change in time. Our planner provides an intuitive interface that lets the user specify relevant inputs and visualize reachable areas and times from a starting location.

Given a set of desired waypoints, the planner searches for subsets and sequences of these waypoints that maximize science return while minimizing risk. Several algorithms for waypoint sequencing are implemented that provide different levels of optimality and speed, including depth-first search, greedy search, and a genetic algorithm [1]. At each step of the optimization, paths between waypoints are evaluated using an A*-based path planner that considers energy, slope, and direct-to-Earth communication from maps simulated using Astrobotic's planetary renderer tool [2]. Path evaluation is efficient due to a novel temporal compression of the state space. The planner ignores states in homogenous regions, which significantly reduces both time and space complexity, enabling evaluation of multi-month traverses in just a few seconds.

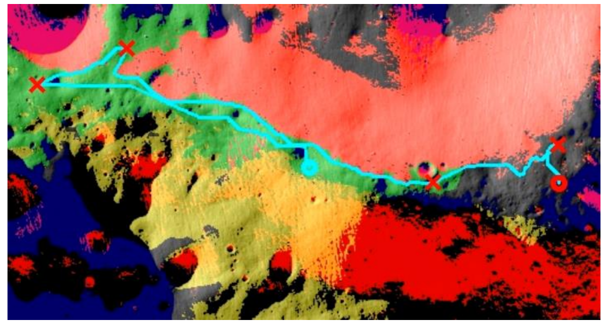

Figure 1: Example path on the Malapert region of the lunar south pole. Yellow indicates light and no communication, blue is communication and no light, grayscale is communication and light, black is no communication or light, high slope regions are in red, and green regions indicate the areas the rover may be in at the current time which are reachable from the given starting location and facilitate reaching the ending location.

Finally, once a path or set of paths is computed, they are displayed to the user. Because there can be many possible paths returned, they are clustered spatiotemporally and only representative paths for each cluster are displayed. Planner-computed statistics about the set of viable paths are presented to operators enabling them to select routes that consider a range of priorities including risk, duration, and scientific goals visited. Our planner generates trajectories that are calibrated in time and feasibility, easing operator load and increasing planning rate. The computationally efficient underlying algorithms coupled with the intuitive user interface enable effective mission planning for rovers operating on the poles of the Moon.

Acknowledgment: This work was supported by the NASA Small Business Innovation Research program under contract NNX13CA55P. Three authors were also supported by NASA Space Technology Research Fellowships.

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MOON TREK: NASA'S NEW ONLINE PORTAL FOR LUNAR MAPPING AND MODELING. B. H. Day[1] and E. S. Law[2], [1] NASA Solar System Exploration Research Virtual Institute. NASA Ames Research Center. M/S 17-1. Moffett Field, CA, USA. 94035. (Brian.H.Day@nasa.gov), [2] Jet Propulsion Laboratory, California Institute of Technology. M/S 168-200. 4800 Oak Grove Dr. Pasadena, CA, USA 91109. (Emily.S.Law@jpl.nasa.gov).

Introduction: This presentation will introduce Moon Trek, a new name accompanying a major new release of NASA's Lunar Mapping and Modeling Portal (LMMP). Upgrading to the new Trek interface provides greatly improved navigation, 3D visualization, performance, and reliability. The new Moon Trek interface also provides compatibility with the other portals developed by NASA's Lunar and Planetary Mapping and Modeling Project. Behind the scenes, this release also entails upgrades to the portal's back end infrastructure and services. These will significantly facilitate the implementation of exciting new features and capabilities in the months to come, some of which will be previewed in this presentation.

An Integrated Suite of Interactive Tools: Originally designed to support site selection and analysis for the Constellation program, LMMP has evolved to Moon Trek to meet the needs of mission planners in a new era of lunar exploration. The portal integrates a suite of interactive tools that incorporate observations from past and current lunar missions, creating a comprehensive lunar research Web portal. The online Web portal allows anyone with access to a computer to search through and view a vast number of lunar images and other digital products. As a web-based toolset, Moon Trek does not require users to purchase or install any software be-yond current web browsers. The portal provides easy-to-use tools for browsing, data layering and feature search, including detailed information on the source of each assembled data product. Using Moon Trek, many hundreds of lunar data products can be both visualized and downloaded. Detailed metadata for each data product is also made available to the user. While emphasizing mission planning, Moon Trek also addresses the lunar science community, the lunar commercial community, education and public outreach (E/PO), and anyone else interested in accessing or utilizing lunar data. Its visualization and analysis tools allow users to perform analysis such as lighting and local hazard assessments including slope, surface roughness and crater/boulder distribution. Moon Trek provides a generalized suite of tools facilitating a wide range of activities including the planning, design, development, test and operations associated with lunar sortie missions; robotic (and potentially crewed) operations on the surface; planning tasks in the areas of landing site evaluation and selection; design and placement of landers and other stationary assets; design of rovers and other mobile assets; developing terrain-relative navigation (TRN) capabilities; deorbit/impact site visualization; and assessment and planning of science traverses.

Current data products include image mosaics, digital elevation models, local hazard assessment tools (such as maps of slope, surface roughness and crater/boulder distribution), lighting assessment tools, gravity models, and resource maps such as soil maturity and hydrogen abundance.

Moon Trek fosters outreach, education, and explora-tion of the Moon by educators, students, amateur astronomers, and the general public. It has been designated by NASA as a component of its Science Education Infrastructure While great utility is provided by Moon Trek's interface and tools, it also provides particu-lar value through its ability to serve data to a variety of other applications. In the outreach realm, this has been demonstrated with data served to planetariums and NASA's Eyes on the Solar System.

New Features and Coming Enhancements: The most notable enhancement in the new release is the greatly improved visualization and navigation capabilities provided by the new Moon Trek interface. Users can also now draw a bounding box around any surface feature and generate an STL file for use with 3D printers. New enhancements are also being made to hazard analysis tools. Looking further ahead, we are working on automated traverse planning tools, developing plans to facilitate examining surface temperatures as a function of time, and are collaborating with Bill Farrell and the DREAM2 SSERVI team on a Surface Potential Analysis Tool. We will collaborate with the NASA Astromaterials Acquisition and Curation Office to integrate with their Lunar Apollo Sample database in order to help better visualize the geographic contexts from which samples were retrieved. Additional clients in the works include a gesture-controlled touch table and virtual reality/augmented reality capabilities

Acknowledgements: Moon Trek is an integral project of NASA's Solar System Exploration Research Virtual Institute, with development done at NASA's Jet Propulsion Laboratory.The authors would like to thank the the Planetary Science Division of NASA's Science Mission Directorate and the Advanced Explorations Systems Program of NASA's Human Exploration Operations Directorate for their support and guidance in the continuing development of this project.

CHARACTERIZATION OF THE LUNAR SURFACE WITHIN TSIOLKOVSKY CRATER: THE PHOTOMETRIC, ALBEDO, AND THERMAL PROPERTIES OF THE REGOLITH.
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Introduction: After suspecting hydrated materials might exist on the Moon [1], the actual detection of surficial OH/H_2O on the Moon by 4 different missions has changed our views of the interactions of the lunar surface with the space environment and the stability of water on the surface [2-5]. Most results stem from examination of spectra beyond 2μm, where reflected sunlight and thermal emission both contribute to the spectral signature. The detection and examination of the OH/H_2O signatures across the surface are dependent on the removal of the thermal signature, which is especially difficult for the Moon Mineralogy Mapper (M^3) data.

Photometric characterization of a surface can provide information on the physical structure of a surface (such as roughness) in addition to derivation of surface albedo properties (geometric and Bond albedos). This characterization is highly dependent on the accuracy to which the illumination and viewing conditions can be determined. We present a technique that allows us to utilize local topographic information (on meter scales) to photometrically characterize the lunar surface, and provide the albedo information needed to generate a thermal correction for the M^3 data, improving the dectection and mapping the distribution of OH/H_2O across the lunar surface.

Stereophotoclinometry: Using Lunar Reconnaissance Orbiter Camera (LROC) data, we constructed a digital elevation model (DEM) for a region within Tsiolkovsky crater using the techniques of sterophotoclinometry [6]. The selected region contains several types of terrains and a variety of slopes and slope orientations, including south-facing slopes that will have lower temperatures due to their lower insolation. The selected region includes mare floor materials, a rill within the mare, and an andesitic uplift from the central peak. The source LROC data has a resolution of 0.5 meters, while the DEM has a grid spaceing of 1.5 meters with a vertical precision of ~1 meter.

Photometric Analysis: Photometric cubes (layered images, in which each layer contains specific data relevant to the pixel position within the cube) were constructed from each LROC image that fell within our region. We generated a 4-band cube where the four layers contain the reflectance (I/F), phase angle (α), incidence angle (i), and emission angle (e). The I/F values come directly from the calibrated LRO NAC images. The phase angle is generated from the United States Geologic Survey (USGS) Integrated Software for Imagers and Spectrometers (ISIS) tool. Incidence and emission angles are calculated directly from the topographic model using the spacecraft and sun positions. The NAC images are narrower than our region, so multiple images are required to fully mosaic the selected area.

The key component to generating the photometric cubes is the registration process performed by SPC. We use SPC to identify several thousand control-points (a.k.a. landmarks) in an image that locks its position to the existing DEM and registers it at one pixel accuracy. Once this is performed on all the images, any location within the working region (2,000 x 2,000 pixel) can be selected and the exact I/F for each observation of that surface feature, along with the associated α, i, and e can be retrieved. The data within the photometric cubes were modeled using Hapke's set of equations [7 – 13], where 10 x 10 pixel areas within the cubes defined a single data set to be modeled. The results are image cubes where the layers correspond to the parameter values for each parameter in the Hapke model.

Thermal Spectrum: The next step in the analysis was the derivation of the thermal parameters in support of a thermal model. We calculated the geometric albedo, phase integral, and Bond albedo images using the Hapke parameters at each location.

We generate a thermal sepectrum for every pixel using the insolution, the Bond albedo, an average emissivity of 0.9 and the incidence angle. The high resolution DEM provides unparalleled detail of the surfaces' thermal model, allowing support for hot spots and shadows underfilling pixels.

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THE CONTRIBUTION OF THERMAL FATIGUE ON LUNAR REGOLITH EVOLUTION. C. El Mir[1], K. T. Ramesh[1], M. Delbo[2], and J. B. Plescia[3]. [1]Johns Hopkins University, Hopkins Extreme Materials Institute, 3400N Charles Street, Malone Hall Suite 140, Baltimore, MD 21218 (celmir1@jhu.edu), [2]CNRS-Observatoire de la Cote d'Azur, Boulevard de l'Observatoire, France. [3]Applied Physics Laboratory, The Johns Hopkins University, Laurel, MD 20723

Introduction: The lunar surface is covered by a complex blanket of regolith that has witnessed a long history of micro- and macro-meteoritic impacts, solar wind sputtering, and a multitude of space weathering processes. Understanding how the lunar regolith is formed and modified over time is therefore paramount to the understanding of the lunar surface as a whole.

The abundant presence of impact-induced agglutinates points towards the dominant role that meteoritic impact had on the evolution of the lunar regolith [1]. Nevertheless, recent studies [2-5] have suggested thermal fatigue as a mechanism for in-place rock breakdown of rocks on some airless bodies in the solar system. In thermal fatigue, a crack's growth is driven by the cyclic stresses that develop within boulders due to the large diurnal temperature variation related to the day/night cycle, and that stress eventually leads to the rock's fracture**.**

Delbo et al. [2] examined thermal fragmentation on km-sized asteroids and found that thermal fatigue could play a dominant role in the generation of smaller rocks on time scales several orders of magnitudes faster than mechanical impact. Furthermore, Eppes et al. [3] collected crack orientation measurements from more than 1,800 cracks visible in nearly 1,500 rocks photographed by the Spirit rover on the Martian surface. These data indicate these cracks exhibit preferred orientations consistent with solar-induced thermal stresses.

Given the major role that thermal fatigue could have in regolith evolution, it is important to extend this work to different bodies in the solar system. Unfortunately, the nature of the thermal fatigue mechanism makes it difficult to extrapolate or generalize the results from a single body. One of the crack tip driving forces in thermal fatigue is the stress concentration resulting from the temperature gradient that develops within a rock. The temperature gradients and temperature profile, in general, depend greatly on the rock's thermal properties, as well as the body's period of rotation and heliocentric distance. In that sense, it is expected that thermal fatigue would manifest differently on a small asteroid with a 6-hour period of rotation, compared with the Moon with its ~28 day period of rotation. Hence, the applicability of thermal fatigue on the lunar surface remains to be carefully quantified.

In this study, we present an advanced thermomechanical model that solves for the thermal stress fields within lunar surface rocks. The model is tailored to allow for bridging between the varying temporal scales: from a single period of rotation (days) until final fragmentation (millions of years), using very fine time-step resolutions as small as 30 minutes, or nearly 1300 time steps for every lunar day.

We use the eXtended Finite Element Method (XFEM) to insert an initial crack in a representative shape model mesh of a lunar rock, and we solve for the time-dependent stress field from the calculated temperature field. The stress concentration at the crack tip is then characterized by means of the stress intensity factor [6] and is recorded at each time step. At the end of a complete rotation, the excursion in stress intensity factors is calculated and is used to obtain the incremental crack growth [7]. The process is repeated until the crack's length becomes comparable to the rock's diameter, at which point we consider the rock to have fragmented.

Using the advanced numerical model, we aim to quantify the thermal fatigue contribution on lunar regolith evolution. The results will allow us to characterize the extent to which thermal fatigue is important on the lunar surface, and if it can couple with other well-known processes, such as the mechanical breakdown by micrometeoritic impacts, by gradually weakening the rocks to further drive the lunar regolith formation and evolution.

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RESOURCE PROSPECTOR LANDING SITE AND TRAVERSE PLAN DEVELOPMENT.

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Introduction: Resource Prospector (RP) will be the first lunar surface robotic expedition to explore the character and feasibility of in situ resource utilization at the lunar poles. It is aimed at determining where, and how much, hydrogen-bearing and other volatiles are sequestered in polar cold traps. To meet its goals, the mission should land where the likelihood of finding polar volatiles is high [1,2,3]. The operational environment is challenging: very low sun elevations, long shadows cast by even moderate relief, cryogenic subsurface temperatures, unknown regolith properties, and very dynamic sun and Earth communications geometries force a unique approach to landing, traverse design and mission operations.

Landing Site Identification: In addition to a high potential of volatile sequestration, a landing site candidate must meet engineering and mission operations requirements: sufficient solar access to power the rover over mission lifetime, sufficient visibility to ground stations for real time communications, manageable hazards such as slopes and block abundance, etc. A landing site must have acceptable slopes within the 3-sigma landing ellipse (200-m diameter); it should also have at least 48 hours of sun and DTE communications access to accommodate checkout, rover egress, and initial operations, with margin.

At this time, four landing sites are being used to study mission design and feasibility, two in the north and two in the south. These are shown in Table 1.

Table 1. Design Reference Mission Landing Sites

Pole	Site Name	Lat.	Lon.
SP	N. Nobile	85.194S	35.436E
SP	N. Shoemaker	87.185S	59.921E
NP	Erlanger	87.19N	29.119E
NP	Hermite-A	87.436N	-49.039E

Maps Needed for Study: Layers in a landing site and traverse planning tool must include the following: *time-varying* sun and comm access; slopes (digital terrain models); water ice stability depth models; hydrogen concentration maps; permanently shadowed regions; LROC NAC photomosaics; LRO Diviner blockiness or rock abundance measure.

Traverse Design Tool: To incorporate the static and time-varying constraints on mission design, a traverse design tool has been developed that combines the functionality of a geographic information system with mission activity planning. The RP tool relies on the ability to use the time-varying parameters of sun and comm access together with static constraints (slope limits, block hazards, etc) to determine a viable and safe traverse corridor through space and time (Fig. 1). By performing a Boolean "and" operation between relevant layers, through time, it is possible to forward-flood the landing site area to establish such corridors. A key capability in this development is "reachability analysis": determining what areas can be attained (with margin) in a given period of time assuming selectable and realistic rover mobility capabilities and science activity durations. Rover performance and real-time decision-making on the ground will vary with the types of terrain, the level of hazard, and limits on situational awareness; these are incorporated into the tool as adjustable parameters based on testing and simulation.

The RP traverse design tool is currently being used to gauge the impact of various rover design attributes on achieving mission success at the four representative landing sites. Details will be provided.

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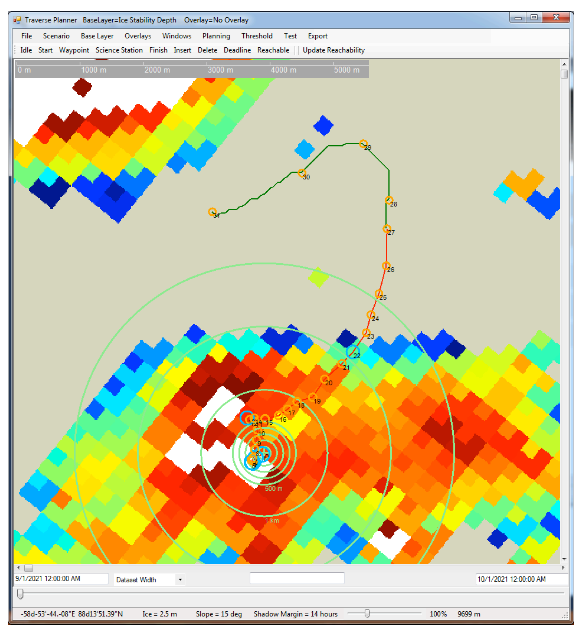


Fig. 1. Example of a traverse design for Hermit-A. The base layer is model depth to stable ice.

THE PEAKS OF ETERNAL LIGHT: A NEAR-TERM PROPERTY ISSUE ON THE MOON. Martin Elvis[1], Tony Milligan[2], and Alanna Krolikowski[3], [1]Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge MA 02138, USA; melvis@cfa.harvard, [2]Department of Theology and Religious Studies, King's College London, Virginia Wolf Building, 22 Kingsway, London WC2B 6NR, [3]Georg-August Universität Göttingen, Heinrich-Düker-Weg 14, 37073, Göttingen, Germany; alanna.krolikowski@gmail.com.

Introduction: The Peaks of Eternal Light (PELs) are a series of ridges and crater rims at the lunar poles that, because of the small obliquity of the Moon's axis, are in almost continuous sunshine. These Peaks are of great interest as they allow continuous solar power and an absence of day/night temperature changes, greatly simplifying experiment design. Moreover the Peaks lie within a few kilometers of several permanently dark craters that are likely to contain valuable resources, notably water. The PELs however cover only a tiny area, less than 1 sq. km, and so are a rare resource. As with any rare, valuable, resource, they are a potential source of conflict. Many teams have plans for lunar landers in the next few years, including landing on the Peaks, so disputes about their use are likely soon.

The Outer Space Treaty makes it clear that the Moon, along with other celestial bodies, is the 'province of all mankind', with the latter ordinarily understood to exclude state or private appropriation of any portion of its surface. This seems clear. However, there are indeterminacies in the Treaty, and in space law generally, over the issue of appropriation. We point out that these indeterminacies might permit a close approximation to a property claim or some manner of 'quasi-property'. The highly inhomogeneous distribution of lunar resourcse, including the PELs, changes the context of these issues, bringing them into sharper focus. The imminent arrival of multiple players deploying lunar landers (China, Japan, and Google Lunar X-Prize teams, including US and Israel) makes these quasi-property claims a near-term issue.

A Thought Experiment: We consider a thought experiment in which a Solar radio telescope, operating at low frequencies inaccessible from Earth, is placed at one of the PELs at the lunar South pole for scientific research. The telescope would consist of a single copper wire laid along the several kilometer length of one of the PELs, forming a dipole antenna.

Under the Outer Space Treaty (OST) the operation of this research facility requires non-disturbance by others. Since any electrical equipment would induce noise signals on the dipole, disturbing the experiment, the PEL has to remain unvisited by others. Effectively this establishes a claim of protective exclusion and *de facto* appropriation. In effect, the operator would need to be compensated in order to give up its use.

Ethical and Policy Considerations: The possibility of such a near-term appropriation raises some significant issues concerning justice, policy, and the safeguarding of scientific practice on the lunar surface. Can we avoid a "scamble for the Moon", like the 1880s "scramble for Africa" precipitated by the discovery of valuable mineral resources?

If China were to appropriate the PELs first, is that acceptable to the US and the rest of the world? Similarly if the US, or US corporations, appropriate them first, should we expect others to accept that status? Water rights in the American West were largely assigned on a first user basis. This was not necessarily the best rights regime to have chosen. Should rights have a limited duration? Should there be a compensatory regime for those excluded? There is no clear way to reduce the ethical complexity of these issus, but the range of ethical considerations in play do not seem unmanageable. Yet they are neither moot nor easily silenced within the policy and legal discussions that must follow.

Even if we decide on a good ethical framework, how will this be implemented? Who would decide if a scientific research program was valid? (c.f. Japanese "scientific" whaling.) Who would enforce time restrictions, or levy the effective taxes for compensation, and who would receive this compensation? How could such a regulatory regime balance incentives to use lunar resources with safeguards against their unjust exploitation?

We posit that the responsible conduct of scientific activities on the Moon should observe two basic principles implied by and inferred from the OST: '*proportionality*' and '*reasonable means*.'

Conclusions: Deliberation about the Peaks of Eternal Light may help to sharpen our understanding of questions about property rights in space and may help us to focus on creating workable policy solutions before some fait accompli shocks us into hasty action.

A version of this paper has been published in Space Policy.

Proposed Experiment for Prospecting and Mining Water from Lunar Permafrost from Boreholes using RF Energy. E. C. Ethridge[1], [1]InSpace Resources (3708 Nolen Ave, Huntsville, AL edwin.ethridge@rocketmail.com)

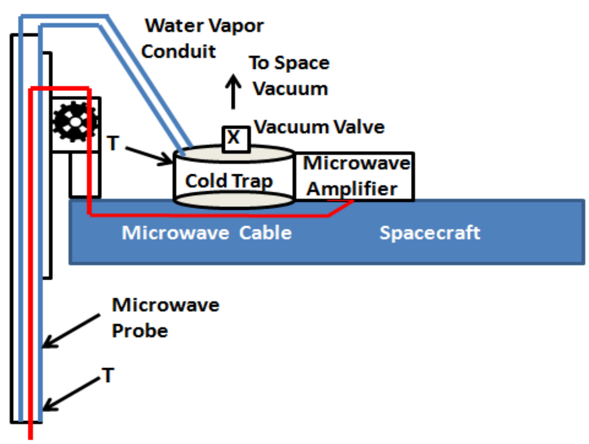
Introduction: Our proof of concept extraction of water from cryogenic lunar permafrost simulant (JSC-1A) was first demonstrated at NASA MSFC [1]. Starting with a cryogenic regolith simulant containing water ice in a high vacuum, RF energy was delivered into the regolith. The regolith heats and water ice begins to sublimate at rates increasing as the regolith heats. The water vapor flows from the regolith down the water pressure gradient out to the surface. Water vapor can then be captured with a cold trap external to the regolith. The proof of concept experiment proved that microwaves will couple to cryogenic regolith simulant and the water vapor was captured in the coldtrap with high efficiency. The process is suitable to recover water from the moon, Mars, and asteroids.

Higher fidelity experiments, such as from a borehole [2] were much more difficult to accomplish. Subsequently, FEM Numerical Simulation of the RF heating of lunar simulant was developed to simulate heating experiments. For the calculations, dielectric properties (electric permeability and magnetic permittivity) were measured at 3 RF frequencies (900 MHz, 2.45 GHz, and 10 GHz) at temperatures from cryogenic to above normal room temperature for all of the lunar and Mars regolith simulants available [3]. COMSOL Multiphysics simulation illustrated the ability of RF heating of different regoliths [4], different RF frequencies as a function of time for several different RF delivery methods [5]. Dr. Ethridge left NASA and founded InSpace Resources to further develop the experimental methods for practical extraction of water from planetary regoliths.

Simulating experiments on Mars, microwaves were beamed into the surface of Mars regolith simulant containing 10% water ice. The vacuum level and temperature was representative of Mars. Water was rapidly extracted from the mars regolith simulant and captured in the external cold trap. In another experiment, a simulated carbonaceous chondrite asteroid was fabricated consisting of oxides (JSC-1A lunar and Mars simulants), charcoal, clays, carbonates, and sulphates. All the constituents were preheated to >100C to remove adsorbed water. 15% water was then added to the asteroid simulant and molded into a spheroidal shape and frozen (-78C). Microwave energy was beamed at the sample in a containment bag in a vacuum chamber. Liberated water vapor flowed through tubing from the containment bag through the cold trap pumped by the vacuum chamber. After one hour 100% of the added water was extracted, further heating resulted in the extraction of water chemically bound in the clay and other minerals.

Our recent NASA SBIR research project permitted further development of the extraction of water from a borehole in the regolith simulant under simulated Mars (lunar) conditions. Our prototype microwave delivery device was used to deliver microwaves down a “borehole” that was sealed with the regolith at the surface. Initially the regolith had to be heated sufficiently to begin the sublimation of the water ice. Subsequently, water was collected in the cold trap with the extraction rate increasing with processing time.

A 3U cubesat is proposed to test the water extraction method using a simulated asteroid in LEO. With our prototype high efficiency small footprint GaN microwave power amplifier we will test the method in microgravity, thereby increasing the TRL. This can be followed with a small light weight water extraction demonstration experiment at the lunar pole. The experiment can be performed with a low mass apparatus using our GaN microwave power amplifier, a drilling apparatus, and in-situ microwave delivery system. The method can be used for in-situ water prospecting and subsequent mining directly from the regolith below the lunar surface. Excavation and strip mining equipment will not be required.



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LOGISTICAL SUPPORT OF LUNAR EXPLORATION AND ECONOMIC ACTIVITY WITH A LUNAR SPACE ELEVATOR T. Marshall Eubanks[1], C.F. Radley[1], [1]Asteroid Initiatives LLC, Clifton, VA 20124 USA; tme@asteroidinitiatives.com;

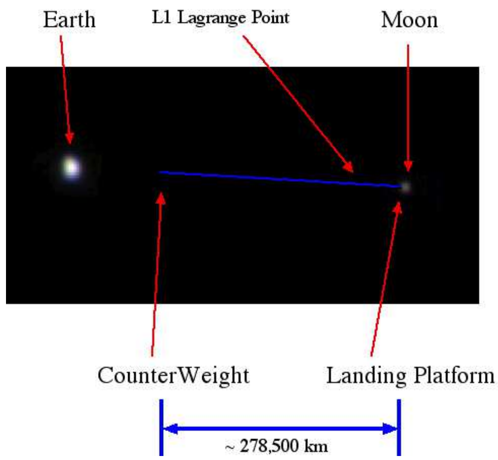

Figure 1: The components of the LSEI LSE, to scale, superimposed on a image of the Earth-Moon system from the *Juno* spacecraft.

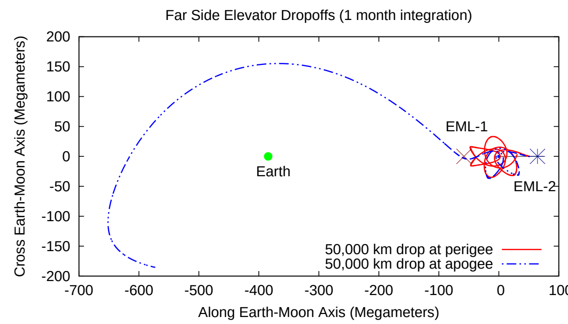

Figure 2: One month three-body integrations of the orbits of material released from a farside elevator at perigee versus apogee from an altitude of 50,000 km.

Introduction: Of the possible near-term space elevator deployments (Earth, Moon, Mars), a Lunar Space Elevator (LSE) is undoubtedly the most technically feasible. The proposed LSE Infrastructure (LSEI), proposed as the first space elevator on any celestial body, would be a very long tether extending from the lunar Surface, through the Earth-Moon Lagrange L1 point (EML-1) 56,000 km above the Moon, and on into cislunar space [1].

A Nearside Lunar Space Elevator: The LSEI currently is planned to be executed in a single Discovery class mission, starting with the delivery of 58,500 kg of Zylon HM fiber plus associated equipment to the EML-1 Lagrange site. Figure 1 shows to scale the major components of LSEI, the string, the Landing Platform (LP), the supply depot at EML-1, and the CounterWeight (CW).

The LP attached to the tether descends to the lunar surface in the initial prototype deployment, referred to after landing as the Landing Station (LS); the planned nearside LS location is Sinus Medii, near 0° Latitude and Longitude. Sample returns can be done without fuel using a nearside LSE, as material (in a suitable return capsule) could be simply released at the right moment for a direct reentry trajectory to a desired landing location; anything separated from the LSE an altitude $\gtrsim$ 220,670 km above lunar surface will re-enter the Earth's atmosphere in $\sim$1.4 days at a velocity of $\sim$10.9 km s^{-1} without any expenditure of fuel. This same technique can be used to return high value ore samples or mining products from a lunar mining enterprise.

A Farside Lunar Elevator: An elevator on the lunar farside (with a landing point at or near longitude 180°, latitude 0°) could fulfill many of the scientific and logistical goals of a nearside LSEI, but would also provide unique advantages of its own [2, 3, 1].

An open research question concerns the low-cost delivery of material from a farside LSE to the Earth. Based on three body simulations, material released from $\lesssim$ 37,000 km immediately falls to the lunar surface, while materials released between that altitude and $\sim$ 45,000 will orbit the Moon a few times with a low perilune, eventually impacting the lunar surface. Above that altitude, material, particularly material released near the lunar apogee, can escape into an Earth orbit in cis-lunar space (Figure 2). Once in a cislunar orbit, it is highly likely that Weak Stability Boundary transfers [4] (and a further lunar flyby) could be used to deliver materials to Earth with a minimal expenditure of fuel, but it is not clear how long such deliveries might take. Research is needed to better describe such orbits, and to find optimum drop altitudes and orbital phases for the reliable delivery of farside material to Earth.

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Camera-Only Kinematics for Small Lunar Rovers

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Abstract:

Knowledge of the kinematic state of rovers is critical to motion control and exploration, especially on rugged terrain like the surface of the Moon. Existing methods employ many internal encoders, potentiometers, and Hall effect sensors, which add components and wiring to moving parts and are susceptible to mechanical and electronic failures. Sensors may require thermal isolation and wiring must be routed to prevent bending, flexing, and wear. Where miniaturization counts, the limitations on mass, size, and power encourage elimination of sensors wherever possible. When not resource constrained, another sensing modality offers redundancy to proprioceptive measurements.

This work presents a novel method to estimate the kinematic state of rovers using a single downward-facing fisheye camera. Kinematic state is estimated by self-perception – combining fiducial marker tracking, optical flow techniques, and known rover kinematic constraints. Marker detection and optical flow are made more efficient by using information from links higher up in the kinematic chain to eliminate impossible search regions for links lower in the chain.

Experimental results are obtained from a rover operating in an environment analogous to the lunar surface. The estimated axle motions, steering angles, and wheel rotations are compared with ground truth data to validate the approach.

Figure 1. The test platform traversing uneven terrain in a lunar analog environment

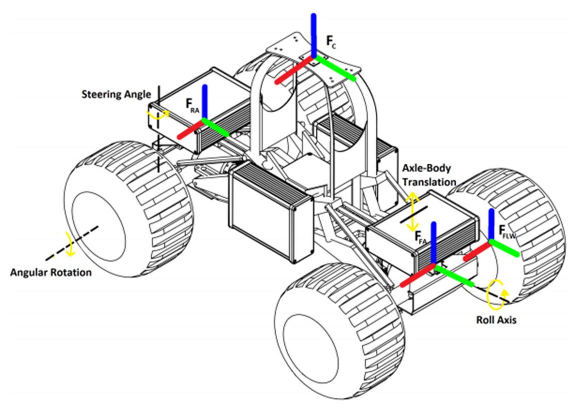

Figure 2. A depiction of: (i) The coordinate frames of the camera, axle, and wheels, illustrated with XYZ (RGB) axes (ii) The permitted rotational and translational motions of links about their respective axes

THE STATISTICAL MECHANICS OF SOLAR WIND HYDROXYLATION AT THE MOON. W. M. Farrell[1], D. M. Hurley[2], V. J. Esposito[3], J. L. McLain[4], M. I. Zimmerman[2]; 1. NASA/Goddard Space Flight Center, Greenbelt MD; 2. Johns Hopkins University/Applied Physics Laboratory, Laurel MD; 3. NASA Goddard Summer Intern and U. South Carolina; 4. University of Maryland, College Park, MD. (William.M.Farrell@nasa.gov)

Introduction: We present a new formalism to describe the outgassing of hydrogen initially implanted by the solar wind protons into exposed soils on the Moon. The formalism applies a statistical mechanics approach similar to that applied recently to molecular adsorption onto activated surfaces. The results may explain a possible diurnal effect in hydroxylation and the reported reduced OH content found in magnetic anomaly regions.

The key element enabling this formalism is the recognition that the inter-atomic potential between the implanted H and regolith-residing oxides is not of singular value, but possess a distribution of trapped energy values at a given temperature, *F(U, T)*, U being the activation energy representative of the interatomic potential between H and the regolith atoms and T being the surface temperature (in eV). All subsequent derivations herein of the outward diffusion and H retention rely on the specific properties of this distribution.

Brief Description of Results. We find that solar wind hydrogen can be retained if there are sites in the implantation layer with activation energies > 0.5 eV. Sites having trapping energy close to 0.5 eV display a diurnal effect – with H fast diffusion at high temperatures near local noon and H retention at low temperatures closer to the terminator.

The dependence of H retention is then investigated applying characteristics energies found previously for irradiated silica and mature lunar samples.

We apply the formalism to grains in magnetically unshielded (nominal) lunar regolith, and also to grains in magnetic anomaly regions where lower energy ions are incident with the surface. In magnetic anomalies, H retention is found to be reduced compared to regions outside the anomaly due to both the reduced ion influx and shallower depth of implantation. We will further describe these results in the presentation.

The adjacent figure shows the retained mass fraction of hydrogen implanted from a nominal 1 keV solar wind source – showing a clear diurnal effect. Note that the amount of H retained in the surface depends on the strength of the interatomic potential (value of U). As the population of high U values increases in the volume, so does the amount of H retained.

Conclusions. While temperature appears to be a controlling variable in the solar wind hydrogen retention on airless bodies, we find that a better indicator of hydroxylation is the ratio of U/T that can be considered an index of the H trapping potential. Given that retention goes as the exponent of U/T, the H retention times and subsequent hydroxylation will be strongly influenced by the distribution of the interatomic potentials in the top 10's of nanometers of exposed regolith grains.

We note that the ability of the surface to retain hydrogen is a function of the solid-state crystal damage and associated chemical activation created by the solar wind itself. Thus amorphous rim regions of grains could be ideal for retention. Ironically, the amorphous rims are created in part by solar wind proton damage, with the damage by solar wind weathering self-fortifying the H-retention process.

Based on the continuity equation, we conclude that the hydrogen content in the top tens of nanometers is in dynamic equilibrium with the solar wind ion source, and not necessarily in saturation of all of the trapping sites in the volume.

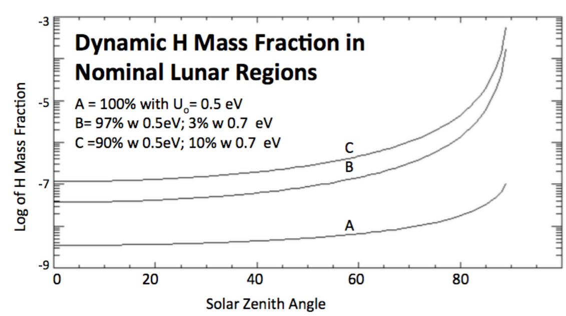

Figure Caption. The H mass fraction as a function of SZA in nominal unshielded lunar regolith for bi-Gaussian distributions of activation energy having varying weighing. Curve A has the activation energy weighed by a Gaussian, F(U_o, ΔU) having 100% of the implantations at F(0.5, 0.1), Curve B has 97% of the implantations at F(0.5, 0.1) and 3% at F(0.7, 0.1). Curve C has 90% at F(0.5, 0.1) and 10% at F(0.7, 0.1). Each curve shows a diurnal effect.

A LUNAR ISRU PILOT PLANT: An Anchor for driving PreCursor mission planning and human architecture preparation

R. Fisackerly* and J. Carpenter. ESA ESTEC (ESTEC, Keplerlaan 1, 2201 AZ, Noordwijk, The Netherlands; *email Richard.fisackerly@esa.int).

Introduction: One of the most vital questions facing space exploration today is, "Can exploration utilise lunar resources?" This question refers not just to the theoretical viability of certain chemical reactions or extraction processes. It links much more broadly with what stakeholders need to see in order to make decisions and take actions based on a confidence that in-situ resource utilisation (ISRU) works and is a viable building block on which to rely. Answering this question and creating this confidence may have the biggest impact on the future course of long term space exploration.

The Pilot Plant concept: The concept of a Lunar ISRU Pilot Plant is proposed as a focal point for understanding what stakeholders need to see in order to be convinced not just of the presence, or extractability of lunar resources, but of the end-to-end viability of In-Situ Resource Utilisation in the context of human exploration activity. Placing a Lunar ISRU Pilot Plant on the exploration roadmap can act as an anchor, linking the planning of near term precursor missions with the architecture of longer term human exploration. A Pilot Plant prepares for the longer term by generating near and medium term concrete technical and scientific questions that need to be addressed including:

- what consumables should be delivered for utilization?
- what source materials are available?
- where should a pilot plant be located?

A Lunar ISRU Pilot Plant preparations would of themselves drive ISRU forwards by requiring mission planners to consider

1. What precisely do stakeholders to need to see to be convinced of lunar ISRU's viability and value
2. What are the specific scientific and technical links between a Pilot Plant and the human exploration architecture it enables,
3. What near term preparatory steps, in the form of precursor missions and technology developments, are required.

Pilot Plants and the age of steam: The Pilot Plant can be seen as analogous to the first steam engines. Their development was critically linked to both the source materials and the initial applications, and they had to demonstrate more than just theoretical principals but actual practical applicability in order to convince investors. If one were to try to 'roadmap' the transition from pre-industrial society, to an industrial one, the steam engine would be a key anchor point. In a similar way, an ISRU Pilot Plant can act as one of the anchor points on our roadmap to a post-industrial, space fairing civilisation.

International Coordination of Exploring and Using Lunar Polar Volatiles. J. E. Gruener[1], N. H. Suzuki[2], and J. D. Carpenter[3] [1]NASA Johnson Space Center (Mail Code KX111, 2101 NASA Parkway, Houston, Texas, 77058, john.e.gruener@nasa.gov) [2]NASA Headquarters (Mail Code CQ000, 300 E Street Southwest, Washington, DC, 20546, nantel.h.suzuki@nasa.gov) [3]ESA ESTEC (Keplerlaan 1, 2401 AZ, Noordwijk, The Netherlands, James.Carpenter@esa.int)

Introduction: Fourteen international space agencies are participating in the International Space Exploration Coordination Group (ISECG), working together to advance a long-range strategy for human and robotic space exploration beyond low earth orbit. The ISECG is a voluntary, non-binding international coordination mechanism through which individual agencies may exchange information regarding interests, objectives, and plans in space exploration with the goal of strengthening both individual exploration programs as well as the collective effort. The ISECG has developed a Global Exploration Roadmap (GER) that reflects the coordinated international dialog and continued preparation for exploration beyond low-Earth orbit, beginning with the Moon and cis-lunar space, and continuing to near-Earth asteroids, and Mars. The GER can be accessed at http://www.globalspaceexploration.org.

The common international goals and objectives of space exploration, documented in the GER, recognize an intention to characterize resources available at exploration destinations including the Moon, and to develop and validate technologies and systems that extract, process, and utilize these resources for the exploration missions of the future. The ISECG has established a study team to coordinate the worldwide interest in lunar polar volatiles, and in particular water ice, in an effort to stimulate cooperation and collaboration, and to maximize the return on individual agency investments.

ISECG Lunar Polar Volatiles Website: ISECG has created a website to share information among the global space community, including government, academia, and industry to facilitate ongoing discussion about the exploration and potential utilization of lunar polar volatiles. Focus areas include the current state of knowledge, questions to be answered, and opportunities for collaboration and coordination of relevant studies, capability development, and lunar missions. The ISECG lunar polar volatiles website can be accessed at http://lunarvolatiles.nasa.gov.

Virtual Workshops and Findings: ISECG also conducts a series of virtual workshops to address key strategic issues, facilitate coordination among the community, and identify possible ways forward for addressing scientific knowledge gaps and advancing technical capabilities for exploration of lunar polar volatiles. Each 2-hour workshop includes a moderator and a panel of international subject matter experts for the particular discussion topic. These workshops are facilitated by the National Aeronautics and Space Administration's (NASA) Solar System Exploration Research Virtual Institute (SSERVI). Presentions, recordings, and findings from past workshop and a calendar for future workshops are archived on the ISECG lunar polar volatiles website.

Workshop #1, Lunar Datasets: The first workshop focused on understanding what remote sensing scientific instruments from lunar orbit or Earth have produced the most beneficial datasets to identify lunar polar volatiles deposits? A primary finding of this workshop is there are sufficient data, without additional new orbital measurements, to support near-term landing site selections for surface missions seeking to provide "ground truth" validation of existing datasets and to further characterize surface and subsurface polar volatiles.

Workshop #2, Where to Explore, and How: The second workshop focused on understanding what are the most promising Regions of Interest (ROI) for lunar polar volatile resource prospecting, and how can lunar exploration systems and instrumentation be used to prospect and characterize polar volatiles on the lunar surface. Three broad ROI at the lunar poles were discussed based on a multi-parameter analysis, including the Cabeus crater region; a region near Shoemaker, Faustini, and Nobile; and the Peary crater region.

Workshop #3, Lunar Surface Prospecting Instruments: The third workshop focused on understanding what science instruments may be most valuable on the lunar surface to locate and characterize polar volatile deposits and determine their distribution, composition, and abundance? Neutron spectroscopy, near-infrared spectroscopy and mass spectroscopy were identified as proven techniques that are very powerful in locating and characterizing polar volatiles. Other techniques, including ground penetrating radar and laser-induced breakdown spectroscopy may also prove useful.

Path Forward: Currently there are several missions at different space agencies that are being developed for lunar polar exploration, including the Russian Space Agency's (RSA) Luna 27 mission with participation from the European Space Agency (ESA), and NASA's Resource Prospector project. However, these missions will only do the impotant first steps, and further surface missions will be required to undertake comprehensive exploration of high priority areas and to realize the ability to extract lunar polar volatiles and utilize them on the surface of the Moon.

UTILIZATION OF NUCLEAR POWER FOR MOON MISSIONS: NUCLEAR BASED POWER AND PROPULSION TECHNIQUES FOR SPACECRAFT AND NUCLEAR POWER GENERATION METHODS FOR MOON HABITATS

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Introduction: As the closest space based natural satellite in space, the moon has been one of the main interests of mankind since the dawn of the civilization. To overcome certain difficulties with power requirements, nuclear power sources will be more advantageous in long term point of view. In space, it is essential to have extensive support to create power for the various requirements such as life support, communications, waste removal, etc. Thus, functional power sources are needed which can function reliably in long term. Due to its basic properties, chemical or thermal means of generating electricity would be quite difficult under reduced gravity conditions. Moreover, it would create several control and stability issues as well, too.

However, with the availability of a nuclear reactor, all of the power requirements in a moon based or space based station with microgravity or reduced gravity conditions can be met for several years without any difficulty. Nuclear reactor power systems can support human exploration at surface outposts and space stations. A nuclear reactor on the surface of the Moon can be a source of reliable power to provide life support, and to supply the large power demands of facilities processing materials. Power levels for surface and space side life support systems are approximately equivalent It will increase the options to improve the conditions for experiments in space and due to which we can install powerful systems to study more about space and also we can initiate programs for Moon.

Naturally, there are different options for utilization of nuclear power for moon based missions. It can be used as a source of power for the spacecraft or it can also be used as a source of propulsion for moon missions in order to achieve quick turnaround time during travel to the Moon. Several different types of nuclear reactors which are suitable for moon bound spacecraft are addressed and limited case study of a gaseous nuclear core based rocket propulsion system is provided as an example for spacecraft.

The paper discusses several different Nuclear Systems which can be used as a source of power and source of propulsion for moon based manned spacecraft and also it describes the use of advanced type nuclear reactors which can be used as a source of power for a moon based habitat. Especially for long term settlements in the moon, it is important to have continuous and sufficient power to power all the life support systems of the moon habitat as well as to power the necessary experiments and mining procedures on the moon.

Since the operation of normal water cooled nuclear reactors would be a challenge due to limited availability of water and due to behavior of water under reduced gravity and vacuum conditions, it will be necessary to utilize more advanced types of nuclear reactors. One such example would be the utilization of a Helium Cooled Nuclear Reactor where Helium will be used as a moderator and as a coolant. Since helium is a noble gas, it will not be chemically reactive and also several studies suggest that Helium circulation would function well in space. Thus, by using a helium cooled reactor, the challenges of using a water cooled reactor can be overcome and the necessary long term power supply can be provided to a Moon Habitat. The paper will discuss the issues while addressing moon based crititeria such as the reduced gravity, lack of atmosphere, availability of large amounts of moon dust and lack of natural resources necessary for operation of such a system.

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ERUPTION OF MAGMATIC FOAMS AND UNUSUAL REGOLITH PROPERTIES: ANOMALOUSLY YOUNG CRATER RETENTION AGES AND THE CASE OF INA. J. W. Head[1], L. Wilson[2], L. Qiao[1,3], L. Xiao[3], [1]Dept. Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912 USA, [2]Lancaster Environmental Centre, Lancaster University, Lancaster LA1 4YQ, UK, [1]Planetary Science Institute, School of Earth Sciences, China University of Geosciences, Wuhan 430074, China. (james_head@brown.edu)

Introduction: The absence of any atmosphere on the Moon means that, on approaching the surface (Fig. 1), all magmas will attempt to release all of the volatile species that they contain in solution or can generate by chemical reactions at low pressures. A common component of mafic melts in the lunar mantle is graphite, and reactions between graphite and various metal oxides produce CO gas at a pressure of ~40 MPa which occurs at ~10 km depth. This gas production ensures that essentially all lunar eruptions begin with an explosive phase. The initial stage of the eruption is fed by a dike that is likely to extend completely through the lunar crust into the upper mantle and the great width of this dike ensures a high magma discharge rate [1-3]. As the initially high excess pressure in the dike is lost and the dike begins to close due to the elastic response of the crust, the discharge rate must decrease and eventually become very small. A uniform distribution of gas bubbles exists in the magma as it reaches the surface, and the expansion of these bubbles into the lunar vacuum causes the magma to fragment into sub-mm-sized droplets that emerge in a nearly steady Hawaiian-style eruption. As the magma rise speed at depth approaches zero, the remaining closure of the dike squeezes out magma in which the only gas production is the release of water vapor. At the several hundred ppm water contents typical of many lunar magmas the gas bubble sizes are so small that surface tension forces allow them to remain stable against the internal gas pressures and so to form a foam that can have a vesicularity up to ~95%. This is the last material to be extruded and can extend for a few to several hundred meters below the surface. This latter stage of foam development should be characteristic of dikes and conduits beneath summit pit craters on small shield volcanoes and extrusion and modification (Fig. 2) may provide an explanation for some of the unusual textures and features observed in these environments, such as in the Ina feature [4].

Application to Ina: The enigmatic Ina feature on the Moon, a 2×3 km D-shaped depression that consists of a host of unusual bleb-like mounds surrounded by a relatively optically fresh hummocky and blocky floor was recently interpreted to represent extrusive basaltic volcanic activity <100 million years ago, an extremely young age for volcanism on the Moon [4]. Documentation of magmatic-volcanic processes from shield volcano summit pit craters in Hawaii, and new insights into shield-building and dike evolution processes on the Moon provide important perspectives on the origin of Ina. The size, location, morphology, topography, and optical maturity of Ina are consistent with an origin as a subsided summit pit crater lava lake atop a broad ~22 km diameter, ~3.5 billion year old shield volcano. New theoretical treatment of lunar shield-building magmatic dike events predict that waning-stage summit activity was characterized by the production of magmatic foam in the dike and pond; the final stages of dike stress relaxation and closure caused the magmatic foam to extrude to the surface through cracks in the lava pond crust to produce the mounds. The high porosity of the extruded foams (>75%) altered the nature of subsequent impact craters (the aerogel effect), causing them to be significantly smaller in diameter, and leading to the buildup of a regolith formed predominantly from crushed micro-vesicular foam material. Accounting for the effects of the reduced diameter of craters formed in magmatic foam results in a shift of the crater size-frequency distribution model ages from <100 million years to ~3.5 billion years, contemporaneous with the underlying shield volcano. We conclude that extremely young mare basalt eruptions are not required.

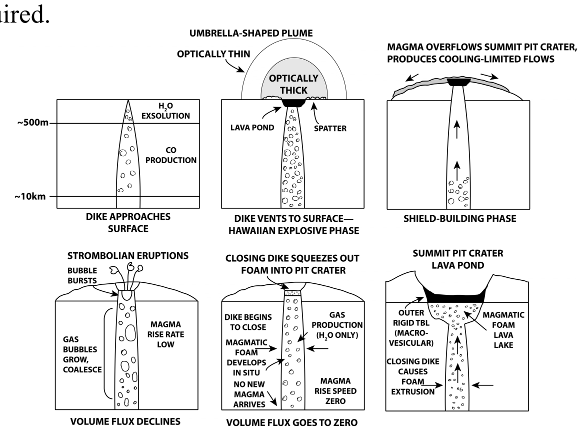

Fig. 1. Stages in summit pit crater formation and evolution.

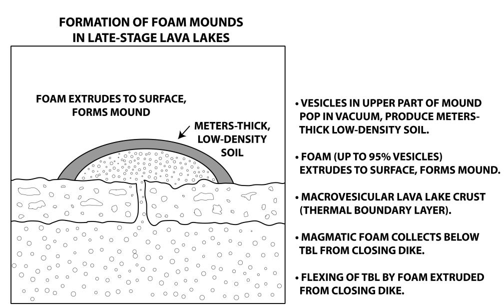

Fig. 2. Foam mound extrusion and regolith development.

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ASTROBOTIC: PAYLOAD OPPORTUNITIES FOR LUNAR SCIENCE AND EXPLORATION. D. B. Hendrickson, Vice President of Business Development, Astrobotic, 2515 Liberty Ave. Pittsburgh, PA 15222, dan.hendrickson@astrobotic.com.

Introduction: This paper describes the latest developments in Astrobotic's lunar payload delivery service, along with a proposed model for science and exploration participation on this service. Topics addressed here include Astrobotic's technical capabilities, business updates, and a proposed NASA solicitation vehicle for science and exploration communities to utilize the service.

Technical Capabilities: In June 2016 at the Berlin Air Show, Astrobotic publicly unveiled the Peregrine Lunar Lander, the spacecraft that will carry customer payloads on Astrobotic's first five commercial missions to the Moon. Peregrine is a modular spacecraft that can carry a diverse collection of payloads from a variety of customers on a single mission. The vehicle has a 35kg payload capacity on its first mission, and will fly as a secondary payload on a SpaceX Falcon 9 launch to geosynchronous transfer orbit (GTO). With minimal configuration changes in tank volume and trajectory, future Peregrine missions can host up to 265kg of payload. Payload customers for Peregrine's first mission can purchase delivery service to lunar orbit or the lunar surface at $1.2 million per kilogram.

Following deployment at GTO by the Falcon 9, Peregrine's ISE-100 propulsion system (built by Aerojet Rocketdyne) will conduct a translunar injection burn. Peregrine will then enter a cruise to the Moon that lasts no more than 4 months. Following this coast, Peregrine carries out maneuvers to enter a 100km near-polar orbit around the Moon. Once in lunar orbit, Peregrine deploys orbital payloads, and then makes a powered descent to the surface. About 55 hours after local sunrise, Peregrine lands on the lunar surface. Following post-landing check out, surface payloads are activated, and Peregrine provides payloads power and communication for the duration of the 8 Earth-day mission. With each kilogram of service purchased, payloads are provided 0.5 watts of power, and 2.8 kbps of data bandwidth. Payload data is transmitted to Earth through Peregrine's direct to Earth communication system, and received by the Swedish Space Corporation ground system for distribution to customers around the world. For those payloads that are deployed to the surface, a wireless communication protocol is provided by Peregrine.

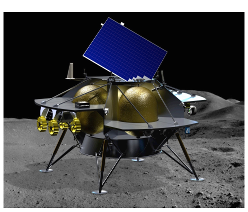

Figure 1: Astrobotic's Peregrine Lunar Lander

Business Updates: In addition to unveiling Peregrine at the Berlin Air Show, Astrobotic also announced two new partners are supporting the company in its development of a lunar payload delivery service. Airbus Defence and Space, the world's second largest aerospace company, is providing Astrobotic initial engineering support as the company advances its lander design to a preliminary design review. The decision to support Astrobotic came after a deep review that concluded, "Airbus Defence and Space clearly regards Astrobotic as the front runner in commercial lunar transportation services." [1] DHL, the world's largest logistics provider, was also announced in Berlin as the "Official Logistics Provider to the Moon." DHL is providing logistics services for the transport of the Peregrine lander to and from assembly facilities, test sites, and launch site. DHL is also providing these services for all Astrobotic payload customers.

These partnerships supplement the existing NASA Lunar CATALYST partnership, which continues to provide Astrobotic access to NASA spacecraft engineers and facilities, as part of NASA's effort to encourage the development of U.S. commercial robotic lunar lander capabilities. Between NASA, Airbus DS, DHL, and Aerojet Rocketdyne, Astrobotic has assembled a world-class team to open access to the Moon. Astrobotic has 10-signed deals toward its first mission, and is nearing completion of its payload manifest for Mission One.

Model for Science and Exploration: The science and exploration communities are now well positioned to make use of this world-class team, and carry out new activities on the Moon. Astrobotic recommends space agencies in particular partner with these communities to make use of this service. Already the Mexican Space Agency, AEM, has signed for a reservation that will deliver a lunar exploration payload determined by an RFP. NASA could utilize a similar model through the use of an "Indefinite Delivery, Indefinite Quantity" (IDIQ) solicitation of payload delivery service, which could outfit Peregrine with additional science and exploration payloads. An IDIQ call could streamline and facilitate the process for sending small to medium sized payloads that have been presented at LEAG and other venues.

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Measurement Concept for Understanding the Water Cycle on the Moon through Commercial Space Opportunities. C. A. Hibbitts[1] and H. T. Smith[1], [1]JHU-APL, 11100 Johns Hopkins Rd., Laurel, Md. 20723, karl.hibbitts@jhuapl.edu, 443-778-2834.

Introduction: Commercial suborbital flights with providers such as Blue Origin, Virgin Galactic and Masten Space Systems offer repetitive, low-cost access to space for short durations (~ 5min). These conditions are amenable to some specific investigations and observations. Understanding the water or hydroxyl that was discovered on the Moon in 2009 [e.g.1,2,3] would address a major LEAG SKG. The existence of this 'water', hypothesized to result from the interaction of implanted solar wind particles with the oxygen in the silicate grains of the regolith, raises some old, and some new, questions.

1. How does OH and possibly H_2O form and remain in the baked, airless lunar surface?
2. Can hydroxyl be formed by solar wind interacting with silicates in the surface? Can this hydroxyl subsequently evolve to form H_2O (which can migrate and accumulate in local and distal cold traps)?
3. If so, does that previously desorbed H_2O subsequently diffuse into a regolith to accumulate or escape to cold trap in places such as the permanently shadowed regions?

Measurement Concept: The concept is to acquire multispectral infrared images of the Moon in the 3- µm region using a multispectral cryocooled imaging camera flown on a suborbital commercial platform. This measurement has two significant advantages. First, is the complete lack of telluric absorptions. Secondly, because commercial suborbital will have a high repetition flight rate (eventually daily on demand flights), the Moon would be observed multiple times per a lunation. Additionally, these manned and unmanned flights are very low cost (1-2 orders of magnitude lower than current costs) with a guaranteed return of payload. A typical flight will last >30 minutes with ~3-5 minutes of microgravity at altitudes up to 100 km, however most providers may soon offer much higher altitudes. This measurement would observe the Moon at a scale of ~ 11 km at the equator, equivalent to ~320 pixels across. These measurements will identify the origin of the 3-µm band (as water or hydroxyl) using approximately 6 bands, as narrow as 10 nm – 40 nm (Figure 1). Compositional and temperature dependencies can be measured with a spatial resolution sufficient to discriminate mare from highland material and spectral sampling that will also measure the thermal continuum.

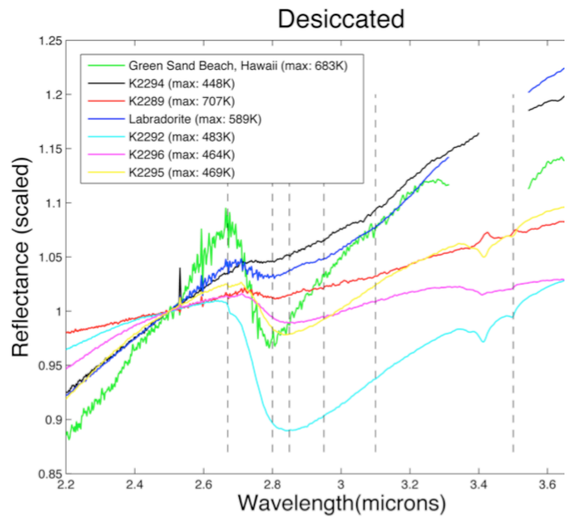

Figure 1. Spectra of vacuum desiccated minerals showing 3-µm band change due to type of 'water'.

Instrument Concept: The instrument consists of a detector, a cooled filter wheel, a cryocooler, a telescope, a mount, and associated electronics for operating the cooler and the camera. The instrument total power usage while in operation is less than 40W. It can operate the 2hr per flight (cooling time and 5 min of operation) for about 80 Wh; easily provided by a simple battery only system.

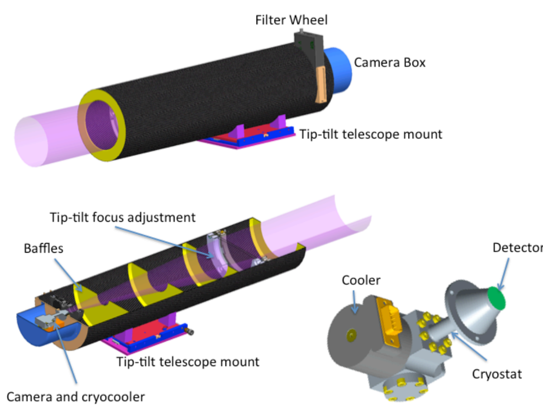

Figure 2. Telescope, detector, mount, and cooler.

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STRUCTURAL MEMBERS PRODUCED FROM UNREFINED LUNAR REGOLITH

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Introduction: The potential of utilizing lunar regolith as the raw material for manufacturing structural members is very appealing for future exploration of the Moon [1,2]. Future lunar missions will depend on in-situ resource utilization (ISRU) for structural components. Manufacturing structural components directly from unrefined lunar regolith would have the advantage of needing less specialized material processing equipment in comparison with refining the lunar regolith for its raw elements. Sintering lunar regolith has been proposed as a structural material by previous researchers but has not been evaluated for its elastic material properties. Sintering can be a highly variable process and only with the material constants can a structure be designed from this material.

Background: Sintering of actual lunar regolith has been accomplished by Taylor and Meek [3] using microwaves. However, there is not enough lunar regolith available for destructive testing to accurately quantify the mechanical material properties of sintered regolith. Lunar simulant substituted for lunar regolith in experiments then becomes the commonplace. The lunar simulant JSC-1A has become the standard for researchers in the topic of structural ISRU and has been used in a multitude of structural member fabrication processes. Through a geothermic reaction produced by the inclusion of additives, JSC-1A has been used to fabricate bricks for constructing a voissoir dome as performed by Faierson et al. [4]. In addition, Balla et. al. [5] has utilized JSC-1A, filtered for particle size, as the base material in a selective laser sintering (SLS) machine to prove the simulants additive manufacturing potential. As a proof of concept, fabrication of small solid cylinders was performed and the parameters for the SLS machine were evaluated. Focusing on developing an optimal method of sintering lunar simulant, Allen, et al. [6] compared the fabrication of bricks with two unrefined simulants, JSC-1and MLS-1.

Figure 1. Sintered JSC-1 specimens.

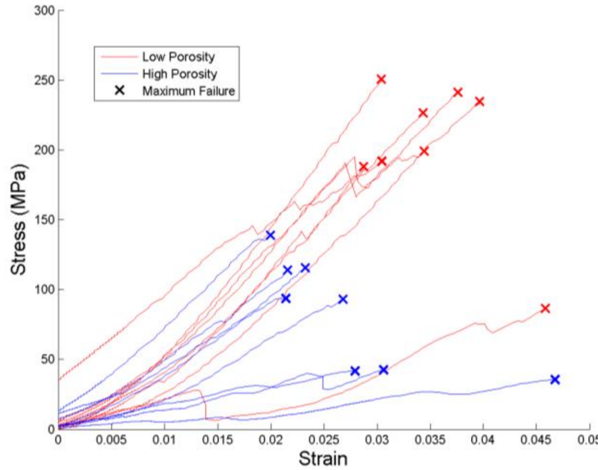

Figure 2. Stress vs strain for all compression tests.

Test Results: Quantification of the material properties was performed for sintered lunar regolith by testing sintered lunar regolith simulant. Two batches of sintered lunar regolith simulant, Figure 1, JSC-1A samples with porosities 1.44% and 11.78% underwent compression testing using an Instron series 4500 Universal Test System machine. Figure 2 shows the stress vs strain until failure of each specimen. Material properties were evaluated from the load vs. deflection data acquired. Stress, strain, modulus of elasticity, toughness, the compression strength, bulk modulus, Poisson's ratio and compressive strength were evaluated as a function of porosity and data were aggregated as probability density functions. The average compressive strengths of the low porosity material were 202 MPa, and 84 MPa for the high porosity material. By comparing these values with other ISRU derived structural materials, sintered lunar regolith is expected to be one of the strongest material derived from lunar sources.

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SPACE LAUNCH SYSTEM TRANS LUNAR PAYLOAD DELIVERY CAPABILITY. A. L. Jackman[1] and D. A. Smith[2], [1]NASA/MSFC Huntsville, AL 35812, angie.jackman@nasa.gov, [2]NASA/MSFC/Victory Solutions Huntsville, AL 35812, david.a.smith-3@nasa.gov.

Introduction: NASA Marshall Space Flight Center (MSFC) has successfully completed the Critical Design Review (CDR) of the heavy lift Space Launch System (SLS) and is working towards first flight of the vehicle in 2018. SLS will begin flying crewed missions with an Orion to a lunar vicinity every year after the first 2 flights starting in the early 2020's. So as early as 2021 these Orion flights will deliver ancillary payload, termed "Co-manifested Payload", with a mass of at least 5.5 mT and volume up to 280m3 to a cis-lunar destination. Later SLS flights have a goal of delivering as much as 10 mT to a cis-lunar destination. This presentation will describe the ground and flight accommodations, interfaces, and resources planned to be made available to Co-manifested Payload providers as part of the SLS system. An additional intention is to promote a two-way dialogue between vehicle developers and potential payload users in order to most efficiently evolve required SLS capabilities to meet diverse payload requirements.

THE LATITUDE DEPENDENCE OF DIELECTRIC BREAKDOWN ON THE MOON. A. P. Jordan[1,2], T. J. Stubbs[3,2], J. K. Wilson[1,2], P. O. Hayne[4], N. A. Schwadron[1,2], H.E. Spence[1,2], N. R. Izenberg[5], [1]EOS Space Science Center, University of New Hampshire, Durham, NH, USA (first author email address: a.p.jordan@unh.edu), [2]Solar System Exploration Research Virtual Institute, NASA Ames Research Center, Moffett Field, CA, USA, [3]NASA Goddard Space Flight Center, Greenbelt, MD, USA, [4]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, [5]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA.

Introduction: Solar energetic particles (SEPs) penetrate the lunar regolith to depths of ~1 mm, causing deep dielectric charging [1]. The regolith is electrically insulating, i.e., it is a dielectric, so it slowly dissipates this buildup of charge. In regions where the regolith is extremely cold (≤ 100 K), it likely has a discharging timescale on the order of at least a few days—longer than an SEP event. Consequently, large SEP events can significantly charge the regolith, possibly creating subsurface electric fields strong enough to cause dielectric breakdown, or "sparking" [1].

Previously, we predicted that dielectric breakdown weathering may be important in the Moon's permanently shadowed regions (PSRs), where the regolith is so cold (≤ 50 K) that it likely has a discharging timescale on the order of weeks [1]. Impact gardened regolith has been typically exposed to SEP events for ~10^6 yr, and events sufficient to cause breakdown have occurred approximately yearly during the Space Age [2]. The Cosmic Ray Telescope for the Effects of Radiation (CRaTER), on the Lunar Reconnaissance Orbiter (LRO), has detected two such events [3]. We thus predicted that breakdown weathering may have melted or vaporized ~10-25 wt% of gardened regolith in PSRs [4]. Building on this, we now predict how breakdown weathering may affect regolith at all latitudes.

Breakdown on the Lunar Nightside: SEPs have gyroradii on the order of or larger than the Moon's diameter, so they are, on average, isotropic and can charge the nightside of the Moon. The nightside may experience dielectric breakdown during large SEP events because it, like PSRs, reaches low (≤ 100 K) temperatures [5], corresponding to discharging timescale of a few days. We use the temperature as a function of latitude and local time [5] to predict the rate at which breakdown occurs as a function of latitude. We estimate that breakdown weathering may have melted or vaporized about 4-11 wt% of impact gardened regolith on the Moon. Near the equator, ~5 wt% may have been affected, and at high (>±70°) latitudes this value increases to about 6-12 wt% (see Fig. 1).

Possible Effects of Breakdown Weathering: Given these percentages, dielectric breakdown could be almost as significant a weathering process as meteoroid impacts, which have melted or vaporized ~10% of the regolith [6]. Unlike impacts, though, which direct most of their energy deeper into the regolith [7], breakdown's explosiveness can impart upward motion to grains [8] and thus may be able to "fluff" up the regolith. Consequently, it may contribute both to the "fairy castle" (high porosity) structures detected in ultraviolet observations of PSRs [9] and to a trend in radar data that suggests that polar regolith may be more porous than regolith at lower latitudes [10]. Also, because dielectric breakdown melts and vaporizes material, it may "mimic" impact features. Perhaps some features attributed to impacts have been misidentified in soil samples returned by the Apollo and Luna missions. Laboratory experiments are being developed to determine the possible effects of breakdown weathering.

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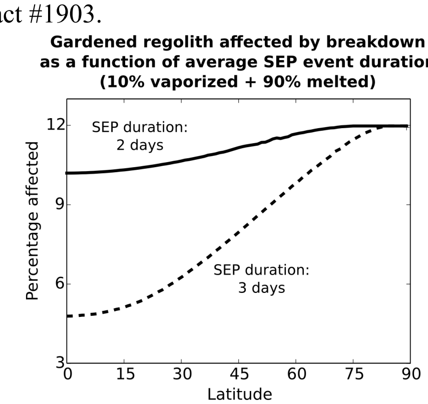

Fig. 1. The percentage of gardened regolith predicted to have been melted or vaporized by dielectric breakdown, as a function of latitude and SEP duration (events typically last 2-3 days). We assume melt and vapor occur in the same percentages as in hypervelocity impacts.

OUTCOME OF THE 1st SILICON VALLEY WORKSHOP ON LUNAR COMMERCIALIZATION TO SUPPORT A PERMANENT HUMAN SETTLEMENT ON THE SURFACE OF THE MOON. Angeliki Kapoglou[1], [1]ILEWG Moon Village Stakeholder Engagement Working Group.

Introduction: On July 19, 2016, fifty (50) Silicon Valley innovators including founders and CEOs of Newspace startups; key personnel from prime contractors and the Google Lunar XPRIZE; NASA and ESA officials; Venture Capitalists, Wall Street and infrastructure finance experts and Stanford University researchers gathered at the Rainbow Mansion in Cupertino, California, to discuss the future of lunar commercialization and start a Moon Village Leaders Consortium with very concrete proposals and clear plans addressing finance, technology and organizational strategies. Through the dynamic “unconference,” attendees self-organized into breakout groups and used creative exercises to encourage discussion and gain experts’ insights. Unlikely groupings of diversely skilled participants from inside and outside of the aerospace sector and other career paths worked together for more than ten hours to define strategies and provide valuable recommendations, summarizing challenges and opportunities, that would advance both the Moon Village vision and lunar commercialization in the near and mid-term

Results: The Workshop consensus saw private funding that might fill a portion of a Low-Cost approach to the Moon Village. However, the timing is mismatched for technology investment and returns, where the economics of profitable Lunar Operation are decades away. Venture capitalists (VCs) interested in allocating parts of their 7-10 year funds to space technology indicated that there is an urgent need to focus discussions on realistic near-term payoffs (2 - 5 years) to attract commercial interest to invest now enabling technologies with credible terrestrial returns in the near term, that also pave the way for a private lunar activity in the future. Additionally, there was broad consensus regarding the need to cut through red tape bureaucracy and to increase the speed of commercially enforceable arrangements that require government permission, cooperation, contract or enforcement support. Therefore, a new Framework for Participation of Private, Public, Investors, and Philanthropists to the Moon Village should be articulated to prepare for novel, low-cost and agile programs for space settlement and allow for space agencies, donors, and commercial space to create an integrated, mutually reinforcing strategy.

Efforts will be made to raise awareness among relevant angel investor networks/ VC groups of the Moon Village vision, its benefits, and how to utilize it for applied commercial research. Efforts will also be made to demonstrate credibility and start a dialogue between Newspace and ISECG taking advantage of the already existing mechanisms for cooperation between ISECG and external entities.

The group suggested setting clearly the objective of a Self-Sustainable Settlement on the Moon which will also drive long-term, financial sustainability. Importance was also given to facilitate explaining how Lunar Commercialization could benefit Earth’s citizens, regions, and the environment in the near-term. The scope of our efforts to bring the Moon Village vision to life should be designed to include –and care about–systems beyond our corporate or governmental needs.

Finally, the group unanimously agreed to have a bias towards action and focus efforts on building real change for the space sector. We cannot any longer just create policy papers and exploration roadmaps. Instead, we need to design policy-consistent legal instruments and financial transaction vehicles that shift established behaviors and exploration roadmap recommendations. The private commercialization of Lunar Exploration will accelerate if policymakers gain the trust of real actions and investments, taken by real people at established and new organizations. The Moon Village is a pivotal setting for demonstrating human, technology, institutional and financial cooperation for doing things not only on the Moon, but as precedent for other destinations on Earth and in space.

Over the next year, we aim to host a series of follow-up, invitation-only workshops made up of leading thinkers, who come together to provide interdisciplinary expertise, stimulate dialogue, as a means to drive a near to mid-term commercial lunar development movement with tangible next steps.

Taken as a whole, our approach enables us to generate action and inclusion of established and new government, corporate and NGO stakeholders. By connecting to and deriving our solutions from real people, we are tapping into the forcing function of a shared vision, the tangible goal of a Self-Sustainable Settlement on the Moon, which is likely to bring new, more agile business models and methods into the space sector. It is our hope that we may serve to spark the excitement and curiosity of entrepreneurs, decision makers, economic researchers, investors and all others interested in a sustainable lunar development and human space exploration.

THE LUNAR RECONNAISSANCE ORBITER CORNERSTONE MISSION: A SYNERGISTIC STUDY OF FUNDAMENTAL SOLAR SYSTEM PROCESSES. J. W. Keller and N. E. Petro, NASA Goddard Space Flight Center, Solar System Exploration Division (John.W.Keller@nasa.gov; Noah.E.Petro@nasa.gov).

Introduction: The Lunar Reconnaissance Orbiter mission (LRO) has been granted a two-year extension, from October 2016 through September 2018, to study the fundamental processes recorded on the Moon. Processes that operate not only at the Moon but generally throughout the Solar System, especially on bodies without a significant atmosphere. This "Cornerstone Mission" (CM) employs all seven LRO instruments in a mission-wide approach to constrain science questions. This synergistic approach allows processes to be constrained at distinct spatial (both lateral and vertical) and temporal scales. These processes are divided into three distinct eras of lunar history.

Contemporary Processes: LRO has been at the Moon for over 7 years, making it the longest active lunar orbital mission ever. This unprecedented baseline of observations enables fundamentally new science, especially in observations of subtle changes to the lunar surface and its environment.

Evolutionary Processes: LRO will look to the recent geologic past to study processes taking place within the interior and their reflection on the surface, such as those that provide evidence of the Moon's recent volcanism, and the evolution of the regolith.

Fundamental Processes: Reaching farther back in time, LRO will employ new observations to determine the relative timing and duration of basin-forming impacts during the proposed period of Late Heavy Bombardment, the formation and evolution of the early crust, and the styles of early volcanism.

Science Focus During the CM: The LRO science teams identified three science themes for the CM, which build on Decadal-relevant science questions: 1) Volatiles and the Space Environment, 2) Volcanism and Interior Processes, and Impacts and 3) Regolith Evolution. A few examples of the science questions we will address during the CM are illustrated in Figure 1.

New Modes of Instrument Operations and Campaigns: As part of the senior review process, the LRO instruments explored new modes of operations or data collection campaigns. These new modes and campaigns offer fundamentally new measurements and capabilities to the mission. Over the two years of the CM, these new modes and campaigns will be employed in a cadence, typically dependent on beta-angle, orbital altitude, and meteor shower activity.

LAMP's New Mode: LAMP will establish a new mode of sensitive dayside operations by opening a failsafe door. This device is intended as a one-time event to guard against a possible failure of the main aperture door. To limit the flux of dayside signal to a comparable level for nightside observations, the aperture door includes a pinhole with 0.13% throughput compared with the door-open nightside mode. Opening the failsafe mechanism expands the throughput from the 0.13% pinhole aperture to 10.7%, providing an up to 80x increase in dayside count rates. LAMP dayside measurements in this mode will assist the detection of surface hydration.

Mini-RF X-Band Measurements: While the Mini-RF instrument did not operate during ESM2, the team continued the analysis of bistatic observations collected during ESM1. Those data provide direct evidence for wavelength-scale deposits of water ice (10s of cm) within the upper meter of the floor of Cabeus crater [1]. On the basis of this positive result, a new mode of bistatic operation is proposed for the CM that utilizes the Goldstone deep space communications complex 34 meter antenna DSS-13 in concert with the Mini-RF receiver to observe the Moon at X-band wavelengths (4.2cm). DSS-13 will provide additional operational capability than is possible with the Arecibo Observatory and the X-band data collected will provide important information on the vertical distribution of potential water ice deposits.

Conclusions: LRO remains a highly productive, scientifically compelling mission. During its Cornerstone Mission LRO will continue to advance the leading edge of lunar and Solar System science.

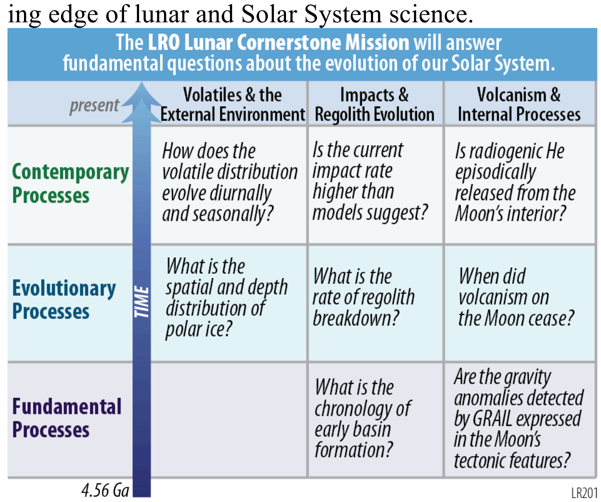

Figure 1. During LRO's CM, a number of science questions address fundamental Solar System science that cover processes that have acted over billions of years.

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MOON DIVER: A MISSION CONCEPT FOR EXPLORING THE HISTORY OF LUNAR MARE DEPOSITS WITH THE AXEL EXTREME TERRAIN ROVER L. Kerber[1], I. Nesnas[1], J.W. Ashley[1], M. J. Malaska[1], C. Parcheta[1], K. L. Mitchell[1], R. C. Anderson[1], A. Stickle[2], L. Cheek[3] [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109 (kerber@jpl.nasa.gov), [2]Applied Physics Laboratory/Johns Hopkins. [3]University of Texas, Austin

Introduction: The lunar mare basalt deposits serve as natural probes into the lunar interior. Studies of the morphologies and spectral properties of exposed surface basalts have yielded major insights into the thermal history and chemical composition of the Moon [e.g., 1-3]. Still unknown are the compositional, petrologic, and thermal changes in each mare basin through time; information which can only be accessed through examination of their cross-sectional exposure. Recent images returned by the Kaguya and Lunar Reconnaissance Orbiter missions have revealed the presence of deep mare pits containing meter-scale layer stratigraphy exposed in their walls ([4-6], **Fig. 1**). A mission to a mare pit would address numerous top priority lunar science goals laid out in community reviews [7], the Decadal Survey [8], and the Lunar Exploration Roadmap [9].

Before now, the desire to send a mission to these targets was tempered by the difficulty of reaching them given the mobility of traditional rovers. The Axel Extreme Terrain Rover [13], developed by the Jet Propulsion Laboratory in collaboration with Caltech, has the mobility necessary to approach, anchor, and rappel into this type of pit, revolutionizing our capability to access and explore in-place stratigraphy on the Moon.

The Axel Rover: The Axel rover consists of two wheels connected by a thick axle containing a winch and a tether [13]. Scientific instruments are housed inside the wheel well (**Fig 1**). Over flat terrains (for example, from the landing site to the investigation area), the Axel rover can traverse like an ordinary rover. Once it approaches a steep section, the Axel rover can set an anchor and rappel down the steep slope by letting out the tether stored inside the axle [10; **Fig. 1**]. Two Axels can be combined to form a "DuAxel" (**Fig. 1**), or one Axel can replace an axle on a more traditional rover body [10].

This functionality allows the rover to descend steep to vertical slopes (and ascend them again). The rover can even dangle in free space and continue to let out its tether.

The rover can communicate through its cable, alleviating common communication problems facing other cave-exploring robots. The rover can also receive power through its tether, meaning that it could leave a solar panel on the surface and still receive power to explore a dark cave below [10]. The functionality of this rover would allow a mission to examine and characterize lava layers exposed in the wall of a mare pit crater during abseil descent. Mineralogy (provided by the miniature spectrometer), texture (provided by the microimager), and measurements by additional instruments (housed by Axel's 6-8 instrument bays), or on the larger body of the DuAxel, would reveal changes in composition and morphology throughout the section. Axel's onboard cameras could record layer thicknesses and document the presence and characteristics of intervening soil layers.

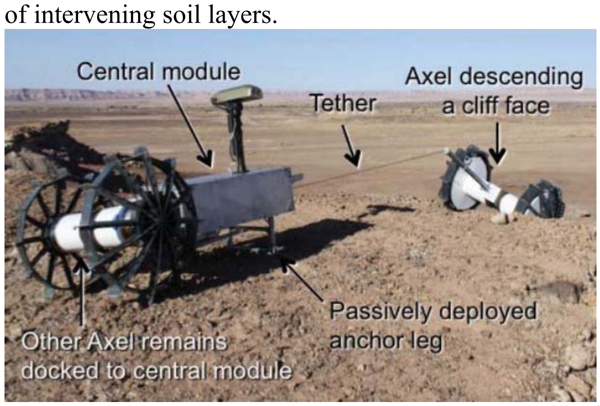

Figure 3. The DuAxel rover configuration at work in the field (figure from [10])

Once on the floor of the pit, or in a subsurface lava tube, Axel could explore potentially up to 1 km underground; [10]). After exploring the pit, the rover could reel itself back up the wall and either continue roving across the surface or rappel down a different side of the pit.

References:

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FACTORS AFFECTING COMMERCIAL DELIVERY OF PAYLOAD TO THE MOON

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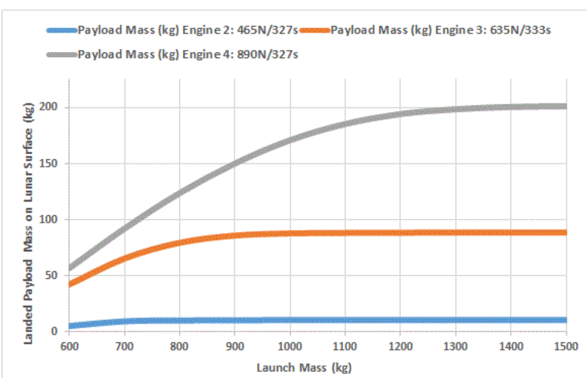
Introduction: Commercial industry has been building up capability in planetary exploration vehicles, stemming from the impetus of China and India's emergence as well as the successes of private companies such as SpaceX and the private enterprises competing in the Google Lunar X Prize (GLXP).

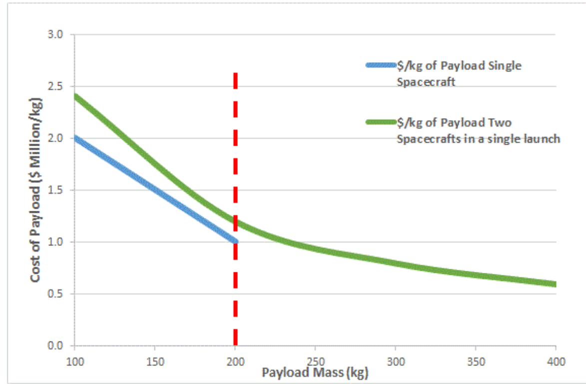
TeamIndus has developed its Lunar Landing Vehicle (LLV) to meet the requirements of the GLXP competition and a Lunar Surface Exploration Rover (LSER) to demonstrate a mobile platform to increase the reach of the robotic mission. The next-generation version of the LLV is being developed to deliver up to 200kg of payload to the lunar surface with a landing accuracy of ±50m, thus opening up access to the challenging areas of interest (like the Peaks of Eternal Light in the polar regions).

In order to provide greater value and longevity of return per launch, it seen that a 'Lander + Orbiter' or a combined launch of two next-generation LLVs in the same manner of compatibility achieve commercial returns faster than a single spacecraft sent to either lunar orbit or surface per launch. The orbiter proposed here has a maximum allowable payload of 200kg, and bridges the gap in the LLV's capabilities, mainly those of data relay for lunar far side and polar landings.



Parametric Study: The propulsion system chosen for a landing mission affects the payload carrying apacity of the Lander. Larger thrust is required to counter the lunar gravity as well as kill all velocity for a larger pre-descent spacecraft mass. A trend is noted in the plot below, where a limit to the maximum payload mass delivered to the surface is reached even if the launch mass is greater. A similar methodology is was used by Ho Lee and Ryool Lee [1].

The above plot shows how the pairing of spacecraft on a single launch reduces the cost per unit mass for



landing missions that utilize commercially available engines. The difference is straightforward, in such, that a single spacecraft per launch can cost $1 million at the least (200kg payload), while launching two simultanesouly brings it down by 40%.

Roadmap: In order to supplement the current demand for low-cost access to the lunar surface (mainly science), it almost becomes mandatory that ISRU and other infrastructure demonstrators for short-term and long-term exploitation [2] are flown side-by-side with lunar scientific payloads. Such a phased transition from science-driven to commerce-driven planetary transportation will increase traffic beyond Earth orbit, and thus start a virtuous cycle of rise-in-demand being met with competitive costs for interplanetary access. This has many historical parallels where exploration capability has jumped ahead dramatically when business drivers and their associated commercial returns are also identified, and used to drive the formulation of the exploration concept [3].

Conclusion: A sustainable service can be established quicker when the transition from exploration to conventional industry (e.g. mining, construction, power and life support) is made in a short time span. With the basic infrastructure now established, it automatically makes the Moon ready as a spaceport for accessing further locations in the solar system, and restarts the cycle for furthering the human presence.

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LUNAR CAPABILITIES ROADMAP. Georgiana Y. Kramer[1], David J. Lawrence[2], Clive R. Neal[3], Pamela E. Clark[4], Robert O. Green[4], Mihaly Horanyi[5], Michael D. Johnson[6], Robert M. Kelso[7], Mahmooda Sultana[6], David R. Thompson[4]. [1]Lunar and Planetary Institute Houston, TX 77058, kramer@lpi.usra.edu. [2]Johns Hopkins University Applied Physics Laboratory Laurel, MD 20723. [3]University of Notre Dame, Notre Dame, IN 46656. [4]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109. [5]Laboratory for Atmospheric and Space Physics, Boulder, CO 80303. [6]Goddard Space Flight Center, Greenbelt, Maryland 20771. Johnson Space Center, Houston, TX 77058.

Introduction: There is international impetus to return to the Moon initially robotically, but eventually with humans. The Lunar Exploration Analysis Group developed the Lunar Exploration Roadmap (LER), a comprehensive roadmap to not only allow a sustainable human presence on the lunar surface, but to use the Moon to enable Solar System exploration [http://www.lpi.usra.edu/leag/LER-Version-1-3-2013.pdf]. The logical build up of capabilities will require technological development and advancement. Therefore, a Lunar Capabilities Roadmap (LCR) is required to highlight what initial technological investments need to be made to support the Lunar Exploration Roadmap as well as the Global Exploration Roadmap (GER) [https://www.nasa.gov/sites/default/files/files/GER-2013_Small.pdf] developed by the International Space Exploration Coordination Group (ISECG), and the LEAG LER implementation document.

Lunar resources will be critical for the next phase of lunar and Solar System exploration, not only for reduction of launch mass from Earth but also for developing commercial "on ramps" for private sector involvement. ***A sustained human presence on the Moon offers the most secure and likely path to develop technologies to realize NASA's ultimate goal of human Mars exploration.***

The LCR will be a strategic and living document. The document does not prescribe a specific architecture, nor does it mandate specific technologies. Instead, it focuses mainly on capabilities with examples of specific technologies to satisfy these needs. The assumptions and instrumentation are intended to be broad and not meant to be prescriptive.

Scope: The LCR document would highlight technical capabilities critical for science and exploration of the Moon as well as their potential for science and exploration beyond the Moon. Specific examples of appropriate instrumentation and technologies will be included to demonstrate feasibility and highlight potential targets for future investment. Although aspects of the LCR may include robotic precursor missions, it must be emphasized that the Specific Action Team (SAT) is tasked with creating a document that focuses on ***enabling technology to prepare humans to go to the Moon***.

The LCR-SAT will identify the top instruments and technologies common across the LER, GER, and LEAG implementation documents that would enable a realistic path forward in lunar exploration and science. The LCR will be particularly focused on the instruments and technologies that promote human space exploration and enable commercial "on-ramps".

The LCR-SAT is working to deliver a draft report to the LEAG Executive Committee no later than 1 December 2016.

Abstract for Consideration for the 2016 LEAG Workshop

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TITLE: **Defining a Need for Assessing the Extraterrestrial Environmental Impacts of Lunar Activities**

ABSTRACT

Assessing the potential environmental consequences of our terrestrial actions has become an increasingly common tool in project planning in the United States and many other countries. It is accepted as a pragmatic step that can help in avoiding unintended adverse consequences, reduce the costs of mitigation and remediation and preserve options for a range of future actions. But the geographic scope of human endeavors is expanding faster than environmental regulation. We are failing to identify and assess the potential environmental impacts of our extraterrestrial actions, limiting future options.

Although existing international instruments such as the Outer Space Treaty and Moon Agreement generally express sentiments for minimizing missions' extraterrestrial environmental impacts, they tend to be limited in scope, vague and generally unenforceable. There is no formal structure for assessing how and to what extent we affect those environments, no opportunity for public participation, no uniform protocol for documenting and registering the effects of our actions and no requirement to mitigate adverse impacts or take them into consideration in the decision-making process. Except for precautions limiting forward biological contamination and issues related to Earth satellites, environmental impact assessment, when done at all, remains focused on how missions affect Earth and near-Earth environments, not how our actions affect the Moon, Mars, comets and other potential destinations. Extraterrestrial environmental impacts are potentially counterproductive to future space exploration, exploitation and scientific investigations. Clear, consistent and effective international protocols guiding a process for assessing such impacts are warranted. While instruments such as the US National Environmental Policy Act provide legally tested and efficient regulatory models that can guide impact assessment here on Earth, statutory legal frameworks may not work as well in the international environment of outer space. A proposal for industry-driven standards and an environmental code of conduct based, in part, on best management practices are offered for consideration.

POTENTIAL EXPLORATION MISSION OBJECTIVES FOR CREW ON ORION. David A. Kring[1,2], [1]USRA Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston TX 77058 (kring@lpi.usra.edu), [2]NASA Solar System Exploration Research Virtual Institute.

Introduction: The Orion crew vehicle and Space Launch System (SLS) provide new capabilities for exploring deep space. A series of Exploration Missions (EMs) with those vehicles are being planned for the cis-lunar region to validate spacecraft performance and evaluate crew health performance. Those efforts will be important contributions to the Global Exploration Roadmap (GER) [1], which includes extended duration crew missions and humans to the lunar surface.

Initial Mission Capabilities: In the initial EMs, I suggest Orion be outfitted with a high-definition camera to image the Moon during 100 km altitude passes over the lunar surface (Fig. 1), an additional camera to detect impact flashes on the farside and/or in the nighttime hemisphere to complement ground-based measurements of the nearside, radiation detectors for measurements external to and within the Orion crew capsule to test crew exposure models, a receiver to make modern measurements of radio noise on the lunar farside for comparison with an RAE-2 occultation of Earth in 1973, and a communication asset that can be deployed into orbit for future farside relay.

Human-assisted Robotic Sample Return: More complex missions that follow can integrate humans in orbit with robotic assets on the lunar surface. The feasibility and productivity of an Orion L2-farside sample return mission involving a 30 km traverse [2] and an astrophysical mission that deploys a radio antenna [3] have previously been studied. Those scenarios will be enhanced if Orion has sufficient bandwidth to accommodate high data rates, including high-definition video from the lunar surface. Once an orbiting facility at the Earth-Moon L2 position is available, then longer duration farside sample return missions as envisioned by the HERACLES concept [4,5] can be implemented. That activity has the capacity to traverse 100 to 300 km and return to Earth 30 to 60 kg of material needed for geologic and in situ resource studies.

Destinations: Historically, two dozen successful missions have explored the lunar nearside surface. None have landed on the farside, so that vast region of unexplored territory is an obvious target of interest. A global landing site study [6] found that the Schrödinger basin, within the South Pole-Aitken basin, on the lunar farside, has the greatest potential for scientific return. Multi-element missions can subsequently target other farside destinations within the South Pole-Aitken basin, either robotically or with humans using Lunar Electric Rovers (LERs) or Space Exploration Vehicles (SEVs). Crew on the surface would greatly accelerate scientific discovery while also testing methods for in situ resource utilization (ISRU) and sustainable exploration. Robotic assets, such as the LERs, could be used to survey additional areas (e.g., for resource volatiles), in between those crew landings.

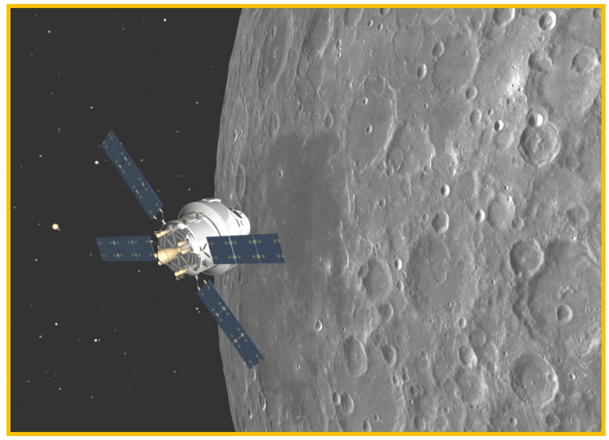

Fig. 1. Concept illustration of the NASA Orion crew vehicle and ESA service module passing over the lunar surface en route to a halo orbit about the Earth-Moon L2 position. Alternative orbits include distant retrograde orbits (DROs) or near-rectilinear orbits (NROs).

Demonstrating Capabilities & Retiring Risk: Human-assisted robotic missions will revalidate our ability to land on and traverse the lunar surface, ascend to and rendezvous in lunar orbit, and return samples to Earth, all of which are essential capabilities to be developed for the GER. In addition, the installation of an orbiting facility and assembly of robotic elements at L2 will validate deep space assembly operations (a Mars-forward capability), while developing the capability for crew to tele-operate surface assets (a Mars-forward technology) and demonstrating a series of crew health performance capabilities (e.g., deconditioning countermeasures, space radiation protection and monitoring, habitation systems) needed for exploration beyond the cis-lunar environment. The eventual deployment of crew on the surface will validate a capability for long-duration activities in relatively low gravity geologic settings while encumbered with pressurized suits, vehicles, and habitats (which are elements of any Mars-forward architecture).

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TRANSPORTATION SUPPORTING A SELF-SUSTAINING SPACE ECONOMY

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Thirty years from now, 1,000 people could be living and working in the space around Earth and the Moon – waking up in commercial habitats, prospecting on the Moon and even harnessing power from solar power satellites for consumption on Earth. NASA's interplanetary probes and human exploration are opening the frontiers of space similar to how the Lewis and Clark Expedition opened the frontiers of America in 1804. This early exploration of America was followed by development of the first transcontinental railroad in 1869 opening America to pioneers and industry. Space is at a similar crossroads where a modern day space transportation system can open cislunar space to commercial development.

Elements of this transportation system are in development at United Launch Alliance. This system will be fueled by hydrogen and oxygen initially carried to space from Earth, but transitioning to space derived resources as lunar and near Earth asteroid water mining develops. The workhorses of this transportation system will be ACES and XEUS plying the trade routes of cislunar space, connecting Low Earth and Geostationary Orbits with Earth Moon L1 and the lunar surface.

This paper will describe the elements of the space transportation system, the benefits of lunar extracted water, and how such a transportation system can enable a prosperous, self-sustaining space economy.

BUILDING STRATEGIC CAPABILITIES FOR SUSTAINED LUNAR EXPLORATION. M. Landgraf[1], and B. Hufenbach[2], [1]European Space Agency, ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands (Markus.Landgraf@esa.int), [2]European Space Agency, ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands (Bernhard.Hufenbach@esa.int).

Introduction:

The benefits of large space exploration programmes such as Apollo [1] and the International Space Station (ISS, [2]) have been well documented. Today's focus of the exploration community is the operation and utilisation of the ISS. It is time to reflect on how these benefits that are so critical for global cooperation will be generated in the future. For many reasons the next logical and achievable step in exploration is lunar exploration. Here, "exploration" is understood as the systematic, step-wise process of advancing the frontier of accessibility and knowledge, which is compatible and harmonious with - yet distinct from - the discovery-driven process of scientific research. The answer to the question: "What follows the ISS as the next logical step?" was given by various international fora, in particular the International Space Eploration Coordination Group (ISECG), which reflects on options in a Global Exploration Roadmap (GER, [3]). The European Space Agency (ESA) as one of the member agencies of ISECG has defined its dedicated Space Exploration Strategy [4] that is in line with the GER. This European strategy is driven by providing affordable access to three destinations: Low Earth Orbit (LEO), as well as the surfaces of Moon, and Mars.

LEO will remain a key destination for advancing our understanding of how to live and work in space for long periods of time. The role of the Moon is that of the next step in expanding the human sphere of influence, while Mars represents the horizon goal. With the vision to continue and expand the partnership in space exploration in the frame of a Moon village [5] formulated by the ESA Director General, the role of the lunar surface as a destination for exploration is emphasised.

Mapping Objectives to Capabilities:

One of the top-level objectives of lunar exploration is forumated in the ESA Exploration Strategy as [4]: *Acquire access to lunar surface for advancing knowledge of the Moon, understanding role of its resources for future human space exploration and advancing scientific questions related to the history of the Solar System and the origin of life on Earth.*

This objective can be clearly matched to capabilities (i.e. systems, vehicles, and operational methods). For access to the lunar surface landing vehicles are needed as the base capability. Understanding the role of resources for exploration requires to take the next step in in-situ resource utilisation (ISRU). Given the advanced understanding of lunar resources provided by the NASA Lunar Reconnaissence Orbiter (LRO) mission [e.g. 6] a capability to establish the small-scale (below ≈100 m resolution) distribution of resources and their accessibility is required.

Linking Strategy and Vision:

We discuss how the on-going process of international coordination has yielded a lunar exploration architecture and a compatible ESA Exploration Strategy that addresses the strategic objective of providing access to the lunar surface. Without this access, no exploration of the lunar surface is conceivable. Realisation of a human and robotic access to the lunar surface is a key element of the proposed European Exploration Envelope Programme. This access enables the most exciting part of the lunar exploration: building a sustained infrastructure on the lunar surface in an international, diverse partnership. It is this goal of sustained lunar exploration that addresses two of the most promiment global challenges: trustful international cooperation and how to manage "spaceship Earth" [10].

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BUILDING ON THE CORNERSTONE: DESTINATIONS FOR NEARSIDE SAMPLE RETURN

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Introduction: Discoveries from LRO have transformed our knowledge of the Moon (e. g., [1-3]), but LRO's instruments were originally designed to collect the measurements required to enable future lunar surface exploration [3]. Compelling science questions and critical resources make the Moon a key destination for future human and robotic exploration.

Lunar surface exploration, including rovers and other landed missions, must be part of a balanced planetary science and exploration portfolio. Among the highest planetary exploration priorities is the collection of new samples and their return to Earth for more comprehensive analysis than can be done in-situ [4]. The Moon is the closest and most accessible location to address key science questions through targeted sample return. The Moon is the only other planet from which we have contextualized samples, yet critical issues need to be addressed: we lack important details of the Moon's early and recent geologic history, the full compositional and age ranges of its crust, and its bulk composition [5].

Rationale: The importance of sample return from South Pole-Aitken basin is well-established [6], but there are numerous other locations where either robotic or human sample return can lead to important advances in planetary science. Automated sample return from the Moon must be a key part of any coherent Solar System exploration strategy. Automated sample return missions, such as those flown in the 1970s by the Soviet Union, can address key planetary science issues and prepare for future human exploration.

Methods: To identify desirable sample return sites, using LRO data we have deployed an in-depth data fusion process described in [7-12] to define an achievability envelope based on the physical characteristics of locations where spacecraft have successfully landed on the Moon [13]. The defined achievability envelope provides a useful starting point to constrain plausible near-term destinations for robotic and human exploration missions.

Results: The resulting achievability envelope was then used to define 1 km x 1 km geographic regions of interest where automated sample return would be feasible. Rationale for these locations was previously discussed at length in [14]. Briefly, automated sample return from these locations will enable dramatic advances in planetary science by addressing fundamental planetary science questions about the evolution of the lunar interior, lunar volcanic processes, lunar time-stratigraphy, and lunar resource potential. These locations include:

Young Procellarum basalts (22.1ºN, 53.9ºW); Nectaris basin rim (16.34ºS, 26.38ºE); Gruithuisen domes (36.1ºN, 39.7ºW); Dewar cryptomare (2.2ºS, 166.8ºE): Aristarchus regional pyroclastic deposit (24.8ºN, 48.5W); Sulpicius Gallus formation (19.9ºN, 10.3ºE); Sinus Aestuum pyroclastic deposit (5.2ºN, 9.2ºW); Compton-Belkovich volcanic complex (61.5ºN, 99.9ºE); Ina Irregular Mare Patch (18.7ºN, 5.3ºE); and the Marius Hills volcanic complex (13.4ºN, 55.9ºW).

Conclusions: The Moon is an especially attractive and accessible target for future mission proposals to competitive announcements of opportunity, particularly as Discovery missions. In terms of preparing for future mission proposals, all of the locations reported here are feasible landing sites where sample returns are needed to advance planetary science [15-18]. Accordingly, automated sample return missions to the nearside destinations described here need to be seriously considered.

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DIFFERING LUNAR REGOLITH HYDROGEN DISTRIBUTIONS AS A POSSIBLE SOURCE OF VARIATIONS IN PROTON ALBEDO: GEANT4 SIMULATIONS. M. D. Looper[1], J. E. Mazur[1], J. B. Blake[1], N. A. Schwadron[2], J. K. Wilson[2], H. E. Spence[2], A. W. Case[3], J. C. Kasper[3], and L. W. Townsend[4], [1]The Aerospace Corporation, El Segundo, CA (mark.d.looper@aero.org); [2]University of New Hampshire, Durham, NH; [3]University of Michigan, Ann Arbor, MI; [4]University of Tennessee, Knoxville, TN.

Since entering lunar orbit in 2009, the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) aboard the Lunar Reconnaissance Orbiter (LRO) has measured “albedo” protons coming upward from the moon after being produced by nuclear interactions of galactic cosmic rays (GCRs) in the regolith. Over the past seven years, we have measured variations in the yield of albedo protons as a function of their source locations on the moon and of local time at those locations. In our ongoing efforts to understand the causes of these variations, we have considered changes in the composition of in the lunar regolith struck by the GCRs, modeling the production of upward-going albedo using the Geant4 open-source radiation transport code. In this talk we will present the results of simulations of the albedo proton yield as we vary the amount and thickness of hydrogen (or hydrogen-bearing compounds) mixed with the regolith. The modeling predicts significant changes in yield with changing hydrogen concentrations within tens of centimeters of the lunar surface. Such changes in hydrogen concentrations in the upper regolith layer may contribute to observed diurnal changes in the proton albedo yield.

SEARCH FOR TRANSIENT SURFACE WATER ICE AT THE LUNAR SOUTH POLE: RESULTS FROM LOLA AND DIVINER. P. G. Lucey[1], E. F. Fisher[2], B.T. Greenhagen[3], M. Lemelin[4], T. P. McClanahan[5], E. Mazarico[5], G. A. Neumann[5], M. A. Siegler[6], D. E. Smith[7], M.T. Zuber[7], and D. A. Paige[8], [1]University of Hawaii at Manoa, 1680 East-West Rd, Honolulu, HI 96822, lucey@higp.hawaii.edu, [2]Brown University, Providence RI 02912, [3]JHU APL, Laurel, MD 20723, [4]York University, ON M3J 1P3, Canada, [5]NASA/Goddard Space Flight Center, Greenbelt, MD 20771, [6]PSI, Tucson, AZ 85719, [7]MIT, Cambridge, MA 02139, [8]University of California Los Angeles, Los Angeles, CA 90095

Introduction: The Lunar Orbiter Laser Altimeter (LOLA) experiment [1] on the Lunar Reconnaissance Orbiter [2] measures the reflectance of the lunar surface at 1064 nm using its own illumination at a phase angle of zero enabling derivation of reflectance without regard to the illumination conditions. For dark surfaces like the Moon, at zero phase (the angle between source, object and observer) there is negligible dependence of the reflectance on the incident or emission angle, so LOLA observations are not sensitive to topography, and its constant measurement condition requires no photometric models or normalization to compare reflectances among regions on the Moon.

Using these data we have previously shown that regions in permanent shadow are systematically brighter at 1064 nm than areas in the polar regions that receive some illumination [3]. Among the hypotheses for this reflectance anomaly is the presence of surface frost cold trapped on low temperature surfaces [4].

We have integrated data from the Diviner Lunar Radiometer Experiment [5] with the LOLA polar data set to examine the relationship between reflectance and temperature. Using data from the MESSENGER Mercury Laser Altimeter, reflectance-temperature anomalies were used to identify surface frost on Mercury [6,7].

Data: LOLA reflectance data are newly recalibrated [8] and are in units of normal albedo, the reflectance of a surface relative to a Lambert surface illuminated normallly, and at zero phase angle. The Diviner temperature data are of two varieties. First, for the location of each LOLA reflectance measurement, we report the the maximum temperature experienced by the surface over the course of the Diviner experiment. Maximum temperature is a critical quantity for volatile studies because of the exponential dependence of sublimation rate on temperature. For water ice, below about 100K surface ice is stable against sublimation for geologic time; at temperature much above 100K ice is rapidly lost to sublimation. We previously reported that within five degrees of latitude of the lunar South pole, the reflectance of the surface rapidly rises at maximum temperatures below about 110K. We interpret this to be due to the presence of surface frost. Assuming a patchy distribution, about 10% of the surface near the South pole may be covered with water ice frost. This rapid increase in reflectance below 100K is not observed elsewhere in the South polar region, or anywhere in the North Pole [9].

Here we use the temperature at the actual time of the LOLA observation, what we call the instantaneous temperature. This quantity is relevant to detection of reversible temperature dependent optical properties, and to the search for transient water ice and other volatiles at the lunar poles.

Results: We confined our analysis to regions with maximum surface temperatures above 200K, sufficient to sublimate water ice with even a brief exposure to this temperature, but instantaneous temperatures below 125K, sufficiently low to retain ice for 30 days. A statistical analysis shows that around the South pole there is an extensive area meeting these temperature constraints that is two sigma more reflective than regions with maximum and instantaneous temperature forbidding persistent or transient frost. However, binning the data to compare local regions as a function of instantaneous temperature has not revealed any spatially coherent region that shows a consistent increase in reflectance with decreasing instantaneous temperature.

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THE LUNAR VOLATILES ORBITER: A DISCOVERY CLASS LUNAR WATER MISSION. P. G. Lucey[1], X. Sun[2], N. Petro[2], W. Farrell[2], J. B. Abshire[2], E. Mazarico[2], G. A. Neumann[2], R. Green[3], D. Thompson[3], R. Greenberger[3], D. Hurley[4], T. P. McClanahan[2], D. E. Smith[5], and M.T. Zuber[5], [1]University of Hawaii at Manoa, 1680 East-West Rd, Honolulu, HI 96822, lucey@higp.hawaii.edu, [2]NASA/Goddard Space Flight Center, Greenbelt, MD 20771, [3]JPL, Pasadena, CA 91109, [4]JHU APL, Laurel, MD 20723, [5]MIT, Cambridge, MA 02139.

Introduction: The Moon features at least three types of water, all of which are expressed at its surface. Water exists in the deep interior, primordial to the formation of the Moon as demonstrated by water in lunar rocks and glasses [1]. At least one location exposes this interior water at the surface in the central peak of the crater Bullialdus [2]. Water is present at the lunar poles as discovered by the LCROSS impact experiment and suggested by several remote sensing experiments. Finally, water was dramatically discovered in data collected by three spacecraft [3,4,5], manifest in a strong absorption near 3 microns in reflectance spectra of the lunar surface, the same absorption used to detect water in lunar samples in FTIR studies.

Beyond these important detections of water on the (now-literally?) bone-dry Moon, understanding of the relationships among these types of water and how they were acquired and evolved in lunar history is quite limited. When and how the water was introduced into the lunar interior is unknown; there it appears to be variable [6]. Water is certainly variable spatially at the lunar surface, and variation in the depth of the 3 micron absorption may indicate it varies in time [4]. The processes that give rise to the remotely sensed lunar surface water are still only partly understood [e.g. 7] and uncertainties in the remote sensing results limit the ability to apply constraints. Water at the lunar poles is entirely baffling. While the measured pole of Mercury behaves like a physical chemical laboratory experiment, where temperature can be used to uniquely predict the distribution of detected ice, no such easy correlations are manifest at the lunar poles, where temperature is a poor predictor of the distributions of water-sensitive quantities.

A reasonable cure for a lack of understanding is more data, and we fill that prescription with the Lunar Volatiles Orbiter.

Missing Data: The surface of the Moon is arguably the most comprehensively measured surface of any planet, including the Earth (a repeated plaintive claim by oceanographers). Yet, in the study of surface water, there is a key omission. The three micron region is the most sensitive spectral region for deteetion and characterization of water (see the voluminous FTIR literature) and the Chandryaan-1 Moon Mineralogy Mapper provides wide surface coverage of an important portion of the spectral region, for example enabling the detection of the Bullialdus anomaly. These data are inherently limited by the nature of passive spectral measurements of the Moon near 3 microns. In this wavelength region the spectral signal is a mixture of reflected light, and thermal emission, requiring very accurate thermal models to separate, if they can be separated at all. Beyond the startling detection of water, the variation in the depth of the water band is a crucial observation, interpreted to be due to diurnal variation in the amount of surface water [4]. But this variation may be entirely due to the competing effects of thermal emission and reflectance [8].

LVO Instrumentation: The centerpiece of LVO is a multiwavelength laser spectrometer that will characterize the true depth of the lunar water band with complete immunity to thermal emission, and include measurement of water band strength on the lunar nightside and in regions of permanent shadow. The absorption near 3 microns is so strong water can be detected to the lunar background level of a few tens of ppm (as demonstrated by 3-5). This instrument will produce a definitive global map of the form, distribution and time variability of lunar surface water, whether it be in the form of hydroxyl, bound water or surface ice.

Because laser spectrometers are largely profiling instruments, 100% global coverage will be supplied by a passive spectrometer, the Lunar Volatiles Imaging Spectrometer, an improved version of M3. The ground track of the laser spectrometer provides unique calibration of the reflectance of the surface, enabling near-perfect reflectance-emissivity separation at the ground-track in LVIS data and extrapolation to the entire mapping swath.

Finally LVO features a sensitive ion mass spectrometer, borne in a polar orbit to complement LADEEs equatorial measurement, to measure migration of water from equator to pole, if such a lunar volatiles cycle exists.

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ON THE SPATIAL AND AGE BASED VARIATION OF OPTICAL MATURITY FOR COPERNICAN CRATERS .
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Introduction: The high reflectance, shallower spectral slope, and stronger absorption bands of impact crater ejecta are an indicator of a crater's "maturity" – rayed craters are the youngest lunar features[1] and define the Copernican System, the youngest relative age class. Quantitative assessment of maturity is possible with spectral parameters like optical maturity (OMAT from Clementine images [2]) or ratios of UV bands (LROC WAC [3,4]). Per current knowledge, higher values of OMAT and lower values of 321/360 nm ratio indicate fresher craters, and OMAT was used to classify rayed craters [5] into Young, Intermediate and Old classes and Copernicus (crater) was selected as the base for the Copernican system. However calibration (absolute age vs OMAT) and spatial characterization of maturity indices (value vs distance) is not explored to much detail. In this work we investigate the relationship of OMAT values at different radial distances (from the crater center) to the absolute model age (AMA) of the crater, and identify the region where such an analysis will be effective.

Methods: We consider a total of 8 craters (Table 1, Figure 1) for this initial study, for which the AMA is known from previous work [6-11,14]. The raster OMAT values for a crater are converted to a radial median profile (Figure 1) from the center of the crater (r/R = 0) to twice the radius (r/R = 2). To model the OMAT radial variation, we consider only from the rim of (r/R =1) to half the radial distance from the rim (r/R = 1.5).

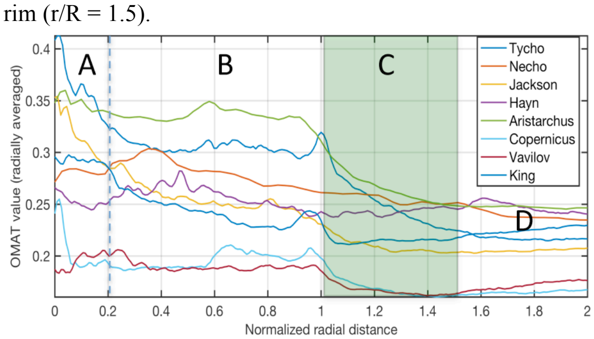

Figure1: OMAT variation with r/R; Tycho has the largest OMAT value at crater center.

Observations: For the craters studied, the OMAT radial profile was divided into 4 segments, based on the topography. A) the center of the crater where presence of central peak increases local slope processes that expose deeper immature layers leading to increased brightness or high OMAT (Tycho, King, Aristarchus, Jackson, Copernicus). Note that the OMAT values for a flat or fractured floor are very different. B) The crater wall where slope process are active as a result of the crater formation process (e.g. terraces) or due to degradation and other modification process resulting in changes in OMAT. C) The rim and proximal flank (up to r/R = 2) and, D) the distal flank which merges with the surrounding terrain near the pre-impact plane (r/R>2). The radial variation in OMAT is not generally monotonous (decreasing) for Necho, Hayn and Vavilov compared to the other craters– the most probable cause for this is proximal impacts and pre-existing topography. In C, the effect of the slope is less compared to A and B and we model the variation of OMAT in this region to posess minimal influence from distal ejecta of other nearby craters. OMAT values decrease quicker than a linear decay between r/R = 1 and r/R = 1.5 and attempt modeling the variation by a second order polynomial, a decaying exponential as well as by an inverse power law. Radial variation of OMAT was best modeled by an inverse power law (better goodness of fit compared to other models) $OMAT\left(\frac{r}{R}\right)=c_1\left[\frac{r}{R}\right]^{c_2}+c_0$ where c_0 is a maximum OMAT value at r/R = 1.5; c_1 is the OMAT value at rim and c_2 defines the rate of decrease of OMAT away from rim. The inverse power law model suggests that high rim OMAT decrease quickly outward radially to the target region OMAT values. For craters younger than Copernicus, OMAT values (r/R = 1 to 1.5) are higher than 0.2 for the selected craters. OMAT values at rim are generally well correlated to the approximate model ages but only up to Copernicus, beyond which the age vs OMAT calibration has much larger uncertainty (Table 1-Copernicus & Vavilov OMAT values).

Name	D (km)	OMAT value at different values of r/R				Age (My)
		0	1	1.5	2	
Tycho	86	0.41	0.32	0.22	0.22	100 [6]
Necho	30	0.27	0.26	0.25	0.23	100 [10]
Jackson	71	0.35	0.23	0.2	0.21	200 [8]
Hayn	87	0.27	0.24	0.25	0.24	1800 [9]
Aristarchus	40	0.35	0.31	0.25	0.25	200 [7]
Copernicus	93	0.24	0.2	0.16	0.17	800 [14]
Vavilov	98	0.19	0.19	0.16	0.18	1700 [9]
King	76	0.30	0.23	0.22	0.23	1000 [11]

Conclusion: We propose that OMAT variation away from crater rim up out one radius can be used to obtain a calibration curve to estimate the AMA of craters younger than Copernicus with uncertainty increasing with age (Copernicus and older). OMAT radial variation is similar to the ejecta thickness variation [12,13] (varies as inverse power of radial distance) but the degree to which the OMAT value is dependent on the ejecta thickness is not well established. At any point on the ejecta, the maturity of the ejecta will be dependent on many factors, including: 1) Thickness of ejecta 2) Distance from the crater center 3) actual time elapsed since the crater was formed 4) Degree of mixing with local mature regolith. Decoupling these factors by analyzing how ejecta maturity varies for a large number of craters will be the focus of future work.

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High Concentrations of Hydrogen-bearing Volatiles at the Base of Poleward-facing slopes in the Large Southern Permanently Shadowed Regions T. P. McClanahan[1], I. G. Mitrofanov[2], W. V. Boynton[3], G. Chin[1], T. A. Livengood[1,4], J. J. Su[4], R. D. Starr[5], M. Litvak[2], A. G. Sanin[2], [1]NASA Goddard Space Flight Center, Greenbelt, MD USA 20776 (timothy.p.mcclanahan@nasa.gov). [2]Space Research Institute, Moscow Russia, [3]Lunar and Planetary Laboratory, Tucson AZ, [4]University of Maryland, College Park MD, USA, [5]Catholic University, Washington D. C., USA

Introduction:.

In this paper we review evidence that indicates that high concentrations of hydrogen-bearing volatiles are biased towards the base of poleward-facing slopes (PFS) in the Moon's southern permanently shadowed regions (PSR). Results are derived from a correlated study of Lunar Reconnaissance Orbiter instrument maps of epithermal neutron leakage flux from the Lunar Exploration Neutron Detector (LEND), topography from the Lunar Observing Laser Altimeter (LOLA) and surface thermal maps from the Diviner radiometer. Maximum concentrations of hydrogen-volatiles, likely as water ice, are shown in Cabeus crater's PSR, 0.62 wght% water-equivalent-hydrogen. Detailed studies show that hydrogen-volatiles at the base of the (PFS) are correlated with the locations of low PSR temperatures of Cabeus, Haworth, Shoemaker and Faustini. High volatile concentrations in these regions may reflect down slope transport on PFS or thermally constrained volatile losses. 15-km Full-width at Half-Maximum (FWHM) is shown to be an upper-bounds condition for the LEND collimated sensor's spatial resolution, observed from a cross sectional profile through the permanently shadowed region at Cabeus' and the LCROSS impact point. LEND's high-resolution spatial response is further illustrated in a 220-km long profile that cuts through the co-aligned permanently shadowed regions and partially-illuminated ridges of Haworth, Shoemaker, Faustini and Amundsen craters.

A POWER SOURCE FOR SUNLESS LUNAR MISSIONS USING LITHIUM COMBUSTION. T. F. Miller[1] and M.V. Paul[2], [1]Applied Research Lab-Penn State, P.O. Box 30, State College, PA, 16804, nfn@psu.edu, [2]Applied Research Lab-Penn State, P.O. Box 30, State College, PA, 16804.

Introduction: One target of interest for lunar exploration is the South Pole-Aitken Basin, which requires non-solar power sources due to permanent shading from the sun. A mission of this type is often conceived with a radioisotope power source in mind, but the scarcity and expense of such fuel reduces the number of such missions that NASA can consider, let alone execute, in any decade. Battery power can be used for brief excursions into these sunless regions, but to advance our scientific understanding of permanently shaded regions, probes must be able to operate for more than the time allowed by the energy density of chemical batteries. For decades, the Applied Research Laboratory at Penn State has been developing advanced metal combustion systems for power generation via turbine-alternators and dynamic free-piston Stirling engines that have significantly higher specific energy than primary batteries for driving undersea powerplants for the US Navy. These engines burn lithium with no exhaust, providing high levels of energy in a challenging environment.

The Reaction: The basic reaction for the stored chemical energy propulsion system (SCEPS) is:

$$8Li + SF_6 \rightarrow 6LiF + Li_2S + Heat$$

The standard heat of reaction at 298 K is 14.7 MJ/kg of Li and SF_6. This reaction has some particularly interesting features. At operational temperatures (~ 1100-1250 K) the lithium fuel and the products exist as liquids. The products of the reaction are immiscible in the lithium fuel and are >3x denser. The practical result of this is that the products of reaction can be stored in the same volume once occupied by the fuel. Also as a result of the production of condensed phase products, the reaction takes place at low pressures; typically near the vapor pressure of lithium (~ 10^{-2} bar at 1150 K). Prior to the start of power production, the lithium is actually stored in its tank as a solid; at the start of reaction, the lithium is melted by either electrical heater or pyrotechnic charge. For terrestrial applications, the oxidizer SF_6 in an adjacent tank as a saturated liquid with a vapor pressure of 22 bars (at 294 K). Sulfur hexafluoride at lower temperatures is essentially inert; combustion on a quiescent molten lithium surface could only proceed above the melting point of the product (1065 K). In practical systems combustion can proceed in a moving lithium flow at or above the lithium melting point (453 K).

Energy Conversion: Two reactor types have been developed for application with this energy system; batch and wick ([1] Kiely). With the wick combustion system, molten lithium wicks up a porous structure from the fuel tank into the main combustor. The heat of combustion acts to evaporate the liquid lithium off of the wick. The evaporated vapor then reacts with the sulfur hexafluoride oxidizer by virtual of the reaction described by the equation. The condensed phase products of combustion fall into the molten lithium bath where there sensible and latent heat is recuperated by the fuel. Heat is transferred to the working fluid which is flowing through tubes embedded in the wick structure. A critical requirement for the efficient use of a Stirling convertor is a very intimate heat transfer relationship between the heat source and the hot end of the Stirling engine. The ability to embed the Stirling hot end (i.e. the tubes containing the helium working fluid) into the combustor wick produces this intimacy.

A fully integrated brass-board system was tested at the Applied Research Laboratory at Penn State within the pressure shells for a subsequent at-sea deployment and test. It used a 3 kW Stirling engine (see [2] White et al.), and demonstrated 35% chemical to electrical conversion efficiency. A photograph of that system is shown in Figure 1. The system operated for 80 hours total (until fuel exhaustion) and massed 372 kg. Heat addition to the Stirling hot side was at 1260 K, and heat rejected to a simulated 293 K ocean. The system demonstrated a specific energy ~ 600W-hr/kg and delivered 10 kW-hr total energy.

For a SCEPS wick-Stirling engine operating at 2 kW and rejecting heat to only 50 K, operation of over 150 hours may be expected. For a 700 kg system, (additional mass comprised of fuel, oxidizer, tankage), an estimate would be >400 hours; for a specific energy of >925W-hr/kg.

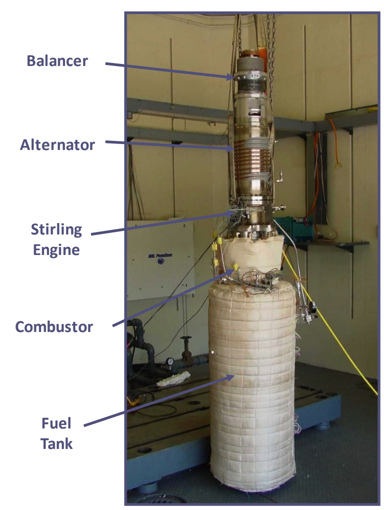

Figure 1. Brassboard SCEPS wick Stirling Powerplant.

References:

[1] Kiely D.H. (1994) Underwater Thermal Propulsion, AIAA. [2] White M.A.Qiu S., Olan R.W.Erbznik R.M. (1999) *Space Power System, AIP Conf*. 458, 1413-1419.

COST EFFECTIVE MISSION STRATEGY FOR LUNAR SAMPLE RETURN MISSION PROBE

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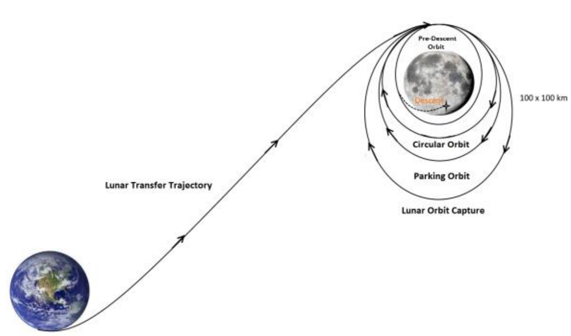
Introduction: The intent of this paper is to illustrate the importance of lunar sample return mission and to come up with a cost effective strategy that will shed light on the utilization of potential resources on the lunar surface. These resources could enable sustainable exploration of the Moon and may eventually suffice the requirements for terrestrial application. We propose a lunar sample return mission, targeting the Malapert located in the lunar south pole. The Sun moves 1.5° with respect to lunar equator and a landing site at southern hemi-sphere will have Sun towards the North and vice-versa for a site in northern hemisphere. Malapert mountain has height of about 5000 meters and can be considered as abundance of sunlight for carrying out critical surface operations [1]. The mission is configured with the following module system: (i) Orbiter, (ii) Lander, and (iii) Lunar Sample return module.

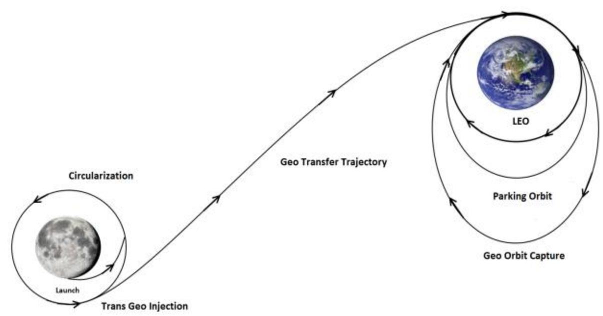
Mission Profile: The Orbiter, Lander and the Lunar Sample Return module will be launched as a composite stack and injected into Lunar Transfer Trajectory by Falcon 9. Lunar Orbit insertion maneuver can be carried out so that the Lander and Orbiter stack gets captured by the Moon into a stable orbit. Post-capture the Lander and Orbiter along with lunar return module will be injected into circular orbit of 100 km. In the circular orbit, high resolution images acquired by Lander and the Orbiter will be transmitted to the ground to precisely locate the landing site. Once the conditions for lunar descent has been achieved the lander will be separated from the Orbiter with the help of its propulsion system. The Landing phase starts with a small de-orbit maneuver at 100 km circular orbit. When Lander reaches the perilune, powered descent



will be initiated by with the help of autonomous navigation and guidance. The Orbiter and Lander will carry out scientific experiments after reaching its intended location.

After collecting the Lunar sample, the return module will ascent and inject into Geo-transfer trajectory leaving behind the Lander and the Orbiter. The mission objective is three-folds: (i) surface operations, (ii) lunar orbit operations, and (iii) sample return. The surface and orbit operations will continue even after return module ascent.

Advantages of proposed strategy for Lunar Sample Return [2] are (i) ascent into a circular orbit after col-



lecting the lunar sample will increase the injection window for Lunar Sample Return Module back to Earth; (ii) this strategy will be cost effective as multiple mission objectives can be achieved with the lander which will be left behind along with the Orbiter; (iii) the Perigee altitude targeted for Lunar sample re-entry will minimize Mission Delta-V requirements; (iv) the Mission Duration until the sample return will be minimized taking into consideration Sun-Earth-Moon geometry; (v) multiple robotic assets on the lander will carry out various lunar experiments.

Conclusion: A cost effective strategy for lunar sample return is de-signed which will provide vital knowledge regarding lunar south pole regions. Other strategies to investigate lunar surface via orbital remote sensing or through Impact related modules cannot suffice timely and unassailable requirements to investigate suitability for human exploration in the south pole landing region. This strategy for Lunar Sample return mission will offer the potential of returning at least 10 kg of precision targeted lunar materials from Malapert at a pre-defined location.

References: [1] Lemelin M. et al (2014) *High-priority lunar landing sites for in-situ and sample return studies of polar volatiles*, [2] Duke M.B. (2003) Colorado School of Mines, Center for thee Commercial Application of Combustion in Space, *Sample Return from Lunar South Pole-Aitken Basin*.

LAVA ERUPTION AND EMPLACEMENT: USING CLUES FROM HAWAII AND ICELAND TO PROBE THE LUNAR PAST. D. H. Needham[1], C. W. Hamilton[2], J. E. Bleacher[3], P. L. Whelley[3,4], K. E. Young[3,5], S. P. Scheidt[2], J. A. Richardson[3,4], S. S. Sutton[2]. [1]NASA MSFC, 320 Sparkman Dr., Huntsville, AL 35805, debra.m.hurwitz@nasa.gov, [2]LPL University of Arizona, [3]NASA GSFC, [4]USRA, [5]Jacobs Engineering Group.

Introduction: Investigating recent eruptions on Earth is crucial to improving understanding of relationships between eruption dynamics and final lava flow morphology. In this study, we investigated the 2014/15 Holuhraun, Iceland, and December, 1974 Kilauea, HI eruptions to gain insight into the dynamics in the source vent, the initiation of lava channels, and the origin of down-channel features. Insights are applied to Rima Bode on the lunar nearside to deduce the sequence of events that formed this sinuous rille system.

Geology of Rima Bode: Rima Bode is located on the Moon in SE Sinus Aestuum and is characterized by an elongate source vent (Fig. 1a) and two channel segments separated by a smooth plain 266 km^2 in area (Fig. 2a). The channel segments are 109 and 139 km long, 870 and 670 m wide, and 100 and 75 m deep, respectively, measured using Kaguya Terrain Camera (TC) imagery and Lunar Orbiter Laser Altimeter (LOLA) topography tracks. Vent depth varies from 160 to 500 m and has a volume of ~6 km^3, and the upper channel initiates at the NW rim of the vent (Fig. 1a). The down-channel smooth plain has a marginal ledge that encircles the entire feature (Fig. 2a, arrow). By studying recent terrestrial eruptions, we gain insight into (1) the origin of vent morphology and its variable depths, (2) the timing of initial channel formation, and (3) the origin of the down-channel plain.

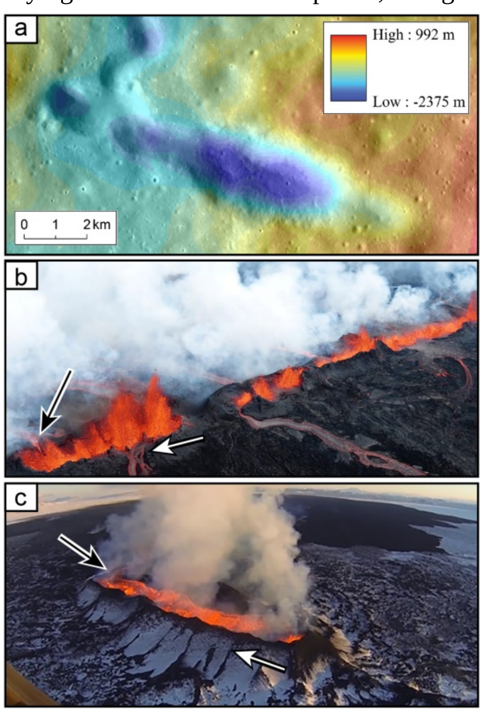


Fig. 1: (a) Rima Bode source vent (LOLA on Kaguya TC) and Holuhraun vent, (b) late 2014 and (c) February, 2015.

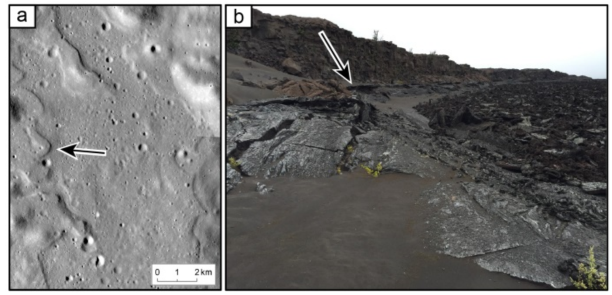


Fig. 2: (a) Rima Bode feature with marginal ledge, and (b) Kilauea, HI December, 1974 lava pond with marginal ledge.

Origin of the Vent and Channel: The 2014/15 eruption at Holuhraun, Iceland provides an analog for the vent/channel system of Rima Bode. This widely documented fissure eruption initiated August 29, 2014, and over the ensuing 183 days deposited 1.5 km^3 of lava over an area of 83.5 km^2, with a mean eruption flux of 161 m^3/s [1]. The fissure developed spatter cones around distinct centers of explosive eruptions, with the largest encircling the longest-lived, 0.5 km-long NE cluster of eruption centers (Fig. 1b,c). Lava channels formed throughout the eruption — some were cut off by spatter deposition while others widened (Fig. 1b,c, arrows), possibly through small-scale local erosion as lava carried portions of the vent down channel.

Origin of the Down-Channel Plain: The December, 1974 eruption at the West Rift of Kilauea, HI has a similar mid-channel feature to that observed at Rima Bode. The eruption occurred December 31, 1974 and lasted 6 hours, depositing 0.014 km^3 over 7.5 km^2, with a mean eruption flux of 662 m^3/s. The relatively smooth plain is characterized by crusted lava in the interior exhibiting three episodes of separation, and a marginal ledge of lava that denotes high lava stands (Fig. 2b). These observations are consistent with the formation of a lava pond that subsequently drained [2].

Applications to Rima Bode: Rima Bode likely developed analogously to these terrestrial cases. The lunar vent's morphology is consistent with varied eruption rates observed in Iceland, and the smooth plains ledges are consistent with the high lava marks of the drained lava pond seen in Hawaii. Additional analyses will yield insight into dynamics of the lunar eruption.

References: [1] Gudmundsson et al. (2016) *Science*, 353. [2] Hamilton et al. (2015) *LPSC 46*, #1072.

REQUIRED PERFORMANCES FOR FUTURE LUNAR AND ASTEROID NEUTRON SPECTROSCOPY.

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Instruments using neutron spectrometry have made significant contributions to planetary science through the detection of volatiles (including H_2O) [1-3], and by constraining the mechanisms of planetary formation and surface magmatic processes through the detection of other neutron-absorbing elements (e.g., iron, titanium, gadolinium, samarium) [4]. However, the spatial resolution of the neutron measurement technique is currently quite coarse due to the use of omni-directional neutron sensors without the usage of bulky collimators. Omni-directional techniques rely only on the geometrical cut off of the sensor FOV, restricting us to the FWHM spatial resolution equal to (or greater than) the altitude above the target planet/small body surface. As a consequence, many important science questions related to the distribution of near-surface compositions cannot be addressed with currently operated instruments.

Volatiles on the Moon are of great scientific and exploration interest, particularly the spatial distribution of hydrogen-bearing minerals, which indicates the potential presence of water. Reduced epithermal neutron fluxes near the poles have provided compelling evidence for the presence of water [5,6], but the spatial resolution of the Lunar Prospector Neutron Spectrometer (LPNS) experiment was too coarse to directly determine whether hydrogen enhancements are limited to PSRs or to the polar regions in general [5, 7, 8]. Updated hydrogen maps by the collimated Lunar Exploration Neutron Detector (LEND) on Lunar Reconnaissance Orbiter (LRO) [6] show that some areas of enhanced hydrogen do not correlate either with permanent shadow or temperature, and the disagreement between the two sets of observations remains hotly debated [9-12].

Neutron instruments can also map volatile content in the asteroids and small bodies remotely, which is crucial to identify the type of asteroids. Especially, Martian moons Phobos and Deimos have gotten a lot of attention lately, due to their enigmatic origins [13], and may provide a new aspect of the evolution of the inner planets in terms of the transportation of water. The majority of these bodies are irregularly shaped and small [14, 15]. Thus the irregular mass distribution, solar radiation pressure, exospheric drag, and gravitational field can perturb the trajectory of the spacecraft in close proximity to a small body [16]. All of these factors make orbits less than a few kilometers very difficult, and consequently, omnidirectional neutron detectors are unlikely to spatially resolve a small body.

Figure 1 estimates neutron instrument angular resolution as a function of distance from the target body. The resolution of an omnidirectional neutron detector is shown as a solid black line. The shaded regions highlight the orbital range for Rosetta and LRO and the required spatial resolutions for a typical target for neutron spectrometers. For example, in a comet mission case, the size of the nuclei (~3 km) is a key scale range to resolve. In the case of Moon orbiting missions, the crater size (~30 km) is a typical key requirement to resolve the PSR. Omni-directional measurement cannot resolve the required scales for these cases.

In this presentation, we will discuss these issues and possible solutions applicable to neutron sensors.

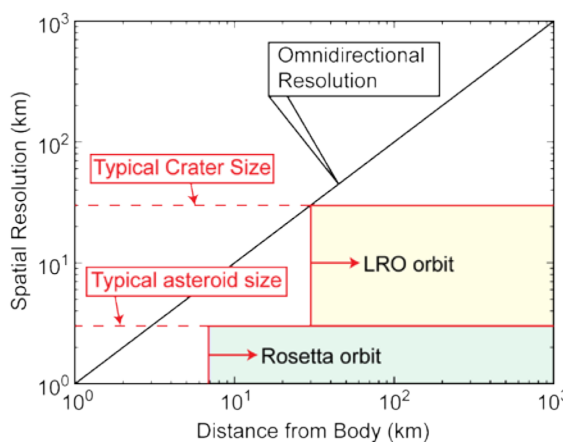


Figure 1: *Omnidirectional neutron resolution as a function of distance. The yellow area shows the required range to resolve 30 km craters on the Moon, assuming LRO orbit. The green area is the required range to resolve the radius of the comet nuclei assuming the Rosetta mission orbital configuration.*

References: [1] Feldman et al., 2000; [2] Feldman et al., 2002; [3] Lawrence et al., 2013 (1997) [4] Lawrence et al., 2010; [5] Feldman et al. 2001; [6] Mitrofanov et al. 2010a; [7] Feldman et al., 1998; [8] Elphic et al., 2007; [9] Lawrence et al., 2011; [10] Eke et al., 2012; [11] Mitrofanov et al., 2010b; [12] Sanin et al., 2012; [13] Murchie et al., 2015; [14] Fujiwara et al., 2006; [15] Sierks et al., 2015; [16] Scheers 2012

MISSION TO MALAPERT.

N. D. Otten[1], E. Amoroso[2], H. L. Jones[1], F. Kitchell[2], D. S. Wettergreen[1], and W. L. Whittaker[1], [1]Carnegie Mellon University, 5000 Forbes Ave, Pittsburgh, PA 15213, otten@cmu.edu, [2]Astrobotic Technology, Inc., 2515 Liberty Ave, Pittsburgh, PA 15222.

Introduction: Lunar ambitions such as pursuit of ice, habitation, lunar observatories, establishment of solar grids, and rover routes of persistent sunlight compel polar destinations. Subtleties of lighting and terrain unique to the poles are the conditions that accreted the ice and also yield the favorable power, siting, and rover scenarios. However, these same subtleties, combined with need of line-of-sight communication to Earth, impose profound constraints on sites that are amenable for landings, missions, and long-term presence. This work presents methodology for evaluating site amenability. The method is applied to Malapert Mountain as an exemplar where prominent elevation, lighting, Earth-view, and slopes combine to illustrate the principles of the method. The work identifies promising sites and regions for landing on Malapert.

Methods: The local terrain slope of the Malapert Mountain region, derived from LOLA digital elevation models [1], is shown in Figure 1.

On the Earth-facing side of the Moon's South Pole, Earth hovers in the northern sky near the horizon. Due to its latitude of 4 degrees off the pole, elevation, and slope orientation, the vast majority of the northern slopes of Malapert Mountain maintain constant line-of-sight to Earth for the entire 6-month period studied. The cumulative duration of surface-to-Earth visibility (as percent of the full 6 months) is shown in Figure 2.

An algorithm computed the maximum number of consecutive Earth days for which each location will receive uninterrupted direct sunlight (Figure 3).

The results of the three computations quantifying slope, Earth-view, and sunlight were combined to identify all locations that meet the following three conditions: 1) local slope no greater than 10 degrees, 2) 100% uninterrupted Earth visibility for 6 months, 3) at least 10 consecutive days of uninterrupted direct sunlight. The resulting region, meeting all three criteria, is shown in Figure 4. Colors represent terrain slope; black indicates that one or more conditions are not met.

These results rely on simulated data generated by a ray-tracing renderer [2] to provide an accurate estimate of future transient lighting and Earth-visibility at the lunar surface. The dataset spans 6-months, from January 1 to July 1, 2019 at 2-hour increments, and covers a 16-by-9-km area at 10 m/pixel, centered at 86°S, 0°E.

Conclusions: At Malapert, four landing sites are viable with a landing accuracy radius of 150 m (Figure 4). Dozens more are possible with 100-m accuracy. One such site is within 100 m of a multi-month continuously lit rover route [3]. The unique combination of elevation, topology, latitude, and longitude combine to make Malapert a premier polar landing destination.

References: [1] Smith D. E. et. al. (2010) *Geophys. Res. Lett., 37,* L18204. [2] Amoroso E. et. al. (2016) *LEAG* (submitted). [3] Otten N. D. et. al. (2015) *ICRA*, 3953–3958.

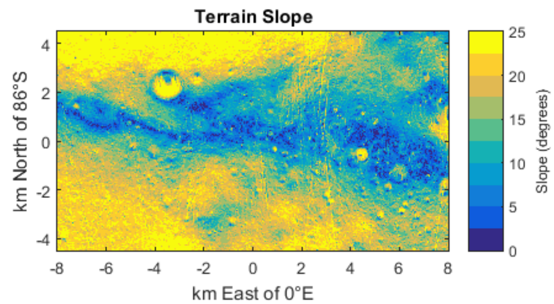


Figure 1. Malapert Mountain local terrain slope.

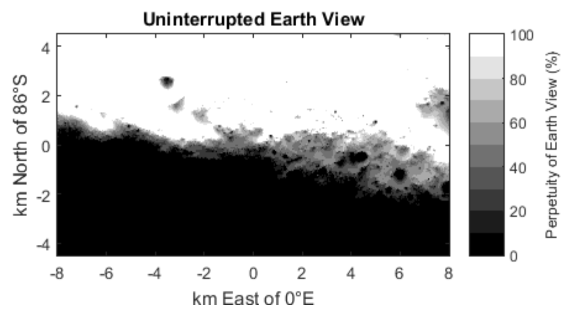


Figure 2. Malapert–Earth view for communication.

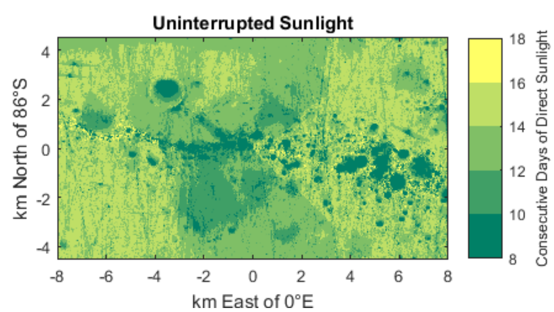


Figure 3. Many days of uninterrupted direct sunlight.

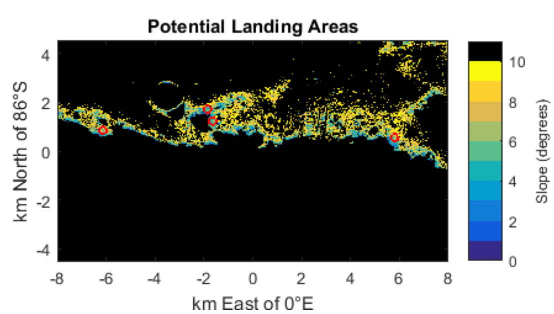
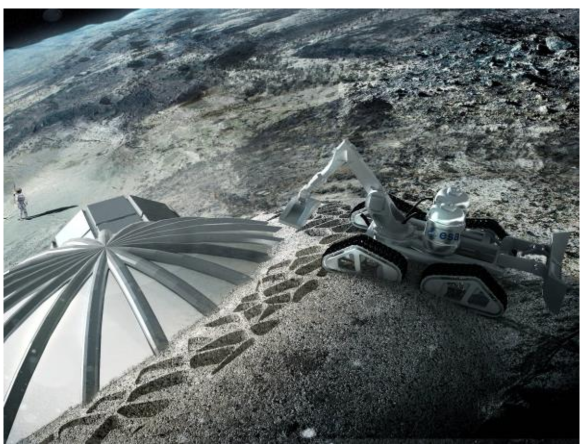


Figure 4. Safe slope, comm., lighting. Top four sites in red.

Utilization of In-situ Resources and Transported Materials for Infrastructure and Hardware Manufacturing on the Moon – Ongoing Developments by ESA Materials Scientists. Laurent Pambaguian[1], Advenit Makaya[1], Ugo Lafont[1], Components Technology & Space Materials Division, ESTEC, European Space Agency, Keplerlaan 1 - PO Box 299, 2200 AG Noordwijk-ZH, The Netherlands. Corresponding author: advenit.makaya@esa.int.

The European Space Agency's Materials Scientist are conducting studies in the use of in-situ resources and materials transported from Earth, to enable exploration activities and the establishment of settlements on the Moon or Mars. A review of completed and ongoing activities, funded by or conducted within ESA, is presented here. These include the development of 3D printing processes to produce building material from Lunar regolith, with or without binders brought from Earth. The analysis of processes for on-site hardware manufacturing with limited resources is being explored. In addition, optimum usage and recycling of materials brought for the mission – in particular functional polymers – is being investigated, for the production of hardware for maintenance of infrastructure and equipment. These activities will be key elements for conceiving manned Moon missions at system level and to allow the building and the maintenance of a safe shelter for the Astronauts.



LUNAR EXPLORATION PRODUCTS GENERATED FROM LRO DATA: ENABLING FUTURE SURFACE EXPLORATION. N. E. Petro and J. W. Keller, NASA Goddard Space Flight Center, Solar System Exploration Division (Noah.E.Petro@nasa.gov; John.W.Keller@nasa.gov).

Introduction: While LRO has been successfully operated as a science mission for much of its seven plus years at the Moon, it's initial objectives focused on enabling future surface exploration, both human and robotic [1]. The extended life of LRO has allowed the science teams to not only revolutionize our scientific understanding of the Moon and its environment, the teams have generated a wide range of products that will be critical for future exploration. These products will be useful for any future NASA exploration [e.g., 2] but have already been employed by international agencies in planning their exploration of the Moon [3]. Here we revisit the exploration goals of LRO and highlight data products available for planning future lunar exploration.

Exploration Goals: Prior to LRO's launch, eight requirements were ascribed to the mission [1]:

- Knowledge of the lunar radiation environment and the biological effects caused by exposure to the space environment.
- Global geodetic lunar topography tied to an accurate center-of-mass grid.
- High spatial resolution maps of enhanced hydrogen deposits in the Moon's regolith.
- Temperature maps of the Moon's permanently shadowed regions (PSRs).
- Landform-scale images of areas in permanent shadow.
- Identification of putative deposits of near surface water ice in the Moon's PSRs or evidence that they don't exist.
- Images at meter (and smaller) scales to assess the safety of potential lunar landing sites.
- Characterization of the illumination in the Moon's polar regions at relevant spatial and temporal scales.

LRO Data: LRO has generated a massive data archive within the PDS; at over 700 Tb the volume of data generated by LRO includes a number of special maps/mosaics and derived products. Each of the requirements defined above have been met with a number of datasets and relevant publications. We will present a number of LRO products that will be useful for planning lunar missions, including the following two examples.

Illumination: Multiple instruments contribute to our understanding of the illumination conditions at and near the lunar poles. Whether from direct measurement of illuminated surfaces from the LROC suite, or from modeled illumination conditions by LOLA [4] (Figure 1), these perspectives on illumination allow for detailed planning near the poles that maximize time spent in direct sunlight [5].

Surface and Subsurface Hydrogen: Volatiles are a critical resource that has been, and continues to be, mapped by LRO. With a focus on H_2O/OH every instrument on LRO contributes to our evolving understanding of where volatiles are found (Figure 2).

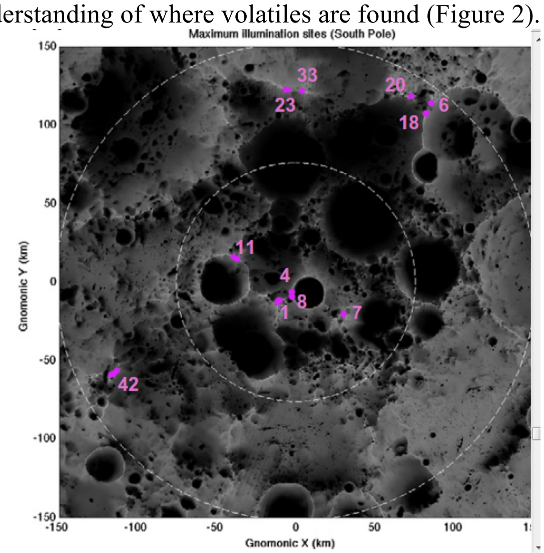


Figure 1. Map of average South Polar illumination, showing the location of several sites that receive ~80% illumination over a lunar day [4].

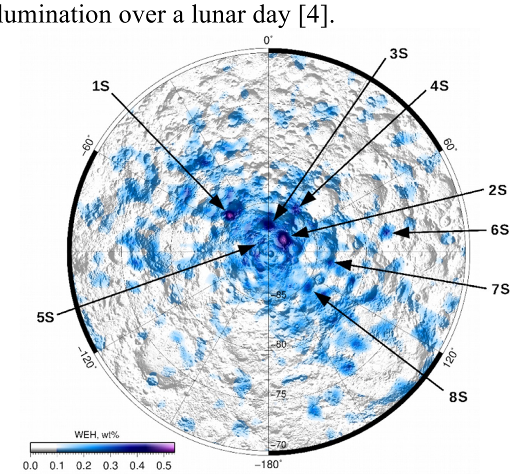


Figure 2. LEND Map of Water Equivalent Hydrogen near the South Pole [6].

References: [1] Vondrak, R., et al., (2010) *Space Science Reviews*, 150, 7-22. [2] Jolliff, B. L., et al., (2015) Science Priorities for Lunar Exploration Missions and Value of Continued LRO Operations for Future Lunar Geoscience, 46, 2616. [3] Keller, J. W., et al., (2016) *Icarus*, 273, 2-24.
[4] Mazarico, E., et al., (2011) *Icarus*, 211, 1066-1081.
[5] Speyerer, E. J., et al., (2016) *Icarus*, 273, 337-345.
[6] Sanin, A. B., et al., *Icarus*, in press

ESTIMATING THE CONTRIBUTION OF BASINS AND LARGE CRATERS TO THE REGOLITH OF THE SOUTH POLE-AITKEN BASIN. N. E. Petro[1], B. A. Cohen[2], B. L. Jolliff[3], D. P. Moriarty[4] [1]NASA Goddard Space Flight Center, Solar System Exploration Division, Planetary Geodynamics Laboratory, [2]NASA Marshall Space Flight Center, [3]Washington University in St. Louis, [4]Brown University. (Noah.E.Petro@nasa.gov)

Introduction: Data from recent lunar missions provides new insight into the composition and geologic evolution of the Moon, particularly the South Pole-Aitken Basin (SPA). From orbital remote sensing data we can investigate surface mineralogy at the ~100 m scale as well as corresponding high-resolution images to evaluate the exposures of various compositions [e.g., 1]. When these results are coupled with the recent joint GRAIL and LOLA analysis of the crustal signature of craters >200 km in diameter [2], we assess the resurfacing effects of large impacts. These analyses are critical for assessing the evolution of the surface regolith in the interior of the South Pole-Aitken Basin (SPA), a key destination for future sample return [3].

Here we revisit the question of how much non-SPA (foreign) material may have been introduced to the regolith of the interior of SPA. If we assume that SPA is indeed the oldest basin on the Moon [4] with an interior that contains an extensive impact melt sheet [5-7], then the SPA event, itself, and the subsequent impact history would be amalgamated in the SPA regolith. Given the extensive post-SPA impact record that extends for >4 Ga, how much of the ancient SPA impact-melt material remains at the surface? We recognize that both basins and large craters in SPA (e.g., Apollo, Schrödinger, Poincaré) contribute to the regolith, and that their ejecta would largely consist of SPA impact-melt and material from beneath the melt sheet. Recent advances in modeling of the fraction of impact-melt in ejecta will allow us to estimate how much non-SPA impact melt material might also "contaminate" the interior of SPA [8]. Thus we estimate the proportions of (1) ancient SPA substrate, (2) materials excavated from within SPA that contain reworked SPA substrate or impact melt, and (3) materials from craters outside of SPA that had a highlands, non-SPA provenance.

Ejecta Contribution by Large Craters and Basins: Using the updated crater catalogue of Neumann et al. [2] and the modeling assumptions defined by Petro and Pieters [9] and Fassett et al. [10], we estimate that, on average, 50-100 meters of crater ejecta accumulated within much of the interior of SPA (Figure 1). Apart from areas immediately surrounding the large craters and basins (and antipodes of large basins), there is, relative to the rest of the Moon, a small accumulation of foreign material. It is important to note that despite the 73 large craters considered here, only two basins, Imbrium and Orientale, contribute a majority of the accumulated ejecta. One aspect of this modeling that may be subject to change relates to the size of the transient cavity of the Orientale Basin. Geophysical analyses [2, 11] suggest that the transient cavity is between ~198.5 - 218 km in radius, while a recent analysis of ejecta surrounding Orientale suggests the transient cavity radius of 310 km [10]. The analysis presented here assumes a larger transient cavity size; if the Orientale transient cavity is indeed smaller the overall thickness of ejecta introduced to SPA is much smaller.

Conclusions: The earlier analyses of SPA regolith provenance by Haskin et al. [12] and Petro and Pieters [13] remains accurate, that much (>60%) of the regolith within SPA contains locally derived material. This conclusion holds up despite changes in the known number of large lunar craters. A factor in controlling the amount of foreign material is contributions from large basins, specifically Orientale and Imbrium (~25% of the SPA, respectively). Once the effects of smaller (<200 km in diameter) craters are considered [8], the proportion of SPA-derived material in the regolith increases to nearly 100% of the regolith, due to the reintroduction of material from depth, material that is directly derived from SPA impact melt [1].

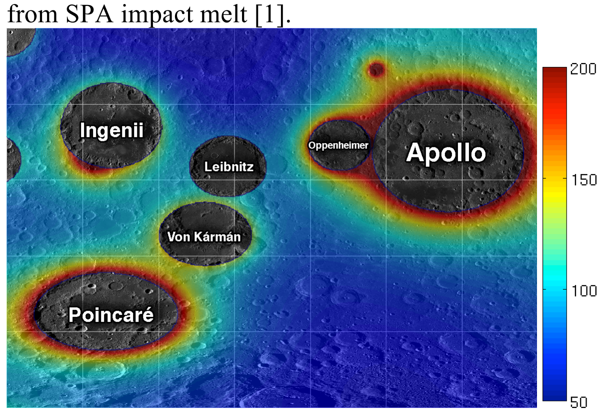


Figure 1. Estimated accumulation of ejecta from the craters defined by Neumann et al. [2]. The interiors of large craters and basins are transparent. Mapped extent of ejecta is from latitudes -20º to -70º and longitudes 150º to 220º. The Serenitatis antipode is northwest of Apollo, while the antipode of Imbrium is to the southwest of Ingenii.

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LUNAR REGOLITH - UNDERSTANDING FOR SCIENCE AND EXPLORATION.
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Introduction: Regolith is the fragmental layer covering the lunar surface, ranging in thickness from a few cm on the youngest surfaces to 10's meters on the oldest mare and highlands surface [1-5]. The regolith is the surface that is observed by remote sensing and the material that is typically sampled and is the surface upon which operations are conducted.

Over the last decade, as interest in the Moon waxed and waned, our understanding of the lunar environment and processes active on the surface have significantly advanced. In many cases, as old questions were answered, new more complex questions were raised. One area receiving considerable attention and for which significant progress has been made is the regolith. Understanding its properties, how it interacts with and stores volatiles, and how it interacts with the space environment has advanced considerably.

Here, we examine the important new conclusions and outline the outstanding scientific and exploration questions with regard to the lunar regolith.

Physical Properties: Apollo core samples demonstrate that while layered, regolith layers are not laterally continuous. Layers represent individual impact ejecta deposits and those deposits extend only ~1 crater diameter from the source crater. The result is a stratigraphy of overlapping, approximately circular deposits of varying thickness and diameter.

Regolith density increases rapidly with depth in the upper 1 m and then appears to be constant with depth [5-7]. Diviner data has provided important constraints on how the form of the depth-density relationship and how it varies. UV and visible photometry [8-9] shows that the uppermost few microns to millimeters is composed of a fine-grained, very porous structure having very low density. Radar data [10], LRO thermal data [11], and Earth-based photometry indicate a latitudinal variation the properties of the regolith.

Volatiles: Hydrogen is abundant in polar areas, particularly in permanent shadow [13-14]. H-bearing species are assumed to be H_2O although it has not been directly sampled. Thermal modeling, UV and radar data suggest it is H_2O [6-7, 15]. OH and H_2O occur across the surface as an ephemeral adsorbed layer migrating on a diurnal time scale [16-17]. It has been suggested that significant transport of H into and out of the regolith occurs on diurnal time scales [18-19]. Understanding the processes of volatile migration requires an understanding the physical structure of the regolith (e.g., porosity, permeability). If H is moving into and out of the regolith on a diurnal time-scale, it has important implications for the structure of the regolith (porosity, permeability) and the thermal regime.

Scientific Questions: Among key scientific questions are the regolith's physical structure on various spatial scales, the importance of thermal fatigue in regolith formation, timescales of regolith evolution, charged particles interaction with the surface, and volatile species interaction with the regolith.

Exploration Questions: Areas of principal concern include regolith physical properties to depths of a few meters, trafficability, and characteristics of polar volatiles. Regolith excavation and processing will be influenced by the density distribution and the presence of rocks. Trafficability is influenced by shallow regolith structure, small-scale topography and larger slopes. Repeated traverses across the surface can result in rutting and regolith softening. Regolith easily moves downslope resulting in sliding and an inability to support loads (e.g., LRV on Stone Mt. Apollo 16).

The form and distribution of volatiles in polar and non-polar regolith is essential information for exploitation as a resource. The economics of the resource will be very different if the physical form was an ice-cemented regolith compared with discrete blocks of ice in an otherwise dry regolith.

Summary: Our understanding of the properties of the lunar regolith, its formation, and the role it plays in the production, transport and storage of volatiles has changed dramatically over the last decade. We now have sufficient information to quantitatively understand many of the active processes.

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Currently, there is a lack of high fidelity lunar highland regolith simulant available in large quantities and contained in an appropriately controlled laboratory environment. The absence of this resource is preventing long term, full-scale testing of proposed lunar technologies which is critical for the success of future exploration and utilization of the moon.

Our group is currently converting more than 20 tons of Shawmere anorthosite, along with other components into enough high-fidelity highland regolith simulant to set up a Lunar Surface Simulation (LSS) Lab about the size of a tennis court, with regolith simulant depths up to 2 meters. The objectives of our efforts are to provide a high-fidelity testing environment for academic, commercial and government research and development that allows researchers to “test it like you fly it”, accumulate a large body of practical knowledge working with regolith, and provide unique opportunities for students who would normally find it difficult to travel to other research opportunities.

This presentation outlines raw material sources, manufacturing methods and application of NASA figures of merit to the simulant production process. Also covered is the set-up of the LSS Lab, including environmental controls, safety and operation protocols, current status, short and long-range goals, research objectives and partnering and outreach efforts.

GENERATION AND MIGRATION OF POTASSIUM IN THE LUNAR EXOSPHERE. M. Sarantos[1,2], A. Colaprete[3], J.R. Szalay[4], J.S. Halekas[5], D. H. Wooden[3], M. Horanyi[6], and D. Janches[2]. [1]University of Maryland, Baltimore County, Baltimore, MD, USA, [2]NASA Goddard Space Flight Center, Greenbelt, MD, USA, [3]NASA Ames Research Center, Mountain View, CA, USA, [4]Southwest Research Institute, San Antonio, TX, USA, [5]Department of Physics and Astronomy, University of Iowa, Iowa City, IA, USA, [6]Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, Boulder, CO, USA.

Introduction: Measurements of Na and K resonant scattering emission from the Ultraviolet Visible Specrometer (UVS) on the Lunar Atmosphere and Dust Environment Explorer (LADEE) spaceraft showed many trends: a brightening of the exosphere during major streams such as Geminids, a repeatable monthly variation, and a correlation of the exosphere to surface composition [1]. These measurements provided a unique opportunity to better understand how lunar gases are released from the surface and how they interact with the lunar regolith.

Simulations: A large number of Monte Carlo simulations were performed to constrain the generation and migration processes. Many separate runs were necessary because of uncertainties in the rates and temperatures for proposed source processes, uncertainty in the photodesorption cross section, and uncertainty about the loss rate to the subsurface as well as the exogenous fraction in impact vapor.

Two types of simulations were performed. “Steady-state” simulations were used to identify constraints imposed by the observed variation with lunar phase. Furthermore, time-dependent simulations were run to describe the evolution of the atmosphere during and following Geminids. The former simulations assumed that impact vaporization and solar wind sputtering were periodic functions of lunar phase and were convolved with the distribution of surficial potassium [2]. The latter simulations adopted hourly-averaged solar wind parameters measured by the two ARTEMIS spacecraft, and used LADEE/Lunar Dust Experiment (LDEX) counts as a proxy for impact vaporization.

As potential source processes for adsorbates we considered: (1) impact vaporization with two different initial velocity distributions (having Maxwellian temperatures of 2,000-5,000K); (2) sputtering from the bulk; and (3) photodesorption of K from glasses and minerals of the lunar surface with intial velocities corresponding to temperatures 1,200-1,800 K.

For desorption of adsorbates by UV photons we considered desorption cross sections that caused the residence times of adsorbates on the surface of grains to vary from a few hours to several days between successive bounces. Photoionization, transport to Permanently Shadowed Regions, and loss to the subsurface were considered as sink processes.

Results: Although LADEE UVS did not directly measure the exospheric temperature, we were able to constrain the source temperature from the amplitude of the observed monthly variation. The modeled exosphere reflected the surface composition too closely if small initial velocities were assumed [Fig 1]. This finding suggests that direct photodesorption of K from glass is not the major source process. Additionally, ejecta with initial temperatures of at least 5,000 K were required to match the increase of the dayside atmosphere during Geminids because this shower had its radiant near lunar midnight. Together, these results indicate that impacts may be the main source process for K adsorbates. However, given the inferred sink rates from Geminids [3], the modeled rates required to populate the atmosphere were approximately 2-4 times higher than published impact vaporization rates, even accounting for the amount of exogenous vapor.

Sinks were found to be dominated by loss of adsorbates to the subsurface. Inward diffusion and/or reactions with oxygen liberated from the regolith during micrometeoroid impacts were both estimated to be sufficient to eliminate the adsorbates within a few days of their being subjected to lunar dayside temperatures.

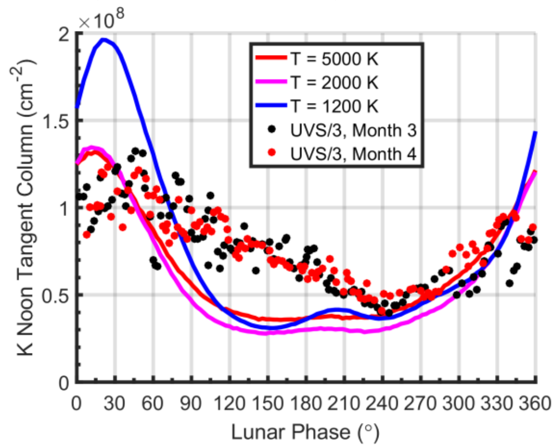

Figure 1. The magnitude of the observed monthly variation suggests a hot process as the primary source of K atoms. Here different rates and source temperatures were assumed.

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Common Standards for Collaborative Inter-Agency Operations as Key Enabler For the Moon Village. M. Sarkarati, V. Reggestad, M. Merri, European Space Agency, ESA, European Space Operations Centre, Robert-Bosch-Str. 5, 64293 Darmstadt, Germany first.lastname@esa.int

Introduction: "Agencies agree that human space exploration will be most successful as an international endeavor because there are many challenges to preparing for these missions and because of the significant social, intellectual, and economic benefits to people on Earth."

– The Global Exploration Roadmap

The vision of building a sustainable human presence on the surface of the Moon is certainly one of the most challenging and at the same time inspiring scenarios for near future human space flight. It goes without saying that such an endovear can hardly be implemented by one single entity. It will require extensive collaboration among traditional institutional entities and new players from private and public domain.

Where collaborations are the topic, international standards become quickly the focus. Our paper will provide an overview of the standardization landscape with regard to Mission Operations and elaborate on how the existing standards, especially those developed by the Consultative Committee for Space Data Systems (CCSDS) can be extended to close the gaps and cover a solid basis for addressing the needs of intensive collaborative operations of a future Moon Village.

The paper will provide real-world examples where the standards are enablers of collaborative operations and reflect on the perspective of the Moon Village.

Building a Moon Village in a near future will require breaking some of the established space programmed traditions. Thinking out-of-the-box and involving none-space stakeholders will likely be an essential part of a financial, cultural and logistical solution for implementation of a Moon village. In this respect, the standardization landscape will need to be broaden much beyond what we are typically used too in the space domain. It would need to encompass open architectures and considerations that go beyond the pure technical specification, hence facilitating contributions and participations from other verticals. Our paper will high-light some of such considerations and links between space and none-space standards and discuss how and what kind of standards can in general serve these objectives.

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NORTH MASSIF REGOLITH AT TAURUS-LITTROW MAY CONTAIN LITHIC-CLASTIC VOLCANIC DEBRIS ERUPTED PRIOR TO MARE BASALT. H. H. Schmitt, University of Wisconsin-Madison, P. O. Box 90730, Albuquerque NM 87199, hhschmitt@earthlink.net.

Introduction: Regional mare basalt eruptions on the Moon likely would be preceded by eruptions of volatiles released as mantle sources of basalt magmas approached their partial melting temperature. As mare basalt lavas must rise through channels in the highly fragmented lunar crust, the absence of non-basalt inclusions suggests that such volatile-rich eruptions may have cleared those channels of most crustal debris.

Clearly, the basalt lavas themselves initially contained dissolved volatiles, as documented by vesicles in the basalt boulders throughout the valley. On the other hand, these remaining volatiles probably came out of solution in the magma as it moved upward to lower pressures; but the vesicles indicate that volatiles inherently were present in the upper mantle source rocks at the time of partial melting.

Analysis: Evidence of pre-mare basalt lithic-clastic eruptive events may exist in regolith developed on features that were not buried by basalt. Apollo 17 astronauts obtained "kilogram" samples of regolith on the North and South Massifs at Stations 6 and Station 2, respectively. In contrast to North Massif regolith, early-formed regolith at Station 2 on the slope of the South Massif was swept away by the light mantle avalanches [1] so 72500 would consist primarily of post-avalanche material derived from the slopes of that massif. This younger regolith, with a source slope that boulder samples indicate is petrologically comparable to the North Massif, could serve as a control in estimating how much of the North Massif regolith consists of old litho-clastic debris. The amounts of post-mare materials would need to be eliminated from such an estimate as they would be younger than any pre-mare, lithic-clastic material. Thus, the following relationship may exist:

Lithic-clastic Debris = Station 6 Regolith – Station 2 Regolith – Pyroclastic Ash – Basalt

Or

Lithic-clastic Debris = 76500 – 72500 – Orange+ Black+clear glass – Basalt

The accompanying table gives the results of this calculation, using the particle analysis (90-150 μm) of Hiken and McKay [2]. The amount of potential lithic-clastic debris shown is, of course, a minimum amount, as some litho-clastic debris has been incorporated into agglutinates; however, 1) whereas impact breccia particles dominate the non-agglutinate component of the South Massif regolith, combined plagioclase, clinopyroxene and orthopyroxene mineral fragments dominate the non-agglutinate component of the North Massif regolith, and 2) the regoliths on the massif slopes have approximately the same agglutinate concentration, although maturity indexes [3] differ significantly (58 and 81, respectively, for 76500 and 72500) due to differences in ilmenite content.

Although a direct comparison of different particle analyses of the two regoliths is difficult due to different particle definitions and size classifications, the work of Simon, et al [4] largely confirms the above conclusions, Particle size-frequency analysis [5] also indicates a major difference between North and South Massif regoliths. South Massif regolith shows a bell-shaped distribution, peaking smoothly at ~60 μm whereas, North Massif regolith has as highly asymmetric distribution, peaking at ~25 μm. The concentration of North Massif regolith particles at a much finer grain-size may reflect particle sorting of the lithic-clastic debris in volatile-rich eruptive columns.

Data on mineral grain compositions [3] appear consistent with a portion of North Massif regolith having been derived from a different source than that contributing to South Massif regolith. This different source may have been primary ferran anorthositic crust containing Mg-suite plutons.

Summary: If volatile-rich, lithic-clastic volcanic eruptions preceded mare basalt eruptions, comparison of North Massif regolith with post-avalanche South Massif regolith suggests that the deposited debris on the massifs was mineral fragment-rich rather than impact breccia-rich. This contrast in apparent sources of regolith material could be explained by incorporation of fine debris of the ferran-anothositic crust's mega-regolith through which the eruptive material passed. This crust also included extensive Mg-Suite intrusions. Formation of the mega-regolith largely by impact shock induced mechanical comminution that would produce fine lithic-clastic debris of the type indicated by this analysis. Potentially, similar lithic-clastic materials may comprise some of the light-colored, smooth Caley Formation [6] units in many regions identified by lunar photogeologiical mapping.

Particle	76500	72500	Lithic-clastic Debris (?)
Maturity Index	58	81	
Agglutinates	47.2	48.0	- 0.8
Basalt	1.7	3.3	
Breccia	12.1	29.6	- 17.5
Anorthosite	1.4	1.7	- 0.3
Norite	-	0.3	- 0.3
Gabbro	-	-	
Plagioclase	17.2	6.3	+ 10.9
Clinopyroxene	7.6	3.3	+ 4.3
Orthopyroxene	7.9	2.0	+ 5.9
Olivine	0.7	0.7	-
Ilmenite	1.7	0.3	+ 1.4
Ash	2.4	2.7	

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DIURNAL VARIATION OF HYDRATION FROM LUNAR SOIL DEDUCED FROM ALBEDO PROTON RADIATION. N. A. Schwadron[1,2], J. K. Wilson[1,2], M. D. Looper[3], A. P. Jordan[1,2], H.E. Spence[1,2], W. M. Farrell[2,4], N. Petro[2,4], T. J. Stubbs[2,4], C. Pieters[5], L. W. Townsend[6], , [1]EOS Space Science Center, University of New Hampshire, Durham, NH, USA (nschwadron@unh.edu), [2]Solar System Exploration Research Virtual Institute, NASA Ames Research Center, Moffett Field, CA, USA, [3]Aerospace Corporation, El Segundo, CA, USA [4]NASA Goddard Space Flight Center, Greenbelt, MD, USA, [5]Brown University, Dept. of Earth Environmental and Planetary Sciences, Providence, RI, USA, [6]Dept. of Nuclear Engineering, University of Tennessee Knoxville, TN, USA

Introduction: For more than half a century water at the Moon has been the topic of active research [e.g., 1,2]. Infrared spectroscopic measurements identify near-surface OH and H_2O [2-4]. The Moon Mineralogy Mapper (M^3) on Chandrayaan-1 detected 2.8 to 3.0 µm absorption features indicative of OH and H_2O on the surface, strongest at high latitudes and at several fresh feldspathic craters, and distributed over regions well below 80° latitude [2]. Infrared (IR) measurements from Deep Impact (during Dec. 2007 and June 2009 lunar flybys) revealed the largest abundance of hydration near the terminator and least near the subsolar point, implying a diurnal cycle of dehydration and rehydration [4]. Nadir-pointed ultraviolet spectroscopy measurements by the Lyman-Alpha Mapping Project instrument on the Lunar Reconnaissance Orbiter (LRO) showed a minimum in hydration at local noon, which increased almost symmetrically toward either terminator [5]. These results further corroborated diurnal dependence of hydration at the surface.

Albedo Proton Radiation – A Novel Method for Probing Volatile Distributions: The Cosmic Ray Telescope for the Effects of Radiation (CRaTER) instrument consists of a linear stack of 3 pairs of thin and thick silicon detecors, labeled D1 through D6 [6, Figure 1]. The thin-thick D1-D2 detector pair nominally points to deep space, away from the Moon, whereas the D5-D6 pair points nominally toward the Moon. The correlated measurements of galactic cosmic rays from deep space are segregated and distinguished from measurements of high-energy albedo protons from the Moon. Thus, CRaTER resolves the 10-100 MeV albedo protons from the moon that carry unique signatures of the composition of the upper ~10-20 cm regolith.

CRaTER measurements show an excess of albedo protons from polar regions requiring additional hydration at and near the surface [7]. The observation invites the question whether diurnal dependence in the protons emitted from this top hydrated layer can be observed. During the slews of LRO used in our analysis, the D4-D6 detectors are shifted from nadir so that its field-of-view (FOV) grazes the horizon [Fig. 1].

First results showing diurnal variation: We show first results from CRaTER comparing horizon to nadir observations in morning and evening sectors. The observations show a significant dusk-dawn asymmetry in the hydration layer. As these are first results, the analysis and comparison with Geant4 simulations are on going. Initial results of the analysis suggest that differences in the column density of hydration in the upper layers of regolith can lead to substantial changes in the fluxes of albedo protons. The significant differences in the ratio of horizon to nadir protons remains puzzling, and suggests migration of volatiles may play an important role in causing observed variations.

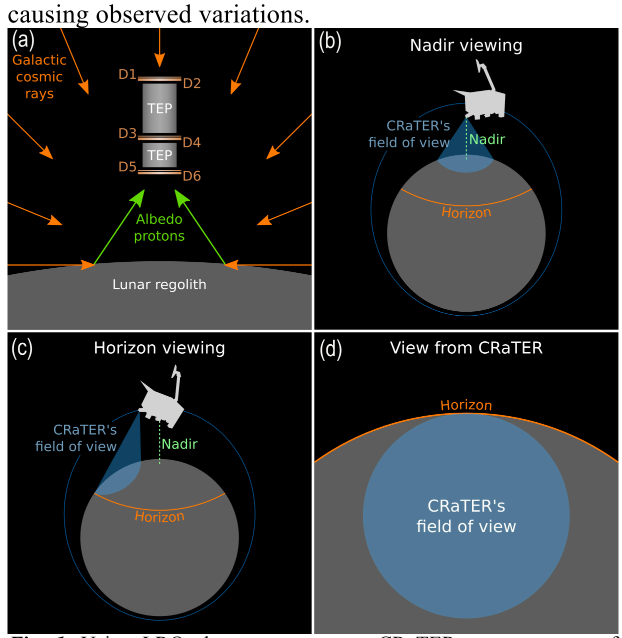

Fig. 1. Using LRO slews, we compare CRaTER measurements of albedo protons (panel a) from nadir, when the instrument boresight is directly normal (panel b) to the surface, versus horizon (panels c and d). The stack of six detectors within CRaTER (panel a) numbered D1 through D6 provides a singularly unique set of measurements of high-energy radiation that allows galactic cosmic rays moving in from deep space into CRaTER (first D2 then D4 detectors) to be segregated from albedo proton radiation (that travels first into the CRaTER D6 and then D4 detector). Horizon viewing makes it possible to search for the production of protons create via knock-on collisions between incident galactic cosmic rays and hydrated material within the upper 10-20 cm of the regolith.

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Results of the Lunar Exploration Analysis Group (LEAG) GAP REVIEW Specific Action Team (SAT). Examination of Strategic Knowledge Gaps (SKGs) for Human Exploration of the Moon. C.K. Shearer[1], D. Eppler[2], W. Farrell[3], J. Gruener[2], S. Lawrence[2], N. Pellis[4], P.D. Spudis[5], J. Stopar[5], R. Zeigler[2], C. Neal[6], and B. Bussey[7]. [1]University of New Mexico, Albuquerque, NM 98122. (cshearer@unm.edu), [2]NASA-Johnson Space Center, Houston, TX 77058, [3]NASA Goddard Space Flight Center, Greenbelt, MD 20771, [4] Division of Space Life Science, USRA, Houston, TX 77058, [5] Lunar and Planetary Institute, Houston TX 77058, [6] University of Notre Dame, Notre Dame, IN 46556 [7]NASA Headquarters, Washington DC 20546.

Introduction The Lunar Exploration Analysis Group (LEAG) was tasked by the Human Exploration Operations Mission Directorate (HEOMD) to establish a Specific Action Team (SAT) to review lunar Strategic Knowledge Gaps (SKGs) within the context of new lunar data and some specific human mission scenarios. Within this review, the SAT was to identify the SKGs that have been fully or partially retired, identify new SKGs resulting from new data and observations, and review quantitative descriptions of measurements that are required to fill knowledge gaps, the fidelity of the measurements needed, and if relevant, provide examples of existing instruments or potential missions capable of filling the SKGs.

Background The starting point of this analysis was the results of earlier analyses by Human Space Flight Architecture Team (HAT) and LEAG. SKGs for implementing the "Moon first" option had previously been defined by HAT and the LEAG GAP-SAT 1 (http://www.lpi.usra.edu/leag/GAP_SAT_03_09_12.pdf) and 2. The LEAG "GAP-SAT" 1 identified important SKG and placed them within the context of (1) enabling or enhancing components in the "Moon First" scenario, (2) the Planetary Science Decadal Survey, (3) the LEAG Lunar Exploration Roadmap (http://www.lpi.usra.edu/leag/roadmap/), and (4) NASA's Human Space Flight Architecture Team's (HAT) mission scenario development. LEAG GAP-SAT 2 provided a quantitative description of measurements that are required to fill knowledge gaps, identifying the fidelity of the measurements needed, and if relevant, providing examples of existing instruments capable of making the measurements.

Results The SKGs were placed within the context of three themes: I. Understanding the Lunar Resource Potential, II. Understanding the Lunar Environment and Its Effects on Human Life, and III. Understand How to Work and Live on the Lunar Surface. SKG categories under each theme were classified as retired, the measurements or mission needed to retire, and whteher it enables or enhances human exploration of the Moon. Some of the SKGs retired from the results of past and current missions and Earth-based testing-observations include such categories as SKG I-A: *Solar illumination mapping*, SKG I-D-*Polar Resources 1: Extent of cold traps*, SKG I-D-*Polar Resources 2: Correlation of cold traps and permanent darkness*, SKG II-C-1: *Earth-based testing of the Biological effects of lunar dust*, and SKG III-1: *Lunar mass concentration and distributions*.

There are numerous SKGs that have not been retired that are enhancing for short-duration missions (less than 28 days), but enabling for long-term sustained, human operations on the Moon. These SKG categories include (but not limited to): SKG I-C *Regolith 3: Preservation of volatile and organic components during robotic and human sampling, handling, storage, and curation*,
SKG I-D *Polar Resources 5: Charging and plasma environment within and near PSR*, SKG II-A-1: *Solar activity/solar event prediction*, SKG II-B-2: *Radiation environment at the lunar surface (measurements)*, and SKG III-D-1: *Lunar dust remediation*.

Findings This LEAG SAT finds that: (1) Recent missions (e.g. LRO, GRAIL, LADDIE) produced data to retire several of the SKGs defined by HAT and the 2011-2012 LEAG GAP-SAT analyses. (2) Thanks to these missions, there are no SKGs that would inhibit the flight of any human mission (e.g., sortie or human-tended surface facility) <28 days duration. (3) However, there are several SKGs that should be addressed that would increase human safety not only at the Moon, but also in LEO, cisLunar space, and beyond the Moon. This includes the development of infrastructure to monitor solar activity (e.g. solar storms). (4) In the context of a "Moon First Scenario" that develops assets and capabilities for human activity within the Earth-Moon system (EMS) and beyond EMS to near-Earth asteroids and Mars, there are numerous SKG**s** that would enable and enhance more mature human exploration capabilities for the Moon and beyond. (5) Future programmatic, competed (Discovery, New Frontiers) and international missions to the Moon should be examined for potential NASA contributions for retiring SKGs. This could take the form of contributed instruments to international missions and "credit" or contributed instruments toward NASA competed missions. (6) NASA programs such as Solar System Exploration Research Virtual Institute (SSERVI) should coordinate and encourage activities to retire SKGs.

LABORATORY SIMULATION OF DIELECTRIC BREAKDOWN OF LUNAR REGOLITH SIMULANT JSC-1A.

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Introduction: Models show solar energetic particle (SEP) events that are capable of generating deep dielectric charging in the top 1 mm of regolith in permanently shadowed regions (PSRs) on the Moon, lead to dielectric breakdown of regolith [1]. Laboratory simulations have been performed both to verify theoretical predictions about breakdown, and to determine the physical and chemical alterations that may result from this process. Lyman-Alpha Mapping Project (LAMP) and Lunar Crater Observation and Sensing Satellite (LCROSS) data indicate reduced far-ultraviolet albedo features in addition to rough, highly porous surfaces in PSRs [2,3]. To date, there has been no comprehensive explanation describing the mechanisms that form the unique physical and optical characteristics specific to these regions, nor have any studies been completed that examine alterations resulting from electrical discharge in a lunar regolith-like environment. The determination of discharge pathways and weathering features created by dielectric breakdown may provide more information about these anomalous regions.

Methods: To replicate the surface charge field in PSRs, two parallel plate electrodes with a gap of 0.4 mm were embedded into lunar regolith simulant JSC-1A at a depth of ~1 mm. Samples were placed under low and high vacuum environments, ~1.0e-3 Torr and ~2.5e-6 Torr, respectively. Voltage was steadily increased until discharge occurred within the sample well. Grains were analyzed with both optical and scanning electron microscopes, in addition to an X-ray spectrometer.

Results: The electric field at which discharge occurred and the abundance of alterations present in each sample differed under low and high vacuum conditions. Discharges under low vacuum occurred at approximately 7.5×10^6 V/m, while the average field at breakdown under high vacuum was 1.59×10^7 V/m. Regolith was displaced radially when a discharge occurred between the plates, creating small craters centered at the electrode gap. Under low vacuum, crater depth and diameter ranged from 3-4 mm, but the range decreased to 2-3 mm under high vacuum. The displacement of grains increased the surface roughness of samples.

Iron vapor deposition was a more prominent feature in samples sparked under low vacuum conditions. The iron likely came from iron-rich silicate grains, and despite the apparent absence of silicate vapor deposition in low vacuum samples, silicate vapor deposits were found in high vacuum samples.

Metallic iron was found to coalesce in samples sparked under low vacuum, while under high vacuum the metal was more likely to be deposited to the surface of grains (Fig. 1). This type of deposition was not typically found on grains exceeding 50 μm and was not found in low vacuum samples.

Discussion: Preliminary simulations indicate that pressure plays a significant role in the electric field required for breakdown and the type and extent of alterations seen in grains. While the breakdown limit of a vacuum well exceeds electric fields observed at discharge in these experiments, for most solids, dielectric breakdown occurs around 10^7 V/m [4]. Electric fields observed in low vacuum experiments were on the order of 10^6 V/m indicating that an alternative discharge pathway, such as metallic iron on the surface of grains, was likely present. For high vacuum samples however, electric fields of 10^7 V/m were observed and indicate that breakdown of grains may have occurred.

Grain displacement and alterations involving iron have shown that discharge, whether across or through regolith, can result in some of the physical and optical characteristics seen in remote sensing data that is not currently well explained. Further experimentation and analysis are planned to better quantify the effects of electric discharge and to determine the preferred discharge pathways.

Figure 1. Alternative discharge pathways in lunar soils may include iron deposited during previous discharge events or inherently abundant metallic iron on the surface of grains.

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TEMPORAL OBSERVATIONS OF REGOLITH GARDENING CAUSED BY SECONDARY IMPACTS.

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Introduction: Orbital remote sensing typically probes from the top few microns down to tens of centimeters within the regolith and these observations along with returned samples form the basis of much of what we know about the Moon. Therefore it is essential that we understand the physics of regolith mixing and overturn in the upper few mm to 10s of cm. Dynamics of the upper layer of lunar regolith was previously modeled using meteoroid flux data [1-3]. However, new observations from the Lunar Reconnaissance Orbiter Narrow Angle Camera (LRO NAC) [4] indicate secondary impacts may play a larger role in near-surface regolith gardening than previously thought.

Temporal Observations: Robinson et al. [5] characterized an 18 m impact crater that formed on 17 March 2013 with before and after images (temporal imaging). In addition to the primary crater, they found 248 localized albedo changes, which they called splotches [5], which have no visible rims or morphologic signatures at the meter scale, but are identified only by a change in the local albedo. These albedo changes are visible in temporal ratio images, which are generated by taking the ratio of two registered images that cover the same terrain and are acquired under similar lighting conditions.

We searched 14,092 LROC NAC temporal pairs and located over 47,000 splotches (**Fig. 1**). 91% of the new splotches identified are classified as low reflectance splotches; the surface reflectance decreases between the time of the first and second observation. 7% are considered high reflectance splotches where the surface reflectance increases. The remaining have mixed patterns of high and low reflectance signatures. While some may be the result of small, primary impacts, we identified dense clusters of splotches around new impact craters, which indicates that many or even a majority of splotches are the result of secondary impacts. Robinson et al. [5] also noted that some splotches have patterns aligned with the 18 m primary impact crater indicating a direction of emplacement consistent with being formed as a secondary impact.

Regolith Gardening: We propose that many of the splotches were the result of poorly consolidated regolith ejected from nearby craters that churned the upper layer of regolith upon impact. Laboratory experiments conducted by Schultz and Gault showed that clustered impacts at relevant speeds (~200 m/s) create a pitted surface surrounded by a subdued rim with a depth:D ratio of 1:30. These simulations imply that most splotches would only churn the top few cms of regolith within the mature zone thus the low reflectance of the splotches (if immature material was excavated the splotches would have relatively high reflectance). This scenario is consistent with our observation that most of the splotches are low reflectance and we note that many of the high reflectance splotches occur on steep slopes or in areas that have been recently resurfaced.

Using a conservative estimate for the churning depth (1:50) and the observed spatial coverage of new splotches formed in temporal pairs, we derived a gardening rate for the upper few cm of regolith. We predict that 99% of the lunar surface is altered by 1-m and larger splotch events over a period of ~80,000 years churning the upper ~2 cm of regolith during that period. This rate is >100 times faster than predicted by Gault et al. [1], but is consistent with measurements of short-lived cosmogenic radionuclides (^{26}Al; $t^{1/2}$=7.3×10^4 yr) in Apollo drive core samples that indicate the upper 2-3 cm of regolith was continuously reworked over a period of 10^5 to 10^6 yrs [6-8].

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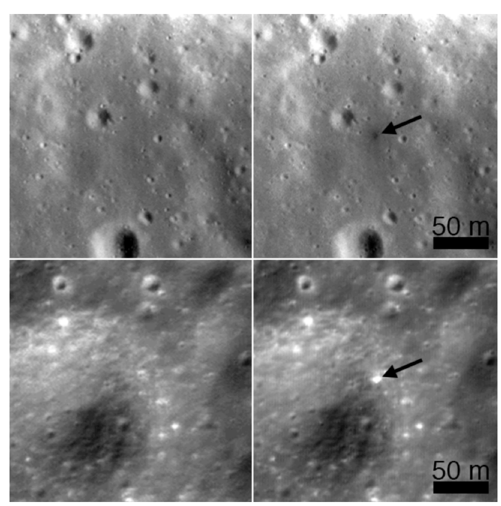

Fig. 1- Temporal pair showing a new low reflectance (top row) and high reflectance (bottom row) splotch.

A NEW ARCHITECTURE TO EXPLORE THE POTENTIAL OF LUNAR RESOURCE UTILIZATION.

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Our current national human spaceflight effort lacks both clarity of purpose and a strategic goal reachable for reasonable expenditures of time and money. Despite the obsession with human missions to Mars, a return to the Moon offers more benefits, a larger number of near-term milestones, develops the infrastructure and prepares us for future missions to the planets. We offer a logical, justifiable alternative to the existing program that identifies a compelling purpose for human spaceflight – to learn how to use the material and energy resources of space to create new spaceflight capabilities [1]. As in our previous plan [2], robotic surface elements begin harvesting lunar water prior to human arrival on the Moon, resulting in the creation of a permanent, space-based cislunar transportation system.

We have modified our previously published architecture with two significant updates [1]. First, we use the Space Launch System (SLS) Block-1 and Block 1B configuration launch vehicle to launch the robotic elements that will build the outpost, which accommodates much more mass and volume in a single launch. Second, our new plan minimizes cost for a crew lunar mission cycle by relying upon Commercial Crew launch services for transport to and from a depot and staging node in low Earth orbit (LEO). Crews are launched commercially by any of several providers and returned 6-months later. The crew then transfers to a reusable cislunar transfer stage that travels only between a fuel depot in LEO and a similar facility in low lunar orbit. We use aerobraking during Earth return to recover the reusable cislunar crew stage; this non-propulsive maneuver removes excess energy for an insertion to Low Earth Orbit for rendezvous with the LEO depot and transfer crew to the Commercial Crew vehicle to return home without significant propellant expenditure.

The LEO fuel depot can be provisioned by commercial or government water deliveries from Earth to fuel the cislunar crew stage on its way to the Moon. As lunar surface production grows, we can provision the LEO depot with lunar water for propellant production. The use of both commercial crew and commercially launched water transferred to the LEO fuel depot allows the campaign to better stimulate commercial space industry, transferring technology and experience from NASA to the commercial sector, expanding human spaceflight capabilities and activities off-planet.

Once the crew reaches low lunar orbit, they transfer into a reusable lander that shuttles crew and cargo to and from the lunar surface and the low lunar orbit (LLO) depot. An Orion spacecraft is stationed at the LLO fuel depot that can be used as an assured crew return vehicle at any time in case of emergency. This facility services all lunar surface-bound vehicles, including robotic, human and cargo landers. Activities on the lunar surface are similar to those described previously [2], with lunar water being harvested and processed via robotic machines operated by humans on Earth (teleoperations). The complete outpost system is deployed and operational (including habitat emplacement) prior to the arrival of the first human crew.

As a consequence of this new strategy, we develop more capability to harvest lunar water for propellant compared to the previous architecture. At the end of the 16-year first phase of the architecture, we are producing more than 300 metric tons of lunar water per year (twice the amount generated in our previous architecture [2]), with a production capacity of 500 metric tons per year.

The total estimated cost for this new architecture is $ 87.7 billion [1], about $ 550 million more than our previous plan [2]. In addition, we have examined the possible contributions of international and commercial partners to this architecture, with specific suggestions for both bartered and in-kind contributions. With these possible contributions, we can reduce peak NASA funding to $ 5.5 billion per year while reducing the total program cost to U.S. taxpayers to ~ $ 69 billion, a reduction of roughly one-quarter (25%) from our previous plan [2].

At the end of the first phase of our lunar resources outpost architecture, we will have demonstrated and determined the degree to which humans can effectively use local resources to live and thrive off-planet. At that point, future missions to other deep-space destinations (like Mars) can be undertaken, leveraging the technology gained and lessons learned from the lunar experience as well as utilize the consumables and propellant produced from lunar resources. These new products can be used and exploited by government, commercial, or international entities as we continue to expand our reach in cislunar space and beyond. By adopting a reachable goal (the Moon) that can be achieved for reasonable budgets and timescales, we invigorate our currently moribund and stagnant civil space program while at the same time lay the groundwork for a permanent spacefaring system, one based upon the leverage provided by the utilization of lunar resources to create new capability [3].

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EXAMINING LUNAR SURFACE MATURITY FROM UV TO RADAR. A. M. Stickle[1], J. T. S. Cahill[1], J. A. Grier[2], B. Greenhagen[1], G. W. Patterson[1], [1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, 20723, USA (angela.stickle@jhuapl.edu),[2]Planetary Science Institute, Tuscon AZ USA.

Background: The physical evolution of the lunar surface with exposure to the space environment (particularly impacts) is termed "maturation", can take place over relatively short timescales, and has been attributed to the amount of glass and agglutinate content within the lunar soil [e.g., 1-8], the amount of trapped solar wind nitrogen [9], solar wind sputtering and vapor deposition [10-11], and/or the amount of sub-microscopic iron (SMFe) in the material. Studies show that the abundance of these glasses and agglutinates increases with age of the soil and can account for large portions of a given mature soil [e.g., 2,4,9,14]. Changes in physical properties of the lunar soil are quantified in terms of specific maturity indices (e.g., Optical maturity (OMAT) [13]), and thus soils are generally classified on the basis of one or more of these specific indices [3]. Though sampling maturity effects from different processes and on different time- and depth-scales, comparisons indicate that maturity of the soil can be tracked across wavelengths [14], which is a powerful tool when examining the surface evolution of the Moon.

Observations of Crater Age Across Wavelengths: There are a number of methods for representing maturity: e.g., OMAT, LROC, Diviner, Mini-RF. Using OMAT, [13] classify Byrgius A as "young", Dufay B as "intermediate" and Golitsyn J as "old". Here, we survey how these ages are manifested across wavelengths to examine if correlations exist for maturity indices as a function of wavelength.

Comparisons of observations from UV to radar for these three craters (e.g., Stickle et al. 2016, and Fig. 1) indicate that maturity of the soil can be tracked across wavelengths. These comparisons suggest that specific "maturity parameters" manifest differently at different wavelengths. Further, more detailed comparisons are underway, and they are necessary to more fully understand when these maturity trends can be correlated and how to quantify the correlation. If trends can be correlated, this will provide a powerful tool when examining the surface evolution of the Moon and determining relative ages between features.

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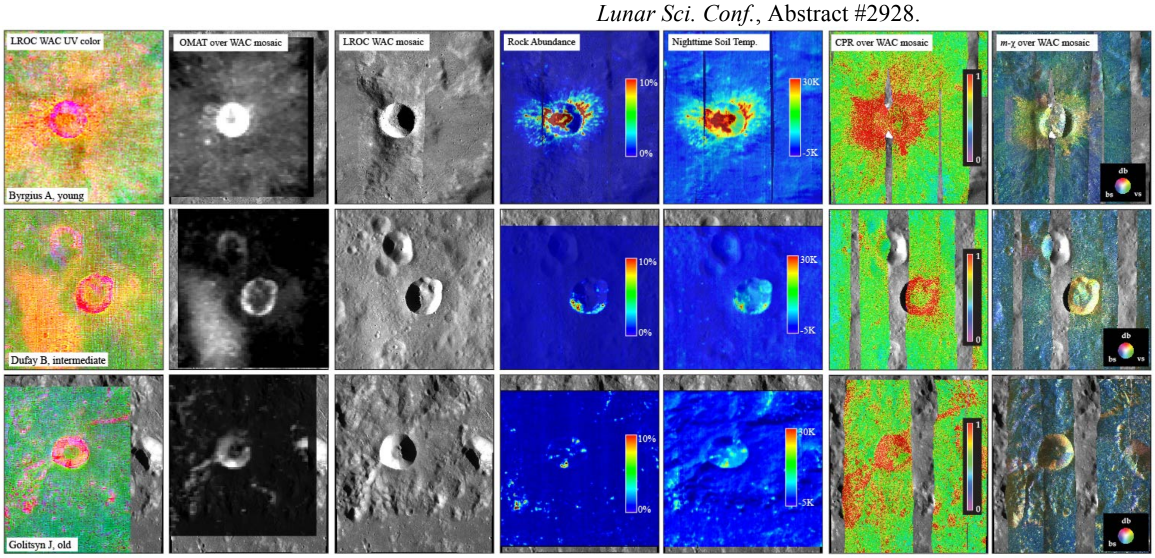

Figure 1. (top) Byrgius A (19.7 km, 24.6°S, 63.5°W), a young highlands crater, (middle) Dufay B (19.8 km, 8.3°N,171°E), an "intermediate" aged highlands crater, (bottom) Golitsyn J (19.5 km, 27.9°S, 102.9°W), an "old" highlands crater. The columns show the appearance of the crater across wavelengths, from UV (WAC UV, left) to radar (Mini-RF radar,right).

DEFINING LONG-DURATION TRAVERSES OF LUNAR VOLCANIC COMPLEXES WITH LROC NAC IMAGES. J. D. Stopar[1], S. J. Lawrence[2], B. L. Jolliff[3], E. J. Speyerer[4], and M. S. Robinson[4], [1]Lunar & Planetary Institute, Houston, TX, [2]NASA Johnson Space Center, Houston, TX, [3]Washington University in St. Louis, MO, [4]Arizona State University, Tempe, AZ.

Introduction: A long-duration lunar rover [e.g., 1] would be ideal for investigating large volcanic complexes like the Marius Hills (MH) (~300 x 330 km), where widely spaced sampling points are needed to explore the full geologic and compositional variability of the region. Over these distances, a rover would encounter varied surface morphologies (ranging from impact craters to rugged lava shields), each of which need to be considered during the rover design phase.

Previous rovers including Apollo, Lunokhod, and most recently Yutu, successfully employed pre-mission orbital data for planning (at scales significantly coarser than that of the surface assets). LROC was specifically designed to provide mission-planning observations at scales useful for accurate rover traverse planning (crewed and robotic) [2]. After-the-fact analyses of the planning data can help improve predictions of future rover performance [e.g., 3-5].

Results and Conclusions: Previously, using a path-planning tool [6] that relates anticipated terrain directly to engineering parameters along with LROC NAC images and derived Digital Terrain Models (DTMs), we characterized slopes, terrain roughness, and potential hazards for the future exploration of a variety of lunar volcanic deposits [7]. Here, we also directly compare a notional MH traverse (in an established "rough terrain" [e.g., 8-11]) to the Apollo 15 (A15) EVAs (in "smooth mare" [e.g., 3,10,12]) using NAC DTMs (Fig. 1).

The notional MH traverse is dominated by slopes <2° (calculated from elevations extracted along the traverse), similar to both of the reconstructed A15 EVAs (Fig. 1). Local slopes between 5 and 10° (from NAC DTMs) are more abundant than was previously determined along the A15 EVAs using 20 m topographic data [3, their Fig. 16]. Slopes of 10-20° are only a minor part, ~3%, of the overall MH and reconstructed A15 EVAs. A maximum navigable slope of 20° was assumed for the MH traverse. The measured slopes of the notional MH traverse, compared to the NAC analysis of the A15 EVAs, suggest that the MH path is viable for future roving.

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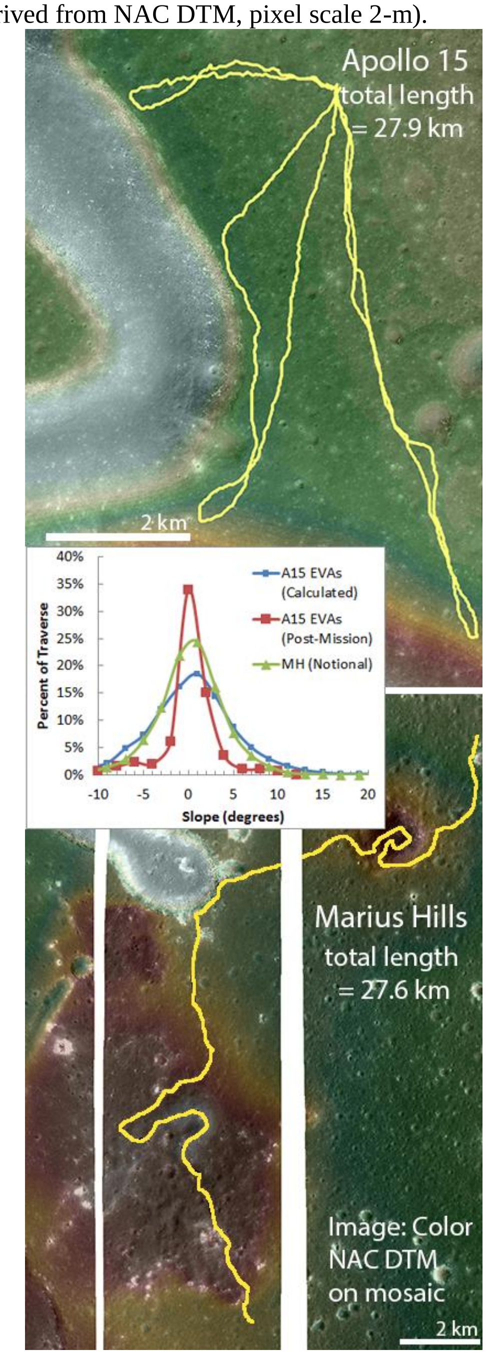
Fig. 1: Apollo 15 EVAs and a notional MH traverse of comparable length (yellow lines). Plot of slope distributions for traverses: A15 (derived from a NAC DTM with pixel scale 1.5-m, and post-mission analysis of 20-m pixel scale maps [3]) and MH (derived from NAC DTM, pixel scale 2-m).



MODELING VOLATILE LOSS DURING RESOURCE PROSPECTOR MISSION SAMPLE ACQUISITION. L. F. A. Teodoro,[1] A. Colaprete,[2] T. Roush,[2] R. C. Elphic,[2] A. Cook,[3] J. Kleinhenz,[4] E. Fritzler,[3] J. T. Smith,[5] K. Zacny,[6] [1]BEARI/NASA Ames Research Center, Moffett Field, CA 94035 (luis.f.teodoro@nasa.gov), [2]NASA Ames Research Center, Moffett Field, CA 94035, [3]Milliennum Engineering, NASA Ames Research Center, Moffett Field, CA 94035, [4]NASA Glenn Research Center, Cleveland, OH 44135, [5]NASA Kennedy Space Center, Cocoa Beach, FL 32899, [6]Honeybee Robotics Pasadena, Pasadena, CA 91103

Introduction: Here we present the modeling of volatile transport in lunar regolith in the context of the NASA's Resource Prospector (RP). This mission to the high latitudes and permanently shadowed regions of the Moon has as its main goal the extraction and identification of volatile species in the top meter of the lunar regolith layer. The RP sample acquisition and analysis system includes: 1) The Drill Sub-system for extracting samples from the top meter of the lunar surface and delivering them to the Oxygen and Volatile Extraction Node (OVEN); 2) OVEN will heat up the sample and extract the volatiles therein, that will be 3) transferred to the Lunar Advanced Volatiles Analysis (LAVA) instrument.

A series of vacuum experiments have been carried out at NASA's Glenn Research Center with the aim of quantifying volatile loss during the RP drilling/sample acquisition phase and sample delivery to the crucibles steps. Outputs of these experiments include: 1) Pressure measurements of several chemical species (e.g. H_2O, OH, CO_2, N_2, Ar); 2) Temperature measurements within and on the surface of the lunar simulant using thermocouples; 3) Surficial temperature NIRVSS measurements; and 4) Temperature measurements at the tip of the drill.

We report on the numerical modeling carried out to understand the physics underpinning these experiments. This modeling contemplates two main parts: 1) Reliable computation of temperature variation throughout the simulant container during the experiment as constrained by temperature measurements; and 2) Volatile molecular diffusion. The latter includes both Fick's (flight of the molecules in the porous) and Knudsen's (sublimation of volatile molecules at the grain surface) laws. Furthermore, we also mimic the soil porosity in randomly allocating 75 microns particles (the size of the average lunar regolith grain) in the simulation volume.

To model the molecular diffusion of volatiles we have implemented a 3-D numerical code that tracks one 1 billion macro-particles (each macro-particle represents a large number of water molecules) within the computational volume. At each instant one computes a time-step that takes into account the relevant time scales. The two types of diffusion have the following temperature-dependent time scales: 1) Fick' law *flying time*: $\tau_F = v_{th}/l$ where v_{th} ($\alpha\ T^{1/2}$) and l denote the thermal velocity and average grain size, respectively; 2) Knudsen's law *residence time*: $\tau_K\ \alpha\ \exp[-Q/(KT)] * T^{1/2}$, where K and Q are the Boltzmann's constant and sublimation enthalpy. As the temperature field is not uniform throughout the simulation volume and changes during the duration of the experiment, one chooses the time-step, Δt, at a given instant in time, t, as the largest of $\tau_F(\mathbf{r},t)$ and $\tau_K(\mathbf{r},t)$ within the simulation volume, where **r** denotes position.

The probability of a super-particle departing from the surface of a grain at a given instant is then computed as the ratio of the local $\tau_K(\mathbf{r},t)$ by the global Δt at that same instant.

Temperature field: an accurate temperature field is fundamental to track the macro-particles within the simulations volume. Temperatures are measured at a series of locations during the experiment. Hence, we have developed an interpolation scheme using the measured temperatures to create a field $T(\mathbf{r},t)$. Currently, we are generalizing this interpolation scheme to include the measurements at the surface and at the location of the drill's tip in a self-consistent manner.

Conclusions: We present the numerical results of large-scale molecular simulations of water molecules during Resource Prospector sample acquisition. We also present the numerical modeling of the temperature field throughout the volume of regolith as constrained by the thermocouple measurements performed during the vacuum experiments. Previous calculations assuming a spatially uniform (and constant in time) temperature showed that both diffusion laws play a major role during the drilling phase. Our preliminary results with a more realistic temperature field $T(\mathbf{r},t)$ reiterate such a conclusion.

ENERGY AND ANGULAR SPECTRA OF ALBEDO PROTONS AND NEUTRONS EMITTED FROM HYDRATED LAYERS OF LUNAR REGOLITH. L.W. Townsend[1], F. Zaman[1], N.A. Schwadron[2], J.K. Wilson[2], H.E. Spence[2], A.W. Case[3], J.C. Kasper[3], J.E. Mazur[4], and M.D. Looper[4], [1]Department of Nuclear Engineering, The University of Tennessee, Knoxville, TN, USA (first author email address: ltownsen@tennessee.edu), [2]EOS Space Science Center, University of New Hampshire, Durham, NH, USA, [3]University of Michigan, Ann Arbor, MI, USA, [4]The Aerospace Corporation, El Segundo, CA, USA.

Introduction. Nuclear interactions of galactic cosmic rays (GCR) with lunar regolith have produced albedo protons detected by the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) instrument onboard the Lunar Reconnaissance Orbiter (LRO) spacecraft [1]. These albedo protons are mainly composed of secondary protons produced by fragmentation/spallation reactions of the incident cosmic ray spectrum, and incident protons themselves scattered by the regolith components. Data analyses by the CRaTER team have indicated that there is an approximate 40% increase in proton flux when observing the lunar limb rather than the nadir [2]. Also, the presence of diurnal variations in albedo proton yields is under investigation.

Modeling of Albedo Yields. In an effort to further understand the measured albedo proton yield variations, we have modeled the energy and angular yields of protons and neutrons emitted from the lunar surface as a function of hydration layer thickness in the lunar regolith using the MCNP (Monte Carlo Neutral Particle) computer code developed at Los Alamos National Laboratory [3]. Estimated yields of albedo protons and neutrons as a function of energy and angle for protons at 100, 300, 500, 750 and 1000 MeV incident energies striking the lunar surface at angles of 5 and 90 degrees above the surface are reported. The lunar surface was assumed to contain thin layers of hydration of varying thicknesses between 1 and 10 cm. Calculations were also performed for a complete, isotropic GCR proton spectrum incident on these same thicknesses of hydrated regolith. For this full spectrum, energy and angular spectra of albedo protons and neutrons were also estimated.

Energy and Angular Spectra Characteristics. As expected, yields of albedo protons increase with increasing incident proton energies and are forward-peaked for incident angles of 5 degrees. Proton yields also increase with increasing depth of the hydrated layer at high energies, but not so at energies around 100 MeV. Yields of albedo neutrons, on the other hand, increase with angle relative to the surface, and are peaked at 90 degrees. Yields of albedo neutrons also increase with incident proton energy at all angles, which is to be expected since the number of neutrons produced in each spallation reaction is known to increase with incident proton energy. Neutron yields for all proton energies are also higher for thinner hydration layers, which indicate that thicker layers tend to attenuate the neutrons through nuclear collisions with the added hydrogen content. Some of this attenuation of neutrons contributes to increased proton yields as the hydration layer thickens.

For an isotropic distribution of incident GCR protons (full GCR spectrum), The calculations indicate that the albedo proton yields are broadly-peaked around 15 degrees from the horizontal, independent of hydrated layer thickness (comparing 1 cm to 10 cm thicknesses). The peak proton yields around 15 degrees are also a factor of two larger than the yields at angles larger than 70 degrees, which tends to explain the observed increased proton yields when observing the lunar limb.

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Forthcoming Lunar Exploration Studies and Technology Development Activities at the European Space Agency. S. Vijendran[1], J. Carpenter, B. Houdou, D. De Rosa, R. Fisackerly, D. Laurini, S. Aziz, H. Schroeven-Deceuninck, M. Landgraf and B. Hufenbach. [1]European Space Agency-ESTEC, Keplerlaan 1, 2201AZ Noordwijk, The Netherlands,

Introduction: As part of the future Exploration programme at the European Space Agency, further studies and technology development activities are intended to be initiated in 2017-2019 to prepare for missions to the Moon in the 2020's. A key element of the preparation for human spaceflight lunar missions is the Deep Space Habitat (DSH), a human-tended outpost which is being considered for launch to cis-lunar space, in collaboration with ISS partners, in the mid- 2020's, while robotic lunar mission studies in the area of volatile prospecting and potentially including polar sample return are also foreseen in the coming years.

Future lunar human exploration studies and technology development:

Deep Space Habitat: Phase A/B1 studies are intended to be intiated in 2017. Technology developments that could be initiated alongside to support the DSH include a continuation of long term Micro-Ecological Life Support System Alternative (MELISSA) activities and the development of high-power (15kW-class) solar electric propulsion thrusters.

Architectures for human-robotic lunar missions enabled by the Deep Space Habitat: Leveraging on past exploration architecture studies and implemented in full coordination with international and commercial partners, the envisaged studies will aim at analysing the European utilisation scenario of the Deep Space Habitat and the definition of lunar surface missions leveraging on the DSH as an enabling mission architecture element.

Future lunar robotic exploration studies and technology development:

Contributions to a Lunar Polar Sample Return mission: An LPSR mission scenario is under discussionn with Russia as a potential follow on to the Luna-25 and Luna-27 landers, which ESA is currently supporting. An architecture option with a rendezvous in orbit has been the subject of an ESA internal CDF study in 2014, followed by an industrial pre-Phase A study with two parallel contracts. The whole return leg of the mission and its elements have been assessed, starting from sample extraction on the surface. Depending on further discussions with Roscosmos, additional studies on the rendezvous and/or direct return architectures could be initiated.

Lunar Volatile Prospecting Rover: A Lunar Volatile Prospector (LVP) mission would determine the regional distribution of water ice at the lunar pole and has been investigated at pre-Phase A level in dual industrial studies. This mission with a prospecting rover informs the resource potential of lunar ice, delivers world class science and could allow determination of landing sites for Lunar Polar Sample Return or be a fully integrated segment in an LPSR mission. The mission concept strongly leverages European investments in mobility, sampling and instrumentation and could greatly benefit from the development of European space nuclear power systems.

The paper and presentation will elaborate further on the background of these planned studies, how they fit within the overall ESA Exploration Programme, their future perspectives and the related technology development activities that are foreseen to be undertaken in the coming years, to advance their maturity.

Results of Lunar Rover Drivetrain TRL-6 Environmental Testing.
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Introduction: Between late 2014 and early 2016, Ontario Drive & Gear Ltd. (ODG), Canadensys Aerospace Corporation and other partners developed two new small to medium-sized lunar/planetary rover prototypes funded by the Canadian Space Agency (CSA). The intent of these vehicles was to demonstrate the compatibility of the ODG rover architecture with higher Technology Readiness Levels (TRLs), with a target of demonstrating TRL-6 on the drivetrain components. Environmental testing was conducted on a drivetrain unit in late 2015 at the NASA Glenn Research Center. A summary of the results of this testing are presented herein.

LRPDP: The Lunar Rover Platform and Drivetrain Prototype (LRPDP) is a mid-size (1.6 by 1.6 meter) mobility platform developed from the successful Juno and Artemis Jr. rover platforms used by CSA and NASA in multiple analogue deployments since 2010. This rover is characterized by a robust, simple architecture that places an emphasis on extreme terrain capability, minimal mass, and modularity. This skid-steered rover features large (55 cm diameter) metallic semi-compliant wheels for maximum performance in rough terrain or soft regolith. All sensitive components such as motors, gearboxes, and avionics are located in sealed compartments in an effort to minimize heat loss and dust contamination. The chassis shape is optimized for quick change-out of large, centrally located payloads such as the RESOLVE payload tested in Hawaii in 2012.

ODG was the prime contractor for LRPDP, while Canadensys was the Environmental Test Lead and also conducted the thermal analysis and provided input on path-to-flight design considerations.

Drivetrain Environmental Testing: In order to demonstrate TRL-6 on the rover drivetrain, "dirty" thermal vacuum testing was carried out in the VF-13 chamber at NASA Glenn Research Center in late 2015. This specially-configured thermal vacuum chamber allowed a drivetrain unit – consisting of a central motor housing, a transmission housing, a motor assembly, three sprockets, two internal chains, three bearings, two bearing extensions, two bearing dust seals and two wheel rims – to be tested under simultaneous exposure to vacuum, Chenobi lunar regolith simulant and temperature extremes. Due to the size limitations of the chamber, the unit was mounted in a vertical orientation in a test fixture, which provided the necessary structural support and mechanical interface to the chamber, as well as a hopper to hold the simulant. A conveyor system, consisting of two large sprockets mounted to each of the two wheel rims, two chains and several simulant scoops, allowed the simulant to be cascaded over the entire drivetrain unit while the drive motor was operated during the test. Performance tests were conducted over the motor's worst-case operational temperature range of -70°C to +130°C. Additionally, the unit was exposed to a cold survival temperature of -175°C, after which it was warmed to -70°C and again tested for performance. The duration of the test campaign was four weeks, during which all drivetrain components accumulated a total mileage (forward and reverse) in excess of 15 km. One anomaly was experienced with the motor during the testing, which was traced to a rotor magnet that had become misaligned during the thermal cycling. The motor was replaced with an identical unit and the testing was successfully completed. Upon completion of the testing, the drivetrain unit was disassembled to inspect for simulant ingress into the motor housing, transmission housing and wheel bearing assemblies. No simulant was found inside, proving the effectiveness of the design in resisting lunar regolith ingress and in particular, the non-contact multi-stage wheel bearing dust seals.

Future Work: In order to address the anomaly experienced with the motor during the thermal vacuum testing, a modification to the method of captivation used on the rotor magnet is being carried out by the motor manufacturer. Subsequent component-level and motor-level environmental testing will be conducted on the revised design to verify its effectiveness.

Acknowledgements: The authors gratefully acknowledge the support of the Canadian Space Agency and the efforts of several additional partners in the work presented herein, including Provectus Robotics Solutions, Maya Heat Transfer Technologies and Centre des Technologies Avancées.

THE SEARCH FOR APOLLO ERA ALSEP DATA AND ITS RESTORATION AND ARCHIVING. D. Williams[1] , NASA/GSFC (david.r.williams@nasa.gov), P. Taylor[1] (patrick.taylor@nasa.gov), S. Naghara[2] (seiichi.nagihara@ttu.edu), Y. Nakamura[3] (yosio@ig.utexas.edu) and W. Kiefer[4] (kiefer@lpi.usra.edu).

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Introduction: Apollo astronauts on missions 12, 14, 15, 16, and 17 installed instruments on the lunar surface, the Apollo Lunar Surface Experiment Package (ALSEP). The last astronauts departed from the Moon in December 1972; however ALSEP instruments continued to send data until 1977. These long-term *in-situ* data, along with data from orbital satellites launched from the Command Module, are some of the best information on the Moon's environment, surface and interior.

Data History: Much of these data were archived at the now NASA Space Science Data Coordinated Archive (NSSDCA) in the 70's and 80's, but some were never submitted. This is particularly true of the ALSEP data returned autonomously after the last Apollo astronauts departed. The data that were archived were generally on microfilm, microfiche, or magnetic tape in now obsolete formats, making them difficult to use. Some of the documentation and metadata are insufficient for current use. The Lunar Data Node at Goddard Space Flight Center, under the auspices of the Planetary Data System (PDS) Geosciences Node, is attempting to collect and restore the original data that were never archived, in addition to much of the archived data that were on media and in formats that are outmoded. 440 original data archival tapes for the ALSEP experiments were found at the Washington National Records Center. We have recently completed extraction of binary files from these tapes filling a number of gaps in the current ALSEP data collection at NSSDCA. Several troubled tapes have been read by three different data recovery specialists to restore as much data as possible.

Data Archiving: Some of these experiments include: Solar Wind Spectrometer (Apollo12, 15); Cold Cathode Ion Gage (14, 15); Heat Flow (15, 17); Dust Detector (11, 12, 14, 15); Lunar Ejecta and Meteorites (17); Lunar Atmosphere Composition Experiment (17); Suprathermal Ion Detector (12, 14, 15); Lunar Surface Magnetometer (12,15, 16). The purpose of the Lunar Data Project is to take data collections already archived at the NSSDCA and prepare them for archive through PDS, and to locate lunar data that were never archived into NSSDCA, and then archive them through PDS. In addition results of recent re-analyses of some of these data with advanced data processing algorithms revealed more detailed interpretation (*e.g.*, seismicity data). We expect that more techniques will be developed in the future.

EXTRACTING LUNAR ALBEDO PROTONS FROM SPARSE PARTICLE DATA. J. K. Wilson[1], N. A. Schwadron[1], H. E. Spence[1], A. P. Jordan[1], T. J. Stubbs[2], D. M. Hurley[2], W. M. Farrell[2], N. E. Petro[2], T. P. McClanahan[2], M. D. Looper[3], C. Pieters[4], L. W. Townsend[5], [1]University of New Hampshire, Space Science Center, Durham, NH (jody.wilson@unh.edu, nschwadron@unh.edu), [2]Goddard Space Flight Center, Greenbelt, MD, [3]The Aerospace Corporation El Segundo, CA, [4]Brown University, Planetary Sciences Group, Dept. of Earth Environmental and Planetary Sciences, Providence, RI, [5]Department of Nuclear Engineering, The University of Tennessee, Knoxville, TN.

Overview: The CRaTER instrument on LRO has detected grazing-angle albedo protons coming from the lunar horizon in specially targeted observations in 2015 and 2016.[1] (See the abstract in this meeting by Schwadron et al.) Given the limited exposure time of these limb observations (10s of hours) compared to the nominal nadir-pointing mission, (7+ years) we required a new and robust method of extracting the proton fluence from the ever-present and changing background signal.

Wilson et al.[2,3] mapped the lunar albedo proton yield using two-detector “cross-plots”, under the assumptions that (1) the distributions within the proton tracks were constant, and that (2) the average background signal over the mission (~three years at that point) was an adequate approximation to the background signal over any location and at any time. They surmised that any variations in the background or proton distribution caused by changing altitude, time of day, temperature, or changing GCR spectra were small and would be averaged-out by multiple observations over each location on Moon. Our findings here call into question these assumptions, and offer a significantly improved method for future mapping studies.

Culled LET spectra: Rather than assuming fixed lineal energy transfer (LET) proton tracks and fixed background LET spectra, we create sparsely-populated cross-plots, cull half of the detection events to select for only one direction of arrival (zenith or nadir) and then co-add the cross-plots into one-dimensional LET spectra, resulting in good signal-to-noise ratios, as shown in Figure 1. In this form it is possible to accurately fit a model to a background LET spectrum for only a small amount of data, meaning we can apply different background fitting parameters for data covering particular local times, or locations, or both. Thus we can unambiguously and accurately subtract out the background, resulting in a proton-only spectrum, and we can account for changes in the exponential shape or magnitude of the background spectrum between any two subsets of data.

Maximum likelihood fitting method: With sufficiently small subsets of CRaTER data, the number of detection events at higher LET channels can be low enough (< 10 events per channel) to preclude least-squares fitting methods that assume Gaussian statistical distributions. We therefore use an iterative maximum likelihood method to fit a two-parameter exponential function to the background, in the manner of Schwadron et al.[4]

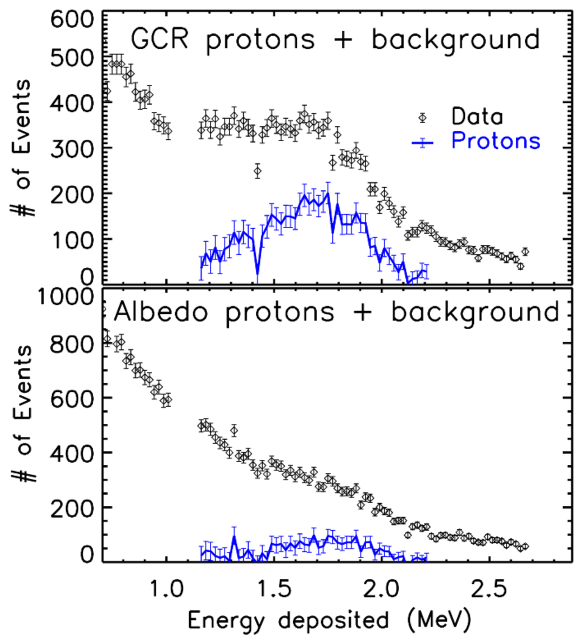

Figure 1. Culled LET spectra (black) and proton-only LET spectra (blue) for cosmic ray protons (top) and lunar albedo protons (bottom) detected by the CRaTER instrument in ~200 hours of dawn observations over the longitudes of Oceanus Procellarum. We fit a two-parameter exponential function to the background on either side of the proton bump, and subtract it to obtain a proton LET spectrum. This method can properly account for any large variations in the background LET spectrum.

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THE "MOON VILLAGE" CONCEPT AND INITIATIVE. Jan Woerner (1), Bernard Foing (2,3) and Moon Village International Support Group, [1]ESA Headquarters, [2]ESA ESTEC, [3]ILEWG (Bernard.Foing@esa.int)

Abstract: ESA is currently elaborating the concept of a Moon Village with the goal of a sustainable human presence and activity on the lunar surface [1-3] as an ensemble where multiple users can carry out multiple activities, This enterprise can federate all interested Nations and partners. The Moon represents a prime choice for political, programmatic, technical, scientific, operational, economical and inspirational reasons.

Why the Moon Village? The Moon Village has the ambition to serve a number of objectives (including planetary science, life sciences, astronomy, fundamental research, resources utilization, human spaceflight, economic development, etc.) to the community and should be the catalyst of new alliances between public and private entities including non-space industries. Additionally the Moon Village should provide a strong inspirational, capacity building, workforce development and education tool for the younger generations .

Previous projects relevant to Moon Village. Future space exploration is building on the International Space Station, and on the current and upcoming automatic and planetary robotic missions. COSPAR and its ILEWG International Lunar Exploration Working Group (created 20 years ago) have been supporting opportunities of collaboration between lunar missions and exchange on future projects [4-8]. A flotilla of lunar orbiters has been deployed for science and reconnaissance in the last international lunar decade (SMART-1, Kaguya, Chang'E1&2, Chandrayaan-1, LCROSS, LRO, GRAIL, LADEE). De facto, collaborative opportunities and elements of a Robotic Village on the Moon exist, as China landed in 2013 the Chang'E3 and its Yutu rover, and from 2017 other landers are planned (GLXP, Chang'E 4&5, SLIM, Luna 25-27, LRP, etc..)

Precursor MoonVillage studies and activities. The MoonVillage discussions are also based on the current activities and plans on board the ISS and the previous roadmaps and studies held in international groups [4-15] such as COSPAR, ILEWG, ISECG, IAF, IAA or national and regional groups (eg LEAG). We shall present the status of these reflections, and give an overview of on-going activities being carried out to enable the vision and implementation of a Moon Village.

How to build the Moon Village and with whom? The Moon Village will rely both on automatic, robotic and human-tendered structures to achieve sustainable moon surface operations serving multiple purposes on an open-architecture basis [1-3]. This Europe-inspired initiative should rally all communities (across disciplines, nations, industries, partners, individuals) and could put it on the top of political agendas as a scientific and technological. but also political and inspirational endeavor for the XXI century.

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PLANETARY VOLATILES EXTRACTOR (PVEX) FOR IN SITU RESOURCE UTILIZATION (ISRU) ON THE MOON. K. Zacny[1], S. Indyk[1], K. Luczek[1], A. Paz, [1]Honeybee Robotics, 398 W. Washington Ave, Suite 200, Pasadena, CA 91103, zacny@honeybeerobotics.com, [2]NASA Johnson Space Center,

Introduction: In Situ Resource Utilization (ISRU) uses local resources to sustain operations (either human or robotic) on extraterrestrial bodies [1]. In a conventional ISRU approach, feedstock is mined, transported to a processing plant, and resource is extracted. Planetary Volatiles Extraction (PVEx) offers an alternative approach that combines mining and extraction into one step and eliminates energy intensive and time consuming transport. We investigated three approaches: "Sniffer", Mobile In Situ Water Extraction (MISWE), and Corer. All three use a drill to penetrate subsurface; which can successfully penetrate regolith saturated with water-ice (worst case material) [2].

Sniffer: The Sniffer is a deep fluted auger with perforated walls. Walls are heated and holes allow for water vapor to flow into the auger and up into a volatiles collection system on the surface.

MISWE/Auger: The MISWE approach, consists of the Icy-Soil Acquisition and Delivery System (ISADS) and the Volatiles Extraction and Capture System (VECS) [3]. The ISADS is a deep fluted auger that retains material within the flutes. The VECS consists of a cylindrical heat exchanger and volatiles transfer system (a reactor). The material on the deep flutes is heated; water sublimes away and flows into a water collection canister, where it re-condenses.

Corer: The Corer is a dual wall coring auger [4]. The outer wall is an auger with shallow flutes, made of low conductivity composite. The inner cylinder is perforated and covered with heaters. The corer penetrates subsurface and captures a core. Heaters are turned on, heat up the core and sublime volatiles within the core. Volatiles then flow within the annual space and into a cold trap on the surface.

Test Results: We perfromed many tests inside a vacuum chamber with a JSC-1a lunar analog simulant. Sniffer did not work well; volatiles escaped through the soil and into the vacuum. MISWE was better in terms of water extraction efficiency and energy conversion efficiency. However, the Corer was the best.

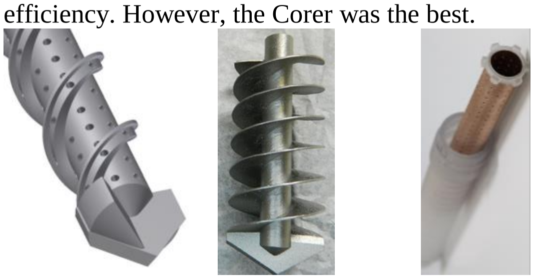

Figure1. Sniffer, MISWE, Corer.

Table 1. Trade study

		Sniffer	MISWE	Corer
Energy Efficiency [Whr/g]	**Min**	1.8	1.3	1.5
	Max	83	5.4	4.4
	Avg	**36**	**2.6**	**2.2**
	StDev	30	1.0	0.8
Water Recovery [%]	**Min**	0.1	18	31
	Max	4.6	78	87
	Avg	**1.2**	**44**	**65**
	StDev	1.7	16	17

Figure 4. Captured water from Corer.

PVEx Corer: The Corer takes advantage of many components developed for the Resource Prospector (RP) drill. With a goal of 30 kg per day the system would need one rover with four Corer systems assuming in-situ material has 12 wt% water saturation (maximum for JSC-1a). The energy per daily operation would be approx. 3.7 kWh supplied as heat (3.4 kWhr) and electircity (0.3 kWh) from MMRTG [4].

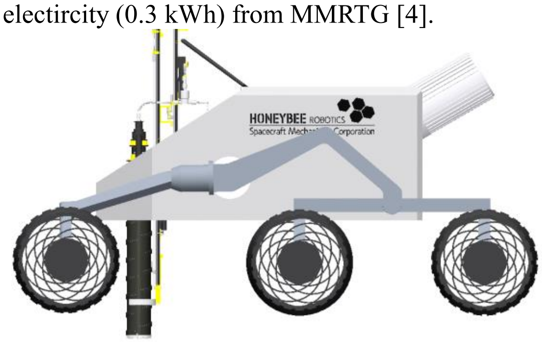

Figure 5. PVEx-Corer Design.

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Grain-scale supercharging on the Moon

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Idealized theory, computer simulations [1], and lab experiments [2] suggest that very strong electric fields - six orders of magnitude greater than predicted by classical plasma sheath theory - can develop in the tiny spaces between lunar grains. Nature tries to short-circuit this "supercharging" effect by allowing current to leak through grain interiors. It is predicted that dielectric breakdown occurs much more frequently and at far lower latitudes than previously thought. Since breakdown is expected to change the exterior appearance of grains [3], supercharging is possibly an important component of space weathering on airless regoliths.

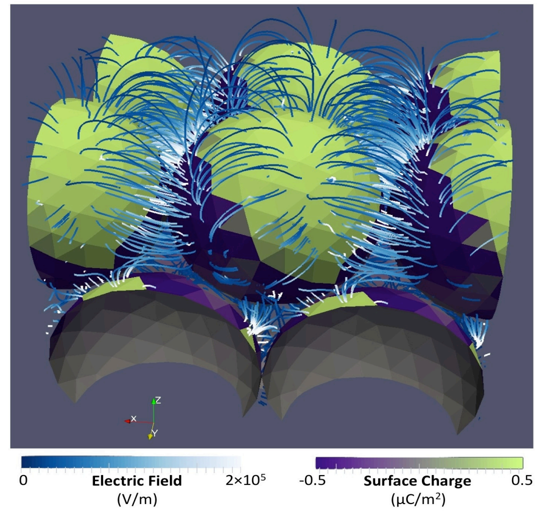

Figure: Surface charge level (colors) and electric field (lines) after 3 seconds of photoemission, under 45° noon-like solar illumination. Note the max field strength has already reached about 20% the nominal dielectric breakdown level.

Lunar regolith and rocks have a well-known exponential relationship between temperature and electrical conductivity. It is shown that the estimated timescale to reach equilibrium τ_{eq} (between supercharging and conductive dissipation through a grain) is shortest on the dayside where the regolith is hot and conduction is relatively high (and fast-acting). For some lunar grains packed tightly in the regolith, and under direct noon-like solar wind bombardment and photoemission, the timescale to reach dielectric breakdown τ_{brkdn} can drop below τ_{eq}. This means that diurnal "sparking" through a grain (breakdown) can occur before the slower process of "bulk" charge dissipation is able to cancel the charge accumulated on the grain's exterior. In some cases, τ_{brkdn} and τ_{eq} are longer than a half-lunar day, meaning that neither breakdown nor equilibrium can be achieved.

The balance between surface charging, internal conduction, and breakdown depends upon grain geometries and sizes, latitude-, topography-, and time-dependent plasma and illumination conditions, and internal grain conductivity. Most of these factors are still under investigation, but suggestions will be made regarding which parameters to measure in future experiments, including the timescales mentioned above. Gaining a better understanding of internal conduction through and between individual grains, and how it interacts with surface charging, will be a crucial part of future simulations (and hopefully future lab experiments and missions).

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[2] Wang, X., et al. (2016), "Dust charging and transport on airless planetary bodies", GRL, 43.
[3] Jordan, A. P, et al. (2014), "Deep dielectric charging of regolith within the Moon's permanently shadowed regions", JGR Planets, 119.

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LUNAR COTS: USING THE MOON'S RESOURCES TO ENABLE AN ECONOMICAL AND SUSTAINABLE PATHWAY TO MARS AND BEYOND. A. F. Zuniga[1] and D. J. Rasky[1], R. B. Pittman[2], [1]NASA Ames Research Center, Moffett Field, CA (allison.f.zuniga@nasa.gov), [2]Lockheed, NASA Ames Space Portal Office, Moffett Field, CA.

Introduction: To support NASA's goal of sending humans to Mars, a new plan was constructed to develop and demonstrate cislunar capabilities and services in partnership with commercial industry using the well-proven Commercial Orbital Transportation Services (COTS) Program acquisition model. The NASA COTS Program was a very successful program that developed and demonstrated cost-effective commercial cargo transportation services to the International Space Station (ISS). As a result of NASA's COTS program, two new launch vehicles and spacecraft were developed and have been successfully performing cargo transportation missions to the ISS since 2012. The COTS acquisition strategy utilized a new model than normally accepted in traditional procurement practices. This new model used Space Act Agreements where NASA entered into partnerships with industry to jointly share cost, development and operational risks to demonstrate new capabilities for mutual benefit. This model proved to be very beneficial to both NASA and its industry partners as NASA saved significantly in development and operational costs, as much as tenfold, while industry partners successfully expanded their market share of the global launch transportation business for significant economic benefit.

Using the COTS acquisition model as a basis, a new plan, notionally referred to as Lunar Commercial Orbital *Transfer* Services (or Lunar COTS), has been developed to determine the potential benefits and challenges of a new Lunar COTS plan[1]. The proposed plan includes low-cost, commercial-enabled missions to prospect for resources, determine the economic viability of extracting those resources and assess the value proposition of using these resources in future exploration architectures such as Mars. These missions would be accomplished in partnership with industry to meet these exploration goals but will also have the capability to carry payloads to meet science goals as well.

As noted in several references, there are a wide variety of lunar resources in the lunar regolith that can be useful to NASA's long-term human exploration missions to Mars and beyond. One major example is water-ice concentrations in the permanently shadowed regions of the lunar poles. Several remote-sensing, lunar missions in the last two decades including DOD's and NASA's Clementine mission launched in 1994; NASA's Lunar Prospector mission launched in 1998; NASA's Lunar Reconnaissance Orbiter (LRO) [2] launched in 2009 and NASA's Lunar Crater Observation and Sensing Satellite (LCROSS) [3] mission launched in 2009 have all indicated the presence of water-ice deposits at the lunar poles. Although these data are strong indications that the presence of water-ice is plentiful at the poles, ground truth data is needed to validate these results and determine the composition, distribution, depth and accessibility of these areas with high concentrations of lunar ice.

Several studies have also examined the In-Situ Resource Utilization (ISRU) processes and facilities necessary to extract and convert the lunar water into LO2 and LH2 propellants. These studies have also provided cost estimates for putting the infrastructure in place for creating the propellant and then delivering it to a cislunar propellant depot for use in a future Mars architecture. Although these studies have provided an excellent strategy and approach for creating propellant on the lunar surface, ground truth data from the Moon is needed to determine the exact methods, tools and machinery needed to extract the lunar ice and create the propellant for a more refined cost estimate. It is also best to obtain this ground truth data and develop extraction techniques in partnership with industry to share cost and risk as well as leverage on industry's capabilities and innovativeness in a competitive environment employing the COTS acquisition model.

Over the past few decades, several architectures for the Moon and Mars have been proposed and studied but ultimately halted or not even started due to the projected costs significantly exceeding NASA's budgets. Therefore a new strategy is needed that will fit within NASA's projected budgets and takes advantage of commercial industry along with its creative and entrepreneurial attributes. The Lunar COTS plan presents a cost-effective approach to partner with industry to establish low-cost cislunar capabilities and services, such as, lunar transportation, lunar mining and lunar ISRU operations. These capabilities and services may enable development of an affordable and economical exploration architecture for future missions to Mars and beyond. This paper will describe a plan for a proposed LCOTS program, its potential impact to an eventual Mars architecture and its many benefits to NASA, commercial space industry and the science community.

References:

[1] Zuniga et al, AIAA Paper 2015-4408, AIAA Space 2015 Conference, Sep 2015. [2] Spudis et al 2013 Journal of Geophysical Research; [3] Colaprete et al 2010, SCIENCE Journal;