ANNUAL MEETING OF THE
LUNAR EXPLORATION ANALYSIS GROUP (LEAG)

Program and Abstracts
LPI Contribution No. 2635
Annual Meeting of the 
Lunar Exploration Analysis Group (LEAG) 
August 31–September 2, 2021 
Virtual

Institutional Support 
Lunar and Planetary Institute 
Universities Space Research Association

Convener 
Amy Fagan 
Western Carolina University

Science Organizing Committee 
Erica Jawin 
Smithsonian National Museum of Natural History 
Amy Fagan 
Western Carolina University 
Ben Greenhagen 
Johns Hopkins University, Applied Physics Laboratory 
Kristen Bennett 
United States Geological Survey 
Sarah Valencia 
NASA Goddard Space Flight Center
Abstracts for this meeting are available via the meeting website at

https://www.hou.usra.edu/meetings/leag2021/

Abstracts can be cited as

ALL TIMES LISTED ARE U.S. EASTERN DAYLIGHT TIME (EDT).

**Tuesday, August 31, 2021**
- 10:30 a.m. Day 1 Welcome Address
- 10:45 a.m. NASA HQ Updates
- 11:15 a.m. NASA SMD Community Updates Panel
- 12:40 p.m. LEAG Service Award and Featured Early Career Presentation
- 1:10 p.m. Artemis Updates: Artemis First Landed Mission
- 2:45 p.m. Decadal Survey Updates
- 3:05 p.m. Highlights from Lunar Reconnaissance Orbiter and Next Generation Concepts

**Wednesday, September 1, 2021**
- 11:00 a.m. Day 2 Welcome Address
- 11:15 a.m. International Lunar Exploration in the Next 12 Months
- 12:20 p.m. Artemis 1 Payloads
- 2:00 p.m. Future Lunar Mission Updates
- 3:05 p.m. CLPS Updates
- 4:10 p.m. Lunar Surface Science and Exploration Goals
- 5:05 p.m. Social Hour on Gather.town

**Thursday, September 2, 2021**
- 11:00 a.m. Day 3 Welcome Address
- 11:35 a.m. Bringing the Lunar Community Together
- 1:30 p.m. Future Lunar Assets and Concepts Part 1 (Science)
- 2:15 p.m. Future Lunar Assets and Concepts Part 2 (Technology)
- 3:00 p.m. Future Lunar Sample Analysis Assets and Concepts
- 3:55 p.m. Draft Findings
# Annual Meeting of the Lunar Exploration Analysis Group (LEAG)

## Day 1 Welcome Address

**Chair:** Amy Fagan

<table>
<thead>
<tr>
<th>Time</th>
<th>Denotes Presenter</th>
<th>Presentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:30 a.m.</td>
<td>Fagan A. *</td>
<td>Welcome Address</td>
</tr>
<tr>
<td>10:37 a.m.</td>
<td>Stadermann A. *</td>
<td>Lunar Next Generation Scientists and Engineers</td>
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</tbody>
</table>

## NASA HQ Updates

**Chair:** Amy Fagan

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<thead>
<tr>
<th>Time</th>
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<tbody>
<tr>
<td>10:45 a.m.</td>
<td>Green J. L. *</td>
<td>A Future as Bright as the Full Moon</td>
</tr>
<tr>
<td>11:00 a.m.</td>
<td></td>
<td>Community Q&amp;A</td>
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## NASA SMD Community Updates Panel

**Moderator:** Ben Greenhagen  
**Panel Members:**  
Lori Glaze  
Craig Kundrot  
Paul Hertz  
Jamie Favors  
Sandra Cauffman

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<tr>
<th>Time</th>
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<th>Presentation</th>
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<tbody>
<tr>
<td>11:15 a.m.</td>
<td>Glaze L. *</td>
<td>Planetary Science Division Update <strong>Pre-recording</strong></td>
</tr>
<tr>
<td>11:18 a.m.</td>
<td>Kundrot C. *</td>
<td>Biological and Physical Science Division Update <strong>Pre-recording</strong></td>
</tr>
<tr>
<td>11:21 a.m.</td>
<td>Hertz P. *</td>
<td>Astrophysics Division Update</td>
</tr>
<tr>
<td>11:24 a.m.</td>
<td>Favors J. *</td>
<td>Heliophysics Division Update <strong>Pre-recording</strong></td>
</tr>
<tr>
<td>11:27 a.m.</td>
<td>Cauffman S.</td>
<td>Earth Science Division Update</td>
</tr>
</tbody>
</table>
Tuesday, August 31, 2021
LEAG SERVICE AWARD AND FEATURED EARLY CAREER PRESENTATION
12:40 p.m. EDT
Chair: Sam Lawrence

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<tr>
<th>Times</th>
<th>* Denotes Presenter</th>
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<tbody>
<tr>
<td>12:40 p.m.</td>
<td>Lawrence S. *</td>
<td>Presentation of the LEAG Service Award</td>
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<tr>
<td>12:45 p.m.</td>
<td>TBD</td>
<td>LEAG Service Award Featured Presentation</td>
</tr>
<tr>
<td>12:55 p.m.</td>
<td>Lawrence S. *</td>
<td>Featured Early Career Presentation Introduction</td>
</tr>
<tr>
<td>1:00 p.m.</td>
<td>Morrissey L. S. * Saxena P. Curran N. McClain J. Killen R. M.</td>
<td>In-Situ Artificial Substrate Witness Plates: Ground Truthing Scientific and Human Operations Relevant Processes on the Moon [#5015]</td>
</tr>
</tbody>
</table>

In this study, we investigated the potential of using an artificial substrate-based witness plate to capture location dependent lunar processes. These plates are low cost, low mass, and produce a low environmental footprint.

Tuesday, August 31, 2021
ARTEMIS UPDATES: ARTEMIS FIRST LANDED MISSION
1:10 p.m. EDT
Chairs: Clive Neal and Jessica Barnes

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<tr>
<th>Times</th>
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<th>Presentation</th>
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<tbody>
<tr>
<td>1:10 p.m.</td>
<td>Budde M. J. *</td>
<td>Artemis 1 and 2 Updates</td>
</tr>
<tr>
<td>1:20 p.m.</td>
<td>Robinson J. *</td>
<td>HEOMD Updates</td>
</tr>
<tr>
<td>1:25 p.m.</td>
<td>Werkheiser N. *</td>
<td>STMD Updates</td>
</tr>
<tr>
<td>1:30 p.m.</td>
<td>Bleacher J. * Noble S. *</td>
<td>Incorporating Science Goals and Objectives into Artemis</td>
</tr>
<tr>
<td>1:35 p.m.</td>
<td>Weber R. *</td>
<td>Science Definition Team Report Overview</td>
</tr>
<tr>
<td>1:40 p.m.</td>
<td>Kearns J. *</td>
<td>LDEP Update</td>
</tr>
<tr>
<td>1:45 p.m.</td>
<td></td>
<td>Community Q&amp;A</td>
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<tr>
<td>2:20 p.m.</td>
<td></td>
<td>BREAK</td>
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### DECADAL SURVEY UPDATES

**2:45 p.m. EDT**

**Chairs:** Hannah Sargeant and Amy Fagan

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<th>Times</th>
<th>* Denotes Presenter</th>
<th>Presentation</th>
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<tbody>
<tr>
<td>2:45 p.m.</td>
<td>Canup R. * Christensen P. *</td>
<td>Update on the Decadal Process</td>
</tr>
<tr>
<td>2:50 p.m.</td>
<td>Grove T. *</td>
<td>Update on the “Panel on Mercury and the Moon”</td>
</tr>
<tr>
<td>2:55 p.m.</td>
<td></td>
<td>Community Q&amp;A</td>
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### HIGHLIGHTS FROM LUNAR RECONNAISSANCE ORBITER AND NEXT GENERATION CONCEPTS

**3:05 p.m. EDT**

**Chairs:** Catherine Elder and Caitlin Ahrens

<table>
<thead>
<tr>
<th>Times</th>
<th>Authors (*Denotes Presenter)</th>
<th>Abstract Title and Summary</th>
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<tbody>
<tr>
<td>3:05 p.m.</td>
<td>Petro N. E. * Elder C. M. Stopar J. Banks M. Keller J.</td>
<td><strong>The Lunar Reconnaissance Orbiter in 2021 and Beyond: Status and Future Plans</strong> [#5030] LRO is in its 12th year at the Moon, enabling new science, observing changes to the lunar surface and environment over the human timescale. Our ability to respond to data requests in support of missions to the surface is a critical resource for NASA.</td>
</tr>
<tr>
<td>3:10 p.m.</td>
<td>Stopar J. D. * Banks M. E. Elder C. M. Keller J. W. Petro N. E. Stopar J. A. M. The LRO Team</td>
<td><strong>New LRO Investigations of Volcanism, Tectonism, and the Lunar Interior</strong> [#5032] LRO will collect new data needed to answer evolving science questions about the lunar interior, volcanism, and tectonics, as well as provide additional orbital context for the forthcoming era of lunar exploration.</td>
</tr>
<tr>
<td>3:25 p.m.</td>
<td>Banks M. E. * Elder C. M. Keller J. W. Petro N. E. Stickle A. M. Stopar J. D.</td>
<td><strong>LRO Support for Lunar Surface Exploration</strong> [#5051] LRO continues to serve the lunar community and facilitate lunar surface exploration with a wealth of data products and PDS-archived data (data volume of &gt;1.2 PB), and ongoing acquisition of Constellation-site-quality observations.</td>
</tr>
<tr>
<td>3:30 p.m.</td>
<td>Barker M. K. * Mazarico E. Smith D. E. Sun X. Zuber M. T. Neumann G. A. Head J. W.</td>
<td><strong>New High Resolution Polar Topographic Products from the Lunar Orbiter Laser Altimeter (LOLA)</strong> [#5033] We are creating new high-resolution (5 m/pix) topographic models of high-priority south pole sites based only on laser altimetry data acquired by the Lunar Orbiter Laser Altimeter (LOLA) onboard the Lunar Reconnaissance Orbiter (LRO).</td>
</tr>
</tbody>
</table>
### Radiation Dosage from Solar Energetic Particles Around a Lunar Crater

The level of radiation exposure at a given location on the Moon is dependent on the amount incident from above the local horizon. Here we consider the radiation exposure around simple lunar craters that are representative of the types of landforms that will be encountered by future landed missions.

### A Next-Generation Lunar Orbiter to Support Lunar Science and Exploration

NASA should consider post-LRO remote sensing strategies for lunar remote sensing. I present a notional payload for a Next-Generation Lunar Orbiter and tie measurements that would be enabled by such a mission to lunar science and exploration goals.
### ARTEMIS 1 PAYLOADS

**Times** | * Denotes Presenter | Presentation
--- | --- | ---
12:20 p.m. | Kunkel S. R. * | Artemis 1 Overview and Payload
12:25 p.m. | Di Tana V. * | ArgoMoon
12:28 p.m. | Hashimoto T. * | EQUULEUS
12:31 p.m. | Hashimoto T. * | OMOTENASHI
12:34 p.m. | Santa Maria S. * | BioSentinel
12:37 p.m. | Desai M. * | CuSP
12:40 p.m. | Hardgrove C. * | LunaH-Map
12:43 p.m. | Hayne P. * | Lunar Flashlight
12:46 p.m. | Ricks J. M. * | LunIR
12:49 p.m. | Faler W. * | Team Miles
12:52 p.m. | Malphrus B. * | Lunar IceCube
12:55 p.m. | **Community Q&A**
1:08 p.m. | **BREAK**

### FUTURE LUNAR MISSION UPDATES

**Times** | * Denotes Presenter | Presentation
--- | --- | ---
2:00 p.m. | Colaprete T. * | VIPER Updates
2:05 p.m. | Ehlmann B. * | Lunar Trailblazer Updates
2:10 p.m. | Dudzinski L. * | RPS Development and the Importance of Pu-238
2:15 p.m. | **Community Q&A**
2:30 p.m. | Needham D. | PRISM Overview
2:35 p.m. | Blewett D. * | Lunar Vertex Overview
2:40 p.m. | Panning M. * | Farside Seismic Suite
Wednesday, September 1, 2021

CLPS UPDATES
3:05 p.m. EDT

**Moderator:** Elizabeth Frank  
**Panel Members:** Dan Hendrickson  
Trent Martin  
Colin Ake  
Will Coogan

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<tr>
<td>3:05 p.m.</td>
<td>Frank E. *</td>
<td><em>Introductions</em></td>
</tr>
<tr>
<td>3:10 p.m.</td>
<td>Hendrickson D. *</td>
<td><em>Astrobotic Updates</em></td>
</tr>
<tr>
<td>3:15 p.m.</td>
<td>Martin T. *</td>
<td><em>Intuitive Machines Updates</em></td>
</tr>
<tr>
<td>3:20 p.m.</td>
<td>Ake C. *</td>
<td><em>Masten Updates</em></td>
</tr>
<tr>
<td>3:25 p.m.</td>
<td>Coogan W. *</td>
<td><em>Firefly Updates</em></td>
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<td>3:30 p.m.</td>
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<td><em>Community Q&amp;A</em></td>
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<td>3:45 p.m.</td>
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<td><em>BREAK</em></td>
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**Wednesday, September 1, 2021**  
LUNAR SURFACE SCIENCE AND EXPLORATION GOALS  
4:10 p.m. EDT

**Chairs:** Timothy Glotch and Dina Bower

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<tr>
<th>Times</th>
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*Science Rationale [#5028]*  
Rationale for landing sites for the Lunar Geophysical Network (LGN) mission is highlighted. Returning to the lunar surface with a long-lived geophysical network is a key next step to advance lunar and planetary science. |
An international lunar resource prospecting campaign allows data to be collected that inform the reserve potential of such resources in compliance with the Outer Space Treaty. |
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<th>Presenter(s)</th>
<th>Presentation Title</th>
<th>Summary</th>
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<tbody>
<tr>
<td>4:20 p.m.</td>
<td>Howley I. J. * Byars M. K.</td>
<td>Advancing Operational and Training Techniques for Artemis Missions [#5010]</td>
<td>MSFC has integrated and operated the scientific payloads that are essential to human spaceflight. This abstract lays clear the challenges and proposes the elements necessary to achieve the aspirational scientific goals set out by the Artemis program.</td>
</tr>
<tr>
<td>4:25 p.m.</td>
<td>Honniball C. I. * Lucey P. G. Reach W. T.</td>
<td>A Legacy of Lunar Water Through SOFIA [#5017]</td>
<td>We have preliminary approval from SOFIA to conduct a two-year Legacy campaign to map water on the sunlit Moon. We will sample a large fraction of the surface and volcanic features to identify areas of concentrated water for possible landing sites.</td>
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<tr>
<td>4:30 p.m.</td>
<td>Bower D. M. * Livengood T. L. Barker M. A. Honniball C. I. Hewagama T.</td>
<td>Gruithusien Domes: Insights from Silicate Mineralogy and Surface Textures [#5023]</td>
<td>A landed mission to GD should emphasize techniques that clarify variations in silica mineralogy to identify different types of silicic minerals and glasses at the surface including Raman spectroscopy, micro-morphometric analysis, and thermal imaging.</td>
</tr>
<tr>
<td>4:35 p.m.</td>
<td>Costello E. S. * Lucey P. G. Ghent R. R.</td>
<td>Knowledge of Impact Gardening is Necessary to Understand the History of Lunar Ice [#5007]</td>
<td>Models of impact gardening reveal the history and context of cores and can help us interpret the history of lunar ice.</td>
</tr>
<tr>
<td>4:40 p.m.</td>
<td>Bremner P. M. * Haviland H. F. Mallik A. Diamond M.</td>
<td>The Unresolved Problem with Deriving a Lunar Temperature Profile from Heat Producing Elements [#5052]</td>
<td>This work is about calculating whole-Moon 1D thermal profiles. The focus of this presentation is to highlight how including internal heating contributions from current estimates of radioactive decay produce hot, or extremely hot selenotherms.</td>
</tr>
<tr>
<td>4:45 p.m.</td>
<td>Head J. W. * Scott D. R.</td>
<td>12 Action Items for Optimizing Human Exploration and Lunar Science in the Next 5 Years [#5022]</td>
<td>We identify 12 themes/objectives for the next 5 years to optimize chances of collecting a representative sample of the Moon outside the Apollo-Luna exploration region, with emphasis on obtaining samples of South Pole-Aitken (SPA) Basin ejecta.</td>
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<td>4:50 p.m.</td>
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<td>Community Q&amp;A</td>
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Wednesday, September 1, 2021
SOCIAL HOUR ON GATHER.TOWN
5:05 p.m. EDT
Chair: Amy Fagan

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| 5:05 p.m. | Fagan A. * | Day 2 Wrap-Up and Transition to Gather.town
Meet and greet with meeting attendees, including a networking session with Artemis 1 payload presenters |
Thursday, September 2, 2021
DAY 3 WELCOME ADDRESS
11:00 a.m. EDT
Chair: Erica Jawin

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<tr>
<td>11:00 a.m.</td>
<td>Jawin E. *</td>
<td>Welcome Address</td>
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<tr>
<td>11:05 a.m.</td>
<td></td>
<td>Community Updates</td>
</tr>
<tr>
<td>11:15 a.m.</td>
<td>Young K. *</td>
<td>LSSW Updates</td>
</tr>
<tr>
<td>11:25 a.m.</td>
<td>Stopar J. *  Stickle A. *</td>
<td>SAT Updates</td>
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Thursday, September 2, 2021
BRINGING THE LUNAR COMMUNITY TOGETHER
11:35 a.m. EDT
Moderator: Lisa Gaddis
Panel Members: Kelsey Young, Brad Bailey, Ben Bussey, Rachel Klima, Jacob Bleacher, Renee Weber, Joel Kearns, Amy Fagan, Greg Schmidt

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<tr>
<td>11:35 a.m.</td>
<td>Gaddis L. *</td>
<td>Introductions</td>
</tr>
<tr>
<td>11:40 a.m.</td>
<td>Young K. *  Bailey B. *</td>
<td>LSSW Overview</td>
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<tr>
<td>11:43 a.m.</td>
<td>Bussey B. *</td>
<td>LSII Overview</td>
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<tr>
<td>11:46 a.m.</td>
<td>Klima R. *</td>
<td>LSIC Overview</td>
</tr>
<tr>
<td>11:49 a.m.</td>
<td>Bleacher J. *</td>
<td>HEO Overview</td>
</tr>
<tr>
<td>11:52 a.m.</td>
<td>Weber R. *</td>
<td>Artemis 3 SDT Overview</td>
</tr>
<tr>
<td>11:55 a.m.</td>
<td>Kearns J. *</td>
<td>ESSIO Overview</td>
</tr>
<tr>
<td>11:58 a.m.</td>
<td>Fagan A. *</td>
<td>LEAG Overview</td>
</tr>
<tr>
<td>12:01 p.m.</td>
<td>Schmidt G. *</td>
<td>SSERVI Overview</td>
</tr>
<tr>
<td>12:04 p.m.</td>
<td>Gaddis L. *</td>
<td>Moderated Q&amp;A</td>
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<tr>
<td>12:40 p.m.</td>
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<td>BREAK</td>
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<td>Times</td>
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<tr>
<td>1:30 p.m.</td>
<td>Kessler P. D. *</td>
<td>NASA Lunar Surface Habitat: Enabling a Sustained Lunar Presence [#5026] This lunar Surface Habitat (SH) topic will provide an overview of the Surface Habitat as an anchor to establishing a sustained lunar presence and the challenges faced operating on the lunar surface.</td>
</tr>
<tr>
<td>1:40 p.m.</td>
<td>Lolachi R. * Glenar D. A. Stubbs T. J.</td>
<td>Optical Monitoring of the Dust Environment Around Lunar Exploration Sites [#5011] A model study of whether it is possible to build an optical dust monitoring camera, using commercial off-the-shelf image sensors with wide-field optics, for use at exploration sites for science and human safety. Our results show that it is possible.</td>
</tr>
<tr>
<td>1:45 p.m.</td>
<td>Wang X. * Sternovsky Z. Horanyi M. Deca J. Garrick-Bethell I. Farrell W. M. Minafra J. Bucciantini L.</td>
<td>Electrostatic Dust Analyzer (EDA) for Measuring Dust Transport on the Lunar Surface [#5019] The Electrostatic Dust Analyzer (EDA) will quantitatively measure electrostatically lofted lunar dust in order to provide insights into its effects on the lunar surface properties and assess potential risks posed by lofted dust to human exploration.</td>
</tr>
<tr>
<td>1:50 p.m.</td>
<td>Patrick E. L. * Blase R. L.</td>
<td>Environmental Analysis of the Bounded Lunar Exosphere (ENABLE): Analytical Chemistry in Extreme High Vacuum (XHV) [#5044] A prototype mass spectrometer is being developed for lunar surface operations from a commercial off-the-shelf (COTS) instrument with wide pressure, mass range, and target mass capabilities and operable in a number of lunar mission scenarios.</td>
</tr>
<tr>
<td>1:55 p.m.</td>
<td>Morrison C. G. *</td>
<td>Intense Passive Commercial X-Ray Sources for Chemical and Elemental Analysis [#5049] USNC-Tech is developing radioisotope technology for heat and electricity called the Chargeable Atomic Battery (CAB). However, the same technology can be used to generate sources of passive X-rays larger than has traditionally been used.</td>
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<tr>
<td>2:00 p.m.</td>
<td></td>
<td>Community Q&amp;A</td>
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<tr>
<td>2:15 p.m.</td>
<td>Meurisse A. * Mousel J. Kapoglou A. Conti M. Makaya A. Cowley A. Carpenter J. Link M. Hufenbach B.</td>
<td><strong>Utilization Scenarios — Outcome of the Space Resources Week 2021 [#5024]</strong>&lt;br&gt;The European Space Agency (ESA) and Luxembourg Space Agency (LSA) gathered the international community at the Space Resources Week 2021 to discuss future Utilization Scenarios. This talk presents the outcome of the discussion groups.</td>
</tr>
<tr>
<td>2:25 p.m.</td>
<td>Muhlberger C. D. *</td>
<td><strong>Cislunar Explorers: A Student Cubesat Demonstrating Low-Cost Technologies for Lunar Exploration [#5054]</strong>&lt;br&gt;Developed in 2014 by students at Cornell, the Cislunar Explorers mission proposes to send a pair of 3U CubeSats to lunar orbit and demonstrate new technologies for water electrolysis propulsion and optical navigation in cislunar space.</td>
</tr>
<tr>
<td>2:30 p.m.</td>
<td>Backus S. B. * Moreland S. Kerber L. McCormick R.</td>
<td><strong>Design and Use of the Cold Operable Lunar Deployable Arm End Effector for Geotechnical Investigations [#5035]</strong>&lt;br&gt;The Cold Operable Lunar Deployable Arm is a Lunar tech demo that consists of a robotic arm and end effector (EE). Here we present the design of the end effector and how it can be used to perform basic excavation and geotechnical surface interactions.</td>
</tr>
<tr>
<td>2:35 p.m.</td>
<td>Gemer A. J. * Cyrus J. A. Meyen F. Cyrus J. B.</td>
<td><strong>Advances in Lunar Science Return via Distributed Instrument Mobility and Swarm Robotics: The Lunar Outpost Mobile Autonomous Prospecting Platform (MAPP) Rovers [#5018]</strong>&lt;br&gt;Lunar Outpost has developed the MAPP rover to enable suites of instruments to be deployed in multi-instrument campaigns across multiple small rovers, deploying large instrument networks and investigating science sites in high resolution.</td>
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<td>2:40 p.m.</td>
<td>Whitaker T. J. L. * Rampolla C. De La Fuente C. C. Provenzano M.</td>
<td><strong>Lunar Mobility as a Service in the Next Five Years: A Software Perspective [#5043]</strong>&lt;br&gt;Astrobotic’s developments of the CubeRover mobility platform and Lunar Mobility as a Service model have provided insights to the software ecosystem that will begin to emerge as lunar surface operations are increased.</td>
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<td>2:45 p.m.</td>
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<td><strong>Community Q&amp;A</strong></td>
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<td>3:00 p.m.</td>
<td>Gross J. * Zeigler R. A. McCubbin F. M. Shearer C. ANGSA Science Team The.</td>
<td>From Apollo to Artemis: How ANGSA Helps Preparing for Future Sample Missions to the Moon and Beyond [#5031] Analyses of ANGSA samples with new tools and technologies will maximize the science return from Apollo and enable new generations of scientists and curators to refine their techniques and help prepare future explorers for future lunar missions.</td>
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<tr>
<td>3:05 p.m.</td>
<td>Gawronska A. J. * McLeod C. L. Gilmour C. M.</td>
<td>X-Ray Computed Tomography for the Analysis of Materials Collected at the Lunar South Pole [#5012] A variety of materials will be collected during future missions to the lunar south pole. We outline what materials may be collected and how the technique of X-ray computed tomography will help investigate these materials.</td>
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<td>3:20 p.m.</td>
<td>Barnes J. J. * Crow C. Jolliff B. L. Joy K. H. Lapen T. Gross J. Mitchell J. Zeigler R. Fagan A. L.</td>
<td>The Scientific Value of Lunar Sample Exchange [#5045] As we consider the future of lunar science and exploration, we emphasize the benefit of sample exchange and sample sharing between all nations. Here we draw attention to the past exchange of Apollo and Luna samples between different countries.</td>
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<td>3:25 p.m.</td>
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<td>Community Q&amp;A</td>
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Thursday, September 2, 2021
DRAFT FINDINGS
3:55 p.m. EDT
Chair: Amy Fagan

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<td>3:55 p.m.</td>
<td>Fagan A. *</td>
<td>Draft Findings</td>
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<td>4:25 p.m.</td>
<td>Fagan A. *</td>
<td>Wrap-Up</td>
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<tr>
<td>Acierno K. O'Neill K.</td>
<td><em>ispace’s 2022 Mission and Future Commercial Capabilities for Lunar Science Missions</em> [#5042] <em>ispacetechnologies U.S. will present how our U.S.-based advanced lander program will facilitate future landed science missions and advanced mobility options for the planetary science community over the next five years.</em></td>
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<tr>
<td>Anzalone E. J. Bone J. C.</td>
<td><em>Lunar Node 1 and Beyond</em> [#5005] <em>Lunar Node 1 is an S-band navigation beacon for lunar applications that was recently designed and built at Marshall Space Flight Center. This presentation will discuss the design, upcoming surface mission, and future development of this concept.</em></td>
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<td>Brooks T. E. Campbell P. S.</td>
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<td>Guillory A. R. Jensen J. V.</td>
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<td>Merrill G. W. Statham T. L.</td>
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<td>Battler M. M. Faragalli M.</td>
<td><em>Distributed Autonomy for Lunar Micro-Rovers — A Case Study for the Emirates Lunar Mission</em> [#5027] <em>In 2022, Mission Control will demonstrate AI-based lunar terrain classification using images from the Rashid micro-rover. This will support science and navigation operations, showcasing how these technologies can add autonomy for future lunar rovers.</em></td>
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<td>Cross M. Raimalwala K. Cole M.</td>
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<td>Smal E. Reid J. E. Cloutis E.</td>
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<td>Newman J. Skonieczny K.</td>
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<td>Blewett D. T. Halekas J. Ho G.</td>
<td><em>Lunar Vertex: A PRISM Mission to a Magnetic Anomaly</em> [#5016] <em>Lunar Vertex is a PRISM lander/rover mission to investigate the Reiner Gamma magnetic anomaly and related phenomena, including a minimagetosphere and a lunar swirl.</em></td>
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<td>Greenhagen B. T. Anderson B. J.</td>
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<td>Kollmann P. Denevi B. W. Meyer H. M.</td>
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<td>Eubanks T. M. Blase W. P.</td>
<td><em>Mote Lunar Penetrator Arrays for Rapid Exploration of Extreme Lunar Terrains</em> [#5036] Here we describe the “Mote” ballistic penetrators developed to support lunar science by allowing precursor missions to difficult to reach terrain, and through the rapid creation of instrument and communications arrays on the lunar surface.</td>
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<td>Grubbs R. P.</td>
<td><em>Replicating or Exceeding the Imagery from Apollo for Artemis Missions</em> [#5013] The Apollo Program is remembered in large part thanks to the iconic imagery produced during the missions. As we plan for humankind’s return to the Moon, there are significant challenges to replicate the quality of the imagery in the digital era.*</td>
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| Morrison C. G. | *Lunar Night Survival and Operation Utilizing Commercial Radioisotope Heaters and Electric Generators* [#5041]
Atomic batteries are enabling lunar operations. USNC-Tech is developing commercial watt-scale batteries looking to license and flight demo the technology around 2024. USNC-Tech is soliciting input from the science community. |
The science and exploration justification behind the Lunar Geophysical Network mission is given in this paper. |
| Page B., Bale S. D., Slosar A. | *A 21-cm Cosmology Experiment on the Far Side of the Moon* [#5040]
We simulated the galactic radio spectrum that would be measured by an antenna located at the Schrödinger Basin. A real antenna will measure this radiation and a weak background of cosmic H I emission. We explore how the H I signal might be detected. |
| Schubert P. J. | *Studies of In Situ Fissile Fuel from Lunar Resources* [#5003]
Lunar surface science for density sorting and neutron generation can be tested with lightweight hardware and modest tending. The outcome can prove technical feasibility of fueling a baseload fission plan on the Moon. |
The Lunar Autonomous Robotic Rover will permit documentation of Artemis science and exploration to be comprehensive, near-real-time, and representative of the advanced technological capabilities of the day. |
| Weber R. C., Dankanich J., Herrmann N. | *Lunar Science and Exploration at Marshall Space Flight Center* [#5020]
Under the Artemis program for lunar exploration, the Agency is planning an ambitious path forward to the Moon. NASA's Marshall Space Flight Center offers unique capabilities in propulsion, technology, engineering, science, and exploration. |
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Three-Dimensional Documentation of the Transition from Sand Ripples to Megaripples

J. R. Zimbelman, S. P. Scheidt, M. M. Baker, and E. Williams
Introduction:
The advent of the Commercial Lunar Payload Services (CLPS) program and the general maturation of lunar exploration is providing revolutionary access to the lunar surface for landed science missions. The Lunar Exploration Analysis Group (LEAG) has previously recognized the value of international and commercial partners and encourages the sharing of information between industry and academia.

ispace Background:
ispace inc. endeavors to expand humanity’s economic sphere beyond Earth by discovering and utilizing resources on the Moon. Utilization of lunar resources, particularly water ice, will be crucial to the economic development of cislunar space and enabling further human exploration to the Moon, Mars and beyond.

Over the past five years, ispace inc. has significantly expanded its global presence. In addition to further expanding our headquarters in Tokyo, ispace is proud to have created major subsidiaries in Luxembourg and, as of 2021, the United States. Over the next five years, ispace anticipates a regular cadence of lunar missions, beginning with the M1, M2, and M3 missions.

M1 & M2 Update
First, our presentation will update the lunar science community on progress made towards ispace’s M1 and M2 missions facilitated by the Hakuto-R lander currently undergoing assembly and integration in Tokyo and Germany. The presentation will provide an overview of the key science objectives accomplished by our upcoming missions and illustrate the payloads that will be flown to Lacus Somnorium and the Lunar South Polar regions.

Novel Capabilities Provided By M3 Lander
Next, we will describe advancements of ispace’s lunar program, showcasing advancements in lander and rover design. The presentation will detail ispace inc.’s expanded presence in the United States and the plans for our advanced lunar lander program, termed “Mission Three” (M3) which will feature significantly greater capability compared to existing offerings.

We intend to present how our U.S.-based advanced lander program will facilitate future landed science missions and advanced mobility options for the planetary science community over the next five years.

Specifically, we will discuss key lander design features that provide flexibility for lunar payload deployment in multiple regimes.
**Lunar Node 1 and Beyond.** E. J. Anzalone¹, J. C. Bone², T. E. Brooks³, P.S. Campbell⁴, A. R. Guillory⁵, J. V. Jenson⁶, G. W. Merrill⁷, and T. L. Statham⁸, ¹NASA Marshall Space Flight Center (evan.j.anzalone@nasa.gov), ²NASA Marshall Space Flight Center (jarret.l.bone@nasa.gov), ³NASA Marshall Space Flight Center (thomas.brooks@nasa.gov), ⁴NASA Marshall Space Flight Center (pat.campbell@nasa.gov), ⁵NASA Marshall Space Flight Center (anthony.r.guillory@nasa.gov), ⁶NASA Marshall Space Flight Center (jacob.v.jensen@nasa.gov), ⁷NASA Marshall Space Flight Center (garrick.merrill@nasa.gov), ⁸NASA Marshall Space Flight Center (tamara.l.statham@nasa.gov).

**Introduction:** Lunar Node 1 (LN-1) is an S-band navigation beacon for lunar applications that was recently designed and built at NASA Marshall Space Flight Center. As part of NASA’s Commercial Lunar Payload Services initiative, this beacon will be delivered to the moon's surface on Intuitive Machine’s NOVA-C lunar lander in early 2022. During this mission, LN-1’s goal will be to demonstrate navigation technologies that can support local surface and orbital operations around the moon, enabling autonomy which would decrease dependency on heavily utilized Earth based assets like the Deep Space Network. To do this, LN-1’s design leverages Cubesat components as well as the Multi-spacecraft Autonomous Positioning System (MAPS) algorithms, which enable the autonomous spacecraft positioning through communication-integrated navigation measurements. In addition to demonstrating the MAPS payload, the radio will also be used in PN-based one-way non-coherent ranging and Doppler tracking to provide alternate approaches and comparisons for navigation performance. LN-1 will represent a single node in a potential greater MAPS network of assets. The LN-1 design details, status, and potential forward work with subsequent missions like LN-2 will be outlined in this presentation.

**Acknowledgments:** We would like to thank the below contributors to the success of the Lunar Node - 1 payload:

Dave Edwards, Steve Elrod, Adam Gowan, Randy Montgomery, Anece Stegall, Jason Stelly, Derek Stokes, and the MSFC electrical shop.
Design and Use of the Cold Operable Lunar Deployable Arm End Effector for Geotechnical Investigations.
S. B. Backus, S. Moreland, L. Kerber, and R. McCormick, 1 Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr. Pasadena, California 91109 (spencer.backus@jpl.nasa.gov, Scott.J.Moreland@jpl.nasa.gov, Laura.A.Kerber@jpl.nasa.gov, Ryan.L.McCormick@jpl.nasa.gov)

Introduction: The Cold Operable Lunar Deployable Arm (COLDArm) is a Lunar technology demonstrator project that consists of a 4 Degree-of-Freedom (DOF) robotic arm developed in partnership with Motiv Space Systems and a geotechnical end effector designed by JPL [1]. The primary technology demonstration goals of the project are to use the arm and end effector to perform basic excavation and geotechnical surface interactions in the lunar regolith to characterize its properties at a previously untested, far-side, high-latitude location and to validate the operation of the novel actuators and motion control electronics at cryogenic temperatures. The data from the geotechnical interactions can be used to inform models of regolith terramechanics (important for landers, rovers, and human explorers), and processability (important for in-situ resource utilization purposes) in support of future missions. The project is funded by the Lunar Surface Innovation Imitative (LSII) and is currently targeting a 2024 mission aboard a Commercial Lunar Payload Services (CLPS) lander.

End Effector: The end effector, shown in Figure 1, consists of a six-axis force torque (F/T) sensor and scoop mounted at the end of the robotic arm. The robotic arm can control the translation and pitch degrees of freedom of the end effector. The F/T sensor is mounted immediately distal to the wrist joint of the arm and can resolve the combined forces and moments applied to the end effector. The scoop is designed to perform both excavation and geotechnical tests. It incorporates a cutting blade and bucket for excavation, a large flat face for pressure-sinkage (bearing plate) tests, and a small flat face (approximately half the area of the larger face) with a grouser like feature extending out from it for both pressure-sinkage and shear tests. Lastly the end effector includes two fiducials that may be tracked by a stereo camera aboard the lander to measure its position accurately to support the geotechnical tests.

Geotechnical investigations: We have identified a number of operations that can be performed by the robotic arm and end effector to collect data that may be used to estimate various geotechnical properties of the regolith as shown in Figure 2. First, we propose to perform a pressure-sinkage test by pressing bearing face 1 of the end effector into the regolith with the robotic arm while measuring the applied force with the F/T sensor and displacement with the camera and fiducials. The pressure-singkage test may be repeated with bearing face 2 to act as a second length-scale dependent measurement or to increase the applied ground pressure within the force producing capabilities of the arm. Next, we propose to perform a shear measurement by applying a quasi-constant vertical pressure followed by commanding lateral shearing motions with bearing face 2 and the grouser. Loads and displacements are measured continuously during the tests. The force displacement data collected during these tests in the lunar regolith may be correlated to standard geotechnical properties through laboratory testing.

Since the end effector will also be able to perform limited excavation, we anticipate that it may be able to perform other opportunistic geotechnical investigations including measuring the forces required during excavation, monitoring how the excavation forces change with depth, observing the angle of repose of a pile of excavated material, and performing slope failure tests next to an excavation trench and observing the failure of the side of the hole.

Acknowledgments: This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Copyright 2021 California Institute of Technology. Government sponsorship acknowledged.


![Figure 1. COLDArm end effector](image)

![Figure 2. Geotechnical tests using the end effector](image)
Lunar Exploration Analysis Group (2021)

LRO SUPPORT FOR LUNAR SURFACE EXPLORATION. M. E. Banks1, C. M. Elder2, J. W. Keller1, N. E. Petro1, A. M. Stickel3, J. D. Stopar4, and the LRO Team, 1NASA Goddard Space Flight Center, (maria.e.banks@nasa.gov), 2Jet Propulsion Laboratory, CA, 3JHU Applied Physics Laboratory, 4Lunar and Planetary Institute, USRA.

Introduction: The Lunar Reconnaissance Orbiter (LRO) is the only US asset at the Moon capable of supporting future lunar landers. The LRO payload was designed to assess future landing sites with an initial objective to complete detailed mapping of regions of interest identified by the Constellation Program Office [1-3]. LRO continues to serve the lunar community and facilitate lunar surface exploration with a wealth of data products and PDS-archived data (data volume of >1.2 PB), and ongoing acquisition of Constellation-site-quality observations.

Support for current and future lunar surface exploration: LRO currently supports landing site characterization with observations requested by NASA sponsored payloads flying on landers through NASA’s CLPS initiative, and international space agencies (via NASA HQ). Members of the community and public can utilize the LRO/LROC Target Observation Request interface to request site specific observations (http://target.lroc.asu.edu/output/lroc/lroc_page.html).

CLPS deliveries to 10 unique locations on the lunar surface carrying more than 40 science and technology demonstration payloads are already scheduled through September 2025, the duration of a fifth LRO extended mission. This time frame will also see extensive landing site and traverse planning to support Artemis, as well as the landing of Artemis III at the south pole. Additionally, a mixture of technology demonstrations, landers, rovers, and sample return missions are planned by the international community. Even with the wealth of existing LRO observations, the images and data products desired to plan and execute landed missions and detailed traverse planning on the Moon are not yet available for the entire lunar surface. New observations will be essential.

New and existing observations from all seven LRO instruments can be utilized to support landing site analysis and selection, operations planning, and science support. For example, targeted LROC observations can be used for digital terrain models and regional mosaics, while oblique images at differing sun angles enable perspective views of landing sites and facilitate assessment of terrains and hazards. New Diviner and CRaTER observations can enhance temporal coverage, enabling targeted temperature, thermal inertia, H-parameter, and radiation mapping. Observations from the multiple LRO instruments can be used to create specialized landing-site specific predictive models of lighting, thermal radiation, and earth visibility for desired locations and dates to optimize mission operation timelines, and to create regional and local maps of rock abundance and size distribution, surface roughness, slopes, craters, and volatiles. Combining the near-Moon measurements of CRaTER with NASA’s Gateway measurements will characterize the full radiation environment (with the exception of the surface) that Artemis astronauts will encounter, and will provide insight into the potential role of small-scale variability. In addition, CRaTER data has been used to predict the strength of the solar cycle during which Artemis will operate. By monitoring the CRaTER measurements through the rising part of this cycle, the team will be able to more accurately predict the galactic cosmic ray environment during the Artemis missions.

In addition to imaging assets on the surface, observations from LRO’s instruments during surface operations can provide characterization of the environment and context for surface science investigations such as temperature, lighting, and radiation conditions. Using the science objectives of the >40 payloads already selected to fly on upcoming CLPS deliveries, LRO is designing synergistic investigations to complement findings from the surface, enable comparisons of surface and orbital observations and ground truth where possible, and potentially coordinate observations between the surface and orbit. LOLA is poised to range to Laser Retroreflector Arays (LRAs) flying onboard CLPS landers. Additionally, LRO can monitor the effects of exploration activities on the lunar environment. For example, the LRO instrument LAMP can remotely observe the exhaust of a landing or the plume of an impact [4-6]. Measurements form orbit can provide insight into the associated migration of water and evolution of vapor through the exosphere and deposition of exhaust from descent burns. LRO will use its instruments to subsequently observe the effects of surface operations on the lunar environment over time. For example, LRO observations have previously been used to characterize changes to the regolith as a result of a landing plume [7-9]. Predicting the extent of disturbance from rocket exhaust through a better understanding of the relationship between lander dry mass and the blast zone area will be essential for planning for future high priority landing sites that might be targeted for multiple landings.


Introduction: NASA plans to send robotic and human explorers to the south pole of the Moon in the next 5 years. These missions require accurate, precise, and high-resolution maps of surface height and slope both outside and within permanently shadowed regions on lander-relevant scales [1-5]. To that end, we have been creating new high-resolution (5 m/pix) topographic models of high-priority south pole sites based only on laser altimetry data acquired by the Lunar Orbiter Laser Altimeter (LOLA) onboard the Lunar Reconnaissance Orbiter (LRO). Imaging-based techniques, such as stereo [6] and shape-from-shading [7], face challenges in the polar regions due to the extreme shadowing conditions prevalent there. LOLA is not hindered by shadows, but by gaps between tracks and laser spots which require interpolation to fill in. Indeed, near the south pole, ~90% of LOLA digital elevation model (LDEM) 5 m pixels are interpolated. Moreover, small errors in the LRO orbit reconstruction (~ a few m horizontal & ~0.5 m vertical) can cause artifacts in hillshade renderings at 5 m/pix (Fig. 1a). Analyzing and mitigating these issues are two of the primary goals of this work [8], in which new LOLA track adjustment and improvement techniques, similar to those applied in [2], reduce the ground track geolocation uncertainty by over a factor of 10. These new LDEM (available from [9]) are substantially improved over previous versions (e.g., Fig. 1b) and are more useful to constrain higher-resolution topographic models derived from imaging [6,7]. A major advantage of this process is that, for the first time, we can estimate realistic LDEM height uncertainties and their effect on illumination conditions. We developed a method to estimate surface height uncertainty that circumvents the infeasible computation of the full LDEM error-covariance matrix. Instead, we use the fractal nature of lunar topography to build a more computationally manageable statistical ensemble of 100 “clones” with similar error properties as the data. We use this ensemble to study height and slope uncertainty, and the uncertainty in illumination conditions. Such an approach can also be useful for a range of other characteristics, in addition to illumination conditions, when examining the feasibility of potential landing sites.


Figure 1 - 2x2 km region centered on Shackleton Ridge (Site 01 in [5,8]) before (a) and after (b) track adjustment and reprocessing. See [8] for further details and [9] for new LDEMs.
THE SCIENTIFIC VALUE OF LUNAR SAMPLE EXCHANGE. J. J. Barnes¹, C. Crow², B. L. Jolliff³, K. H. Joy⁴, T. Lapen⁵, J. Gross⁶, J. Mitchell⁶, R. Zeigler⁶ and A. L. Fagan⁴. ¹University of Arizona, AZ 85721, jjbarnes@arizona.edu, ²University of Colorado Boulder, CO 80309, ³Washington University St Louis, MO 63130, ⁴University of Manchester, M13 9PL, UK, ⁵University of Houston, TX 77204, ⁶NASA’s Johnson Space Center, TX 77058, ⁷Rutgers University, NJ 08854, ⁸Western Carolina University, NC 28723.

Introduction: Our understanding of how the Moon formed and evolved to its current state has been revolutionized through the study of samples collected between 1969 and 1976 by the six Apollo and three Luna surface missions and augmented by the growing lunar meteorite sample set. Over the last fifty years, these returned lunar materials have given us a glimpse into the early history and broad-scale petrogenesis of the Earth-Moon system, planetary formation, evolutionary processes, and the history of the formation of our Solar System [e.g., 1]. Many of these key discoveries have been made in the last decade due to advances in laboratory instrumentation. Long-term curation of the returned materials and sustained availability to the scientific community has enabled us to continue to advance knowledge of planet formation and Solar System processes. As we consider the future of lunar science and exploration in the next five years and beyond, we emphasize the benefit of sample exchange and sample sharing between all nations. Here we draw attention to the past exchange of Apollo and Luna samples between different countries.

Geographical Context: The six Apollo surface missions returned ~382 kg of material from six different locations on the lunar nearside. Approximately 320 g of soil was returned by the three Luna surface missions from the eastern lunar nearside. Importantly, the Apollo samples derived largely from locations within or near the Procellarum KREEP Terrane (PKT), dominated by a geochemical anomaly that is enriched in elements like Th, Ti, and Fe [2]. The Luna samples expand the geographical coverage of sampling beyond that of the Apollo missions and to locations outside of the PKT.

US-USSR agreement: In 1971 the Low-Keldysh agreement was made to enable the exchange of science and pristine NASA Apollo and Soviet Luna samples. Under this agreement, approximately 11 g of soils spanning all three Luna missions were sent to the US between 1971 and 1987. Luna samples were also shared by the Soviet government with the French (CNES) and UK (Royal Society) scientific communities as goodwill gestures between nations [e.g., 3]. Technological improvements and new sample handling knowledge gained on Apollo samples enabled investigators to conduct state-of-the-art chemical, isotopic and petrological investigations on the small-sized Luna samples (typically fine fraction of lunar soil < 2 mm in size). The scientific results from analysis of such limited Luna samples remain impressive and provide important context for the analysis of future robotic and crewed missions to the lunar surface [e.g., 4]. In addition, such sample sharing could provide opportunities for inter-laboratory analytical verification, cross-pollination of ideas, and enable inclusive scientific collaboration.

Modern Lunar Sample Return: Several space agencies are now conducting or planning lunar sample-return missions. In December 2020 the Chinese Chang’e-5 spacecraft returned the first lunar samples since the 1970s. They collected 1.731 kg of regolith from one of the youngest lava flows on the Moon, from a location north of the Aristarchus Plateau [5]. In the next decade, it is anticipated that among others the CNSA and NASA will return to the Moon with the intent to collect more samples. These missions are following a hypothesis-driven design with a view to filling strategic knowledge gaps in our understanding of the Moon and its potential to harbor exploration-enabling resources [6-7]. The lunar South Pole in particular is an important target for sample return as the polar regolith likely harbors volatile species, samples of mantle rocks, and impact melt from South Pole-Aitken Basin. In addition to lunar samples, several groups are producing lunar analog materials and simulants. These are crucial to interpreting remotely sensed data (e.g., ice-regolith mixtures) and to design, development, and testing of hardware, tools, and sampling devices for use on the Moon.

Today Apollo and Luna samples curated by NASA’s Curation Office are still in high demand for study by the international scientific community. The legacy of the bilateral exchange of lunar samples as diplomatic gestures of goodwill transcends generations of lunar scientists. As we enter this new golden era of lunar exploration, the US and other nations must recognize the lasting legacy and benefit of the Apollo-Luna sample exchange program of the 1970s and explore new opportunities to share returned samples in the future.

Introduction: Early lunar micro-rover missions will face several constraints such as limited onboard power, computational and downlink capacity, mobility performance, and will be short-lived without lunar night survival technology. In a traditional mission architecture, rover imagery and telemetry are downlinked to Earth at a constrained data transfer rate, where ground-based operators must make decisions after a series of steps in data processing and analysis. Without onboard autonomy for navigation, it may take several minutes to move a couple meters, resulting in high idle-time, slow mission speeds, and ultimately limited scientific return for instruments onboard.

Autonomy-Enabling Technologies: To maximize scientific return and value of constrained micro-rover missions, Mission Control has developed a suite of novel autonomy-enabling technologies in Artificial Intelligence and robotics that can effectively help increase mission speed, including surface characterization, trafficability & power modeling, mapping, and path planning. With a deep learning model, Mission Control’s ASAS-CRATERS (Autonomous Soil Assessment System: Contextualizing Rocks, Anomalies and Terrains in Exploratory Robotic Science) technology can classify surface features as seen by the rover’s navigation camera [1]. This provides a high-fidelity semantic map of the surrounding terrain. Our path planning tool can then generate trajectories to an operator-specified waypoint, optimizing for metrics like energy consumption and wheel slip based on the rover’s own data-driven models. The terrain representation can also provide rich geologic context for autonomous decisions for instruments to target specific features. To demonstrate autonomous targeting capabilities for scientific instruments, Mission Control is leading the development of the I-SPI (Intelligent Sensing and Perception In Infrared) instrument [2].

Emirates Lunar Mission: To demonstrate these technologies for a lunar micro-rover mission, Mission Control will participate in the international science team of the Emirates Lunar Mission (ELM). ELM is led by the Mohammed Bin Rashid Space Centre (MBRSC) and constitutes a small rover called Rashid. In ELM, Mission Control will demonstrate its advanced computing technologies for AI-based perception and distributed team operations through several investigations.

The primary investigation will demonstrate the feasibility and usefulness of automated terrain classification for science and navigation operations using deep learning models. This will be embedded on a compact and high-performance flight-ready processor, to be integrated on the mission’s lander, demonstrating an Edge AI computing architecture for lunar exploration. The classifier will identify high-level geological features in images from the rover’s navigation camera and downlink the outputs to science teams, to be used in rapid terrain assessment for science and navigation decision-making. This is targeted to be the first demonstration of Deep Learning on a lunar mission, unlocking potential applications for autonomous decision-making in future missions.

![Figure 1. Depiction of the MBRSC Rashid micro-rover and technologies by Mission Control for lunar terrain classification and path planning.](image)

These and other data products will be distributed to our extended Canadian science team in near-real-time using our web-based Mission Control Software platform, to support additional science and robotics investigations. In addition to AI-based terrain classification, Mission Control will lead investigations in trafficability estimation, path planning, and power modeling for skid steer vehicles, to mature our suite of advanced rover navigation applications. The data from Rashid will be used to train the terrain classifier, whose outputs can then be used to intelligently estimate rover wheel slip hazards and power consumption.

The results will be used directly to support path planning decisions for Rashid’s navigation framework, and this will be an important demonstration of capabilities for future lunar rover missions.

In addition to technology demonstrations, Mission Control will also aim to test novel strategies for educational outreach and public engagement for lunar missions such as live mission tracking and data hackathons.

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**Introduction:** In April 2020, the NASA Science Mission Directorate released a Request for Information (RFI) for the Payloads and Research Investigations on the Surface of the Moon (PRISM) program. The RFI asked responders to provide information on scientific instruments or suites that could be delivered to the Moon by a Commercial Lunar Payload Services (CLPS) lander. In November 2020, an announcement of opportunity was published via a PRISM appendix to the Research Opportunities in Space and Earth Science (ROSES 2020) solicitation. The appendix specifically designated Reiner Gamma and the Schrödinger basin as target sites, with one lander to be sent to each location.


**Science at Reiner Gamma:** Reiner Gamma (~7.5° N, 59° W) is the most famous example of a region where the Moon's crust is magnetized, known as a magnetic anomaly. The origins of the magnetic anomalies are unclear, and a variety of hypotheses for their origin have been put forth [2–7]. The local magnetic fields modify the Moon's interaction with the solar wind [e.g., 8, 9], creating structures described as "mini-magnetospheres". The crustal magnetic anomalies are frequently correlated with lunar swirls, unusual markings with high reflectance at visible wavelengths [e.g., 10–14]. A lunar magnetic anomaly is a unique natural laboratory for addressing a wide range of questions that touch on planetary magnetism, lunar geology, space plasma physics, and space weathering.

**Mission Overview:** The PRISM-1a suite is limited to 50 kg, with a $30M mission cost cap (including 20% reserves). The mission duration on the surface is one lunar daylight period (i.e., no night survival).

The Lunar Vertex mission has the following goals:

1. Investigate the origin of lunar magnetic anomalies.
2. Investigate the origin of lunar swirls.
3. Determine the structure of the mini-magnetosphere that forms over the Reiner Gamma magnetic anomaly.
4. Evaluate the importance of micrometeoroid bombardment vs. ion/electron exposure in the space weathering of silicate regolith.
5. Provide data related to certain strategic knowledge gaps (SKGs) for human exploration.

The Lunar Vertex suite consists of instruments on a lander, plus a small instrumented rover. The lander instruments include a fluxgate vector magnetometer, an ion-electron plasma spectrometer, and a camera array. The rover carries a vector magnetometer and a multispectral microscope with active LED illumination.

The landing site will be near the edge of the central Reiner Gamma bright swirl, allowing the rover to traverse from the high-reflectance surface into the adjacent "dark lane".

**Mission Name:** The mission's name adopts the Latin word "vertex", which can mean "swirl". The English word "vertex" invokes an intersection – the crossroads of geoscience and the particles-and-fields domain of space physics. This intersection is the theme of the interdisciplinary Lunar Vertex mission.

**Gruithuisen Domes: Insights from Silicate Mineralogy and Surface Textures.** D.M. Bower\(^1\), T. L. Livengood\(^1\), M.A. Barker\(^2\), T. Hewagama\(^3\) C.I. Honniball\(^4\)\(^5\) \(^\)\(^\) Department of Astronomy, University of Maryland, College Park, MD, dina.m.bower@nasa.gov, \(^2\)NASA Goddard Space Flight Center, Greenbelt, MD, \(^3\)Universities Space Research Association

**Introduction:** The upcoming CLPS mission to Gruithuisen Domes (GD) will provide the opportunity to better understand the Earth-Moon system and the magmatic evolution of the Moon. The GD are a trio of ~10 km-size domes located along the western edge of the Imbrium [1]. The distinct lithologies of the ~3.8 Gyr old GD stand out against the mare materials that dominate the lunar surface. Multiple observations of the region from, e.g., Clementine, Diviner on the Lunar Reconnaissance Orbiter, and M\(^5\) on Chandrayaan-1 indicate highly silicic lithologies including quartz, alkali feldspars, and silica glass with compositional variations among the three domes [2,3]. As in terrestrial rhyolitic volcanism, the high silica and low FeO and TiO\(_2\) compositions that formed GD and their distinct morphologies indicate a more viscous magma material than what formed the mare highlands [1, 3]. Variations in composition within the region also suggest more than one volcanic process, and the mechanisms are not yet well-constrained [5].

**Landed Approach:** The distinct morphologic, morphometric, and spectroscopic characteristics of GD observed in remote sensing data may also exist at scales of individual clasts that require techniques that correlate micro-scale topographic and textural surface features with mineralogy. Suitable spatial scales can be explored with technologies similar to those used for orbital remote sensing maps, while fine scales resolving individual clasts and grains are suitable for in situ technologies. Orbital remote sensing provides an overview of regional variation on the Moon with a resolution element on the order of several 100’s of m. A progressively narrower field of view from 10’s of m to 10’s of cm to 10’s of mm to point-target probing enables finely scaled information to be incorporated into the context of regional mapping.

A landed mission to GD should emphasize techniques that clarify variations in silica mineralogy to identify different types of silicic minerals and glasses and at the surface. Multiple quartz polymorphs are detected in Apollo rocks, each representative of specific formation conditions [6]. Lunar meteorites from Northwest Africa (NWA) contain clasts containing silica polymorphs quartz, cristobalite, tridymite (NWA 773), moganite, coesite, and stishovite (NWA 2727), indicative of silicic volcanism or high-T/high-P silicic fluids [6,7].

Raman spectroscopy (RS) probes the composition of features at 10’s μm. RS facilitates the distinction between polymorphs and is especially sensitive to silicate minerals. The RS characterizations of NWA 2727 and 773 clearly discern silica polymorphs among other silicates, e.g. K-feldspar and plagioclase [4,5]. A landed RS instrument can identify specific polymorphs, determining the properties of the original lava flow.

Coordinated microscopy of regolith is needed to understand top layer structure, its effects on surface photometric properties in reflected and thermally emitted light, and its correlation with mineralogy. Micro-scale imaging of regolith can discern individual grains and grain structures that RS probes, in a larger context. Remote sensing studies of the Moon regularly invoke micro-structural changes to the regolith related to its porosity, surface roughness, and elaborate grain structures (“fairy-castles”) to explain data over a range of wavelengths [7-10], but these hypotheses have never been directly tested. Optical microscopy correlates mineralogy to microtextures, uncovers the nature of “fairy castles”, and provides ground-truth for surface textures inferred from remote sensing.

Thermal imaging and IR hyperspectral imaging resolve terrain features as a ground-level counterpart to orbital measurements. Near-IR spectroscopy distinguishes silicates and space-weathering features related to the deposition age of lava flows or regolith deposits. Landed MWIR studies of the 8 μm silicate Christiansen feature can resolve ambiguities in minerals mapped from orbit. Surface temperature as a function of exposure time, either on sunlit regions exposed over hours or days or regions at the edge of retreating shadows with exposure times on the order of minutes yield thermal inertia related to the porosity of the soil.

**THE UNRESOLVED PROBLEM WITH DERIVING A LUNAR TEMPERATURE PROFILE FROM HEAT PRODUCING ELEMENTS.** P. M. Bremner¹, H. F. Haviland², A. Mallik³, M. Diamond⁴, \(^1\)NASA Marshall Space Flight Center (paul.m.bremner@nasa.gov), \(^2\)U. Arizona, \(^3\)U.C. Berkeley.

**Introduction:** Despite more than four decades of research, the present-day internal state and structure of the Moon is still debated. Previous studies have used total lunar mass, moment of inertia, bulk composition, gravity, as well as Apollo seismic data, to infer the Moon’s internal structure [2,5,7]. However, first-order questions about lunar structure and evolution remain, including: (a) the presence of a metallic core surrounded by a layer of low rigidity, likely a fingerprint of gravitational overturn which may have occurred very early in lunar history; (b) existence of a present-day remnant of an overturned Fe-Ti-rich layer that formed below the crust and sank to the core-mantle boundary; and (c) the evolution of the internal structure starting from crystallization of an early magma ocean. Constraining the thermal state of the present-day lunar interior is a primary challenge to improving estimates of internal structure. The existing estimates of lunar thermal profiles (selenotherms) derived from inversions of seismic [2], gravity [5], and electromagnetic [4] data differ by around 800°C; far too broad a range to constrain the internal lunar structure [1].

**Primary Goal**
Highlight high-to-extreme selenotherms calculated from radioactive decay contributions

Constraining the heat producing element (HPE) concentrations and distribution in the various reservoirs of the Moon would directly inform the thermal state of the interior. Estimates of bulk lunar mantle HPE concentrations can range from that of an ordinary chondrite (U = 0.0068 ppm; Th = 0.025 ppm; K = 17 ppm) to higher estimates (U = 0.039 ppm; Th = 0.15 ppm; K = 212 ppm) based on measurements of Apollo pyroclastic glasses that might represent the least fractionated, near-primary mantle melts. We show preliminary results of selenotherms from lunar interior models whose material properties were calculated using the Birch-Murnaghan equation of state. The selenotherms were calculated by incorporating the HPE estimates into a 1D spherical thermal conduction equation. The total lunar mass and moment of inertia of each interior model were calculated and compared to physical observations.

The focus of this presentation is to illustrate the difficulties of producing a 1D conductive thermal profile near or within geophysically based estimates through accounting for HPE, as well as to highlight future effort to address these problems. Our preliminary search found that incorporating the HPE estimates into a simple 1D spherical thermal conduction equation tends to yield selenotherms on the hot edge or hotter than geophysically derived estimates. At the extreme, the higher HPE concentration estimates yield an impossibly hot mantle with temperatures in excess of 4,000 K, melting large portions of the lunar mantle. This study highlights the importance for future in-situ observations and sample analysis to better constrain this issue.

**Figure 1:** Preliminary selenotherm results compared to the range of geophysically inferred temperatures (gray region). There are four sets of 187 lunar models shown. Each set applied HPE concentration estimates as combinations of:

- **Mantle** - bulk silicate Earth (BSE-based) or [3]
- **Crust** - [6] (FAN) or average of Apollo samples (AltCr)

KNOWLEDGE OF IMPACT GARDENING IS NECESSARY TO UNDERSTAND THE HISTORY OF LUNAR ICE. E. S. Costello1, P.G. Lucey1, and R.R. Ghent2, 1University of Hawaii at Manoa, Honolulu, HI (ecostello@higp.hawaii.edu), 2Planetary Science Institute, Tucson, Az.

Introduction: “Impact Gardening” in the context of planetary surfaces is the process by which impacts mechanically churn the uppermost regolith. The effects of gardening on Earth’s Moon are apparent in the Apollo cores, which show the presence of surface-correlated space weathering products such as submicroscopic iron and cosmogenic radionuclides at depths well below the region where they could be produced on a static surface [e.g., 1]. Impacts have transported these space weathering products to and from depth, homogeneously distributing them in a reworking zone. Gardening has been suggested as shield for ice via burial [e.g., 2] and a threat to ice via excavation [3]. By exploring the relative rates of excavation and burial in impact gardening, we are able to understand the depth to possible buried ice on the Moon and probe the evolution of the lunar regolith at large. To correctly interpret the distribution of ice present in future lunar cores, knowledge of the impact gardening history and context will be critical.

Model: To model the burial and excavation rate by impacts, we adopt and adapt the statistical treatment of impact effects from [3], and include a chronology function [4] to investigate gardening early in lunar history (>1 billion years ago). We calculate the depth of burial under ejecta as a function of distance from source craters to 10 crater radii, assuming exponential ejecta thickness as in [5].

Results: In presenting our gardening predictions, we carry over the definition of the “in-situ reworking zone” from Morris [1], who defined this zone as a region from the surface to some depth where surface-correlated space weathering products and cosmogenic radionuclides are homogeneously mixed. Gardening in the in-situ reworking zone fits observations of the thorough mixing of surface-correlated space weathering products in the Apollo cores.

We also define the “degradation zone.” The degradation zone extends from the bottom of the in-situ reworking zone to a lower boundary defined by averaged model results for equilibrium burial and excavation. Our predictions for the extent and growth of the degradation zone with time fit the degradation rate implied by the disappearance of density-anomalous cold spots [6] and crater rays [7; Figure 1]. Material inside the degradation zone is broken up and mixed but not extensively reworked and exposed at the surface like material in the in-situ reworking zone.

Discussion: We can refer to gardening model results to understand the evolution of specific ice deposits. For example, let us imagine a 1 m thick ice deposit was emplaced 3 billion years ago. Using Figure 1b we can interpret the ice deposit’s current state through assessment of the in-situ reworking and degradation zones (vertical line at 3 Ga). If the ice deposit was never buried by a large, rare, ejecta blanket [e.g., 8], it will have been completely pulverized between the time of its emplacement and the present. The top 2 m will be dry (in-situ reworking zone) and fragments of the ice deposit may reside between 2 - 20 m depths (degradation zone). If the deposit was located in a depositional environment such as the bottom of a crater and was subsequently buried under a 3 m thick blanket of regolith soon after being emplaced 3 billion years ago, then the in-situ reworking zone will remove ice from the uppermost 2 meters, including any ice brought up from below by larger, rarer, degradation zone impacts, but we could expect there to be a relatively high concentration of particulate ice between 3 - 20 m depths within the degradation zone. This example shows that knowledge of impact gardening will be necessary to interpret the history of lunar ice.


Figure 1: These plots show model results for the depth of impact gardening zones. Ice in the “in-situ reworking zone” is frequently destabilized. Ice in the “degradation zone” is patchy and broken up.
LRO INVESTIGATIONS OF REGOLITH AND IMPACTS. C. M. Elder1, N. E. Petro2, J. Keller2, A. M. Stickle3, J. Stopar4, M. Banks2, and the LRO Science Team; 1Jet Propulsion Laboratory, California Institute of Technology, 2NASA Goddard Space Flight Center, 3Johns Hopkins University Applied Physics Laboratory, 4LPI/USRA.

Introduction: Impact bombardment at all scales has been the primary geologic process modifying the lunar surface for over 1 Gyr. This has led to the development of fine-grained regolith blanketing nearly the entire lunar surface. Studying regolith formation and evolution is therefore necessary for understanding the geologic evolution of the lunar surface. As a result, observing the consequences of bombardment at all scales has been central to the LRO mission, including crater formation, crater degradation, regolith overturn rates, and space weathering. Here we discuss some of the recent progress and possible objectives for another LRO extended mission.

Recent and Ongoing Investigations: During the ongoing extended mission 4 (ESM4), LRO is making observations to address four key questions relating to regolith and impacts:

Q1. What is the abundance of impact melt in proximal and distal ejecta deposits of impact craters at all scales? What is the nature of putative basin melt and antipodal deposits?

Q2. How has the impact flux varied over the past billion years, and what are the implications for lunar chronology and for solar system dynamics?

Q3. How, and how fast, are the albedo and texture of newly exposed materials altered at late Copernican craters?

Q4. How does the small-scale structure of the lunar surface affect the photometric and thermal properties we observe? How do variations in the surface texture and thermophysical properties produce anomalous features, such as swirls and distal ejecta deposits?

Some of the many efforts from LRO ESM4 include analysis of Mini-RF and Diviner data that revealed that the rims of km-sized impact craters remain rocky for the lifetime of the lunar maria suggesting that boulders are continually being exhumed at crater rims [1]. LROC NAC images were also used to characterize boulder populations at craters. Specifically, a study of 6 small, young impact craters near spacecraft landing sites constrained how crater age and size affect the size and density of ejected boulders as a function of distance from the crater [2]. Diviner rock abundance in the proximal ejecta blankets of cold-spot craters (<1 Myr old) is not consistent with an abrupt transition between fine-grained regolith and underlying coherent rock but could be explained by a volume fraction of coherent rock that increases exponentially with depth [3]. In 2019 and 2020, 103 unique targets were observed with the LOLA-LR including Copernican-aged craters, large cold-spot craters, swirls, maria, and pyroclastic deposits [4]. Preliminary results from these observations suggest that Reiner Gamma may be smoother than the surrounding maria on sub-mm to sub-cm scales [4]. LRO data was also used to identify possible outcrops of intact Crisium impact melt which could serve as a target for a future lunar sample dating mission [5]. Mapping of Tsiolkovskiy crater and its surrounding ejecta blanket revealed that the initial phase of ballistic ejecta emplacement was followed by a separate melt-bearing ejecta emplacement event [6]. On a larger scale, a global map of lunar light plains (from LROC), suggests that ~70% of light plains are related to the Orientale and Imbrium basins with the stratigraphic extent of an individual basin extending to at least four basin radii, suggesting that basins modified a significant fraction of the lunar surface [7].

Plans for ESM5: LRO is still observing the Moon with LROC, Diviner, Mini-RF, LOLA, CRAzTER, and LAMP, but its ESM4 will end in Sept. 2022. Extended mission 5 (ESM5) will be proposed for Sept. 2022-Sept. 2025, and would enable both continued campaigns for which a long baseline of observations is necessary and investigations of new targets. For example, the detection of additional impact craters formed during the span of the LRO mission will further constrain the present-day impact flux at the Moon. New observations of geologically young landforms observed early in the mission could provide a lower limit on the time-scale of detectable space weathering. Much of the Moon has not been observed in the X-band, and new observations at this wavelength could help constrain how the rock size frequency distribution of crater ejecta changes over time. Furthermore, the time frame of proposed LRO ESM5 overlaps with the planned landings of several Commercial Lunar Payload Services (CLPS) providers and the Artemis III South Pole landing. Observations of these proposed landing sites by LRO could provide valuable scientific context and data for landing hazard assessment.

MOTE LUNAR PENETRATOR ARRAYS FOR RAPID EXPLORATION OF EXTREME LUNAR TERRAINS T. Marshall Eubanks1, W. Paul Blase1, 1Space Initiatives Inc, Newport, Virginia 24128 USA; tme@space-initiatives.com

Introduction: Ballistic penetrators will support lunar science by allowing precursor missions to difficult to reach terrain, and by allowing for the rapid creation of instrument and communications arrays on the lunar surface [1, 2, 3].

Space Initiatives Inc (SII) has developed small “Mote” ballistic penetrators to provide commercial support for robotic and crewed operations on and near the Moon. The ~1.5 kg Mote penetrators will have on-board processing, communications and sensors, and can be deployed from a CubeSat deployer. Motes could be delivered by a dedicated mission (and orbiter or even a lunar flyby) or, as shown in Figure 2, could be carried by lander transporting material to the lunar surface under NASA’s Commercial Lunar Payload Services (CLPS) program. After deployment, Motes fall ballistically, impacting the surface at up to 300 m/s and penetrating 1 meter or more into the typical lunar regolith, resulting in a sensor array spread, in a nominal mission with ±10 m s⁻¹ kick velocity, over ~1 km of the lunar surface (see Figure 2).

Mote Ballistic Penetrator Instrumentation: SII is developing a standard instrument package including a three axis accelerometer, three axis magnetometer, and subsurface thermometers and geophones. Mote penetrators within view of the Earth can also carry COMPASS Very Long Baseline Interferometry (VLBI) Beacons to enable their accurate global positioning on the lunar near-side [4]. Any deployment would immediately provide geotechnical information about the upper 1-2 meters of regolith in the penetrator landing area, from the penetrator deacceleration profile and its depth of penetration. Information about the thermal characteristics of the penetrated regolith will be provided by measurements of the temperature in the penetrator bore.

Deploying into Shackleton Crater: Ballistic penetrators will enable the rapid deployment of instruments into the most difficult lunar terrains, including the permanently shadowed regions. Figure 2 shows the deployment of Motes into Shackleton crater from a supposed CLPS landing delivery on the rim of the crater. In this mission profile the Motes are deployed 24 km downrange and 5 km above the mean lunar surface and take ~78 seconds to reach the crater floor, ~2.8 km below the mean lunar surface. At the time of their landing, the CLPS lander will still be well above the surface of the Crater rim and would be able to observe IR emissions from the gas plumes emitted by surface volatiles vaporized by Mote impacts. The chosen landing site is the ~210 m high “mound unit,” the largest feature on the Shackleton Crater floor [5]. The horizontal spread of the Mote’s landing sites is sufficient to blanket the mound unit with penetrators.

THE LUNAR GEOPHYSICAL NETWORK LANDING SITES SCIENCE RATIONALE. H. F. Haviland\textsuperscript{1}, R. C. Weber\textsuperscript{1}, C. R. Neal\textsuperscript{2}, P. Lognonné\textsuperscript{3}, R. F. Garcia\textsuperscript{4}, N. Schmerr\textsuperscript{5}, S. Nagihara\textsuperscript{6}, R. Grimm\textsuperscript{7}, D. G. Currie\textsuperscript{8}, S. Dell'Agnello\textsuperscript{9}, T. R. Watters\textsuperscript{9}, M. P. Panning\textsuperscript{10}, C. L. Johnson\textsuperscript{11,12}, R. Yamada\textsuperscript{13}, M. Knapmeyer\textsuperscript{14}, L. R. Ostrach\textsuperscript{15}, T. Kawamura\textsuperscript{1}, N. Petro\textsuperscript{16}, P. M. Bremner\textsuperscript{1}, NASA Marshall Space Flight Center (heidihaviland@nasa.gov) \textsuperscript{2}U. Notre Dame, \textsuperscript{3}IPGP, \textsuperscript{4}ISAE-SUPAERO, \textsuperscript{5}UMD, \textsuperscript{6}Texas Tech U., \textsuperscript{7}SwRI, \textsuperscript{8}INFN-LNF, \textsuperscript{9}Smithsonian Institution, \textsuperscript{10}NASA JPL, \textsuperscript{11}U. British Columbia, \textsuperscript{12}Planetary Science Institute, \textsuperscript{13}Aizu University, \textsuperscript{14}DLR, \textsuperscript{15}USGS, \textsuperscript{16}NASA GSFC.

Introduction: The Lunar Geophysical Network (LGN) mission is proposed to land on the Moon in the early 2030’s and deploy packages at four locations to enable continuous geophysical measurements for a minimum of 6 and a goal of 10 years \cite{1}. Returning to the lunar surface with a long-lived geophysical network is a key next step to advance lunar and planetary science. LGN will greatly expand our primarily Apollo-based knowledge of the deep lunar interior by identifying and characterizing mantle melt layers, as well as core size and state.

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<th>LGN Primary Goal</th>
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<td>Understand the initial stages of terrestrial planet evolution</td>
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**LGN Science Objectives**
- Define the interior structure of the Moon
- Constrain the interior and bulk composition of the Moon
- Delineate the vertical and lateral heterogeneities within the interior of the Moon as they relate to surface features and terranes
- Evaluate the current seismo-tectonic activity of the Moon

To meet the mission objectives, the instrument suite provides complementary seismic, geodetic, heat flow, and electromagnetic (EM) observations. We discuss the network landing site requirements and provide example sites that meet these requirements. Landing site selection will continue to be optimized throughout the formulation of this mission. Possible sites include the P-5 region within the Procellarum KREEP Terrane (PKT; (lat:15°; lon:-35°), Schickard basin (lat:-44.3°; lon:-55.1°), Crisium basin (lat:18.5°; lon:61.8°), and the farside Korolev basin (lat:-2.4°; lon:-159.3°) (Figure 1).

Network optimization considers the best locations to observe seismic core phases, e.g., ScS and PKP. Ray path density and proximity to young fault scarps are also analyzed to provide increased opportunities for seismic observations. Geodetic constraints from laser ranging require the LGN to have at least three nearside stations at maximum limb distances. Heat flow and EM measurements should be obtained away from terrane boundaries and from magnetic anomalies at locations representative of global trends. In our recent paper \cite{2}, an in-depth case study is provided for Mare Crisium. We also discuss the consequences for scientific return of less than optimal locations or number of stations.

Figure 1: Candidate LGN landing sites (triangles) compared to Apollo (circles). LGN stations will be placed across major lunar terranes and enable new interrogation of the deep lunar interior and tectonic evolution. The two most active nearside and farside deep moonquake clusters (A01 and A33) and their antipodes (yellow and cyan stars, respectively) are highlighted.

X-RAY COMPUTED TOMOGRAPHY FOR THE ANALYSIS OF MATERIALS COLLECTED AT THE LUNAR SOUTH POLE. A. J. Gawronska1, C. L. McLeod1, C. M. Gilmour2, 1Department of Geology and Environmental Earth Science, Miami University, Oxford, Ohio, USA, 45056 (gawronaj@miamioh.edu). 2Centre for Research in Earth and Space Science, York University, Toronto, Ontario, Canada, M3J 1P3.

Introduction: Studies of materials from rocky bodies across the Solar System have worked to inform and refine our understanding of processes occurring in the universe around us. The future Artemis program will provide new materials from a region of the lunar surface that has never been investigated in-situ. Specifically, the Artemis 3 mission will land at the lunar south pole, which lies on the flank of Shackleton Crater. There, a number of lithologies have been found (Figure 1), and materials associated with these lithologies could potentially be collected by crew during extravehicular activity (EVA) [1]. The most novel materials that could be collected at the lunar south pole are water and other volatile species [2]. However, volatiles are concentrated in permanently shadowed regions (PSRs) which are not easily accessible for direct sampling during EVA [1]. Instead, the crew may focus on rocky materials found on the rim or ejecta blanket of Shackleton. These materials will likely include: 1) crystalline crust (specifically norite, and/or purest anorthosite with >98% feldspar) [3-4], 2) layered materials from nearby ejecta deposits (Figure 1, [1]), 3) impact melt [5], 4) regolith, and 5) core or dredge samples that will include any mixture of the above. It is important to note here that regolith and core/dredge samples in particular will also likely include a mixture of regolith-ice [6].

Analytical Methods: Once new samples are returned from the lunar surface, it will be critical to take advantage of all available analytical methods, and to properly curate and preserve samples. Both can be addressed by utilizing X-ray computed tomography (XCT; e.g., [7-8]), where scans of a sample are gathered by passing X-rays through a sample. The resulting scans may be used to recreate a 3D model of the sample, preserving it for posterity and permitting investigations of sample characteristics at the µm to cm scale (e.g., morphology, mineralogy, textures) [7]. The application of XCT has been demonstrated to be of particular use to extraterrestrial sample preservation and analysis [7-10], and will therefore be integral to the characterization of returned Artemis materials.

Resulting Data and Future Work: Scans returned via XCT are monochromatic and feature different grayscale values for different phases existing in a given sample. These can be used to easily and decisively evaluate the modal proportion of components within sampled materials. With regards to materials gathered at the lunar south pole, this approach will support the characterization of crustal material gathered, and assess whether sampled material appears to contain any layering or mixing features consistent with ejecta deposits. In preparation for the Artemis missions, it will be crucial to utilize XCT in identifying lunar sample characteristics by analyzing already-gathered samples. One way in which this is being accomplished is the Apollo Next Generation Sample Analysis program’s investigation of Apollo 17 drive tubes (e.g., [10]). Future preparation should include further investigation of feldspathic samples, impact melts, and regolith.


Figure 1: Cross-section of Shackleton crater, outlining the major lithologies existing near Shackleton that may be sampled during extravehicular activity at the lunar south pole (south pole delineated by white star). Figure from [2].
APXS Method: Chemistry from X-ray spectroscopy has been a staple of scientific payloads of mobile robotic platforms on Mars. Mars Pathfinder [1], the twin Mars Exploration Rovers (MER) Spirit and Opportunity [2, 3] and the Mars Science Laboratory (MSL) rover Curiosity were all equipped with an Alpha Particle X-ray Spectrometer (APXS) [4]. With each generation, the experience gained from the predecessor mission and available new technology helped improving the capability significantly over time, allowing faster data acquisition, new trace elements and lower detection limits. The APXS uses complementary particle-induced X-ray emission (PIXE) and X-ray fluorescence (XRF) induced by radiogenic $^{241}$Cm sources. It measures the elemental composition of rocks and soils, including major, minor, and some trace elements (depending on the their abundances) [5].

Recent investments made by the Canadian Space Agency (CSA) through their Lunar Exploration Accelerator Program (LEAP) [6] have permitted investigations aimed at modernizing the APXS design, with new electronics and detector technologies to optimize the instrument for the lunar surface. Preliminary results indicate a well understood pathway to further improve the capabilities compared to its MSL predecessor. CSA has recently announced their intention to support up to two Canadian instruments (such as an APXS) as contribution to payloads submitted through NASA’s Commercial Lunar Payload Services (CLPS) 2021 PRISM call [7].

Expected Lunar Performance: The scientific suitability of an APXS is unquestioned for missions to Mars and other rocky bodies such as martian moons or asteroids. The ability to reliably determine the bulk composition of rocks and soils along the traverse and to indicate aqueous alteration through the abundance of salt forming elements like S, Cl or Br, or trace elements like Ni, Zn, Ge was a key part of recent Mars mission results. We posed the question, what science questions could an APXS with MSL-like performance on lunar materials address? We used the ACES (APXS Characterization by Empirical Simulation) software package [5, 8], which simulates an APXS spectrum for a user-defined composition and experimental conditions (e.g., duration, sample proximity and resolution). This alleviates the need for extensive and time-consuming laboratory experiments. The basis of the ACES simulation is the MSL sample calibration suite of ~100 igneous and sedimentary powdered rocks and the empirical analysis model used for MER and MSL [3]. With this it was possible to show that lunar samples can be well analyzed within one hour [5]. Accuracy can be significantly improved when going from the wide ranging Mars calibration to a more appropriate igneous suite for lunar materials. The ability to imply mineralogy from bulk chemistry of likely igneous martian samples has been demonstrated for many samples using Mössbauer spectroscopy [9].

Expected Science to be achieved: For a sample like Apollo 12009 (an Apollo 12 olivine basalt), ACES determined that an MSL-era APXS could precisely quantify (within $\pm 10\%$ error) major oxides such as SiO$_2$, TiO$_2$, Al$_2$O$_3$, Cr$_2$O$_3$, FeO, MgO, CaO, K$_2$O, P$_2$O$_5$, and SO$_3$ within an hour. Na$_2$O, MnO, Ni, Cu, Y can be detected as well but with higher uncertainties for that specific composition. Using three lunar materials (mare basalt, highland anorthosite, and KREEP) as possible endmembers of expected samples, it was found that element groups can be identified that would allow tracking their mixing ratios.

We conclude that an MSL-like APXS would be able to determine the bulk composition of samples along any traverse on the Moon within an hour. The mature method would reliably cope with any unexpected sample composition and provide ground-truth for remote observations and support the mission objectives. Further instrument improvements can be implemented by using updated components. In addition, various other approaches like complementary X-ray sources or self-positioning mechanisms are under investigations that would expand the scientific capabilities even more.

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References:
ADVANCES IN LUNAR SCIENCE RETURN VIA DISTRIBUTED INSTRUMENT MOBILITY AND SWARM ROBOTICS: THE LUNAR OUTPOST MOBILE AUTONOMOUS PROSPECTING PLATFORM (MAPP) ROVERS A.J. Gemer, J.A. Cyrus, F. Meyen, and J.B. Cyrus

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Introduction: Mobile robotic systems for lunar surface operations are essential to provide mobility as a service to lunar science instruments and enable drastic advancement in lunar exploration. Lunar Outpost is addressing these needs through development of the Mobile Autonomous Prospecting Platform (MAPP), a mass-produced, cost-effective robotics platform for enabling greater science return by allowing suites of instruments to be deployed in multi-instrument campaigns hosted across multiple small rovers. Groups of MAPPs can navigate and operate cooperatively in swarms to maximize areal coverage, deploy large instrument networks, and investigate science sites in higher resolution than ever before. With missions currently contracted in 2022 and 2023, multi-rover swarms of MAPPs will be navigating the lunar surface within the next 5 years.

Figure 1: M1-MAPP / COLD-MAPP

Current MAPP capabilities include cryo-capable wheel drives; autonomous navigation, hazard avoidance, path planning, cooperative swarm robotics, and teleoperations software; and sensor capabilities including merging of vision-based navigation (VBN) and LIDAR point-cloud data for driving in high-contrast, deeply-shadowed, or dark conditions. With this flexibility, swarms of MAPPs can be configured for a mission spanning a single lunar day (M1 MAPP), surviving the lunar night (COLD-MAPP), exploring PSRs (PSR-MAPP), or providing mobility to larger payloads (HL-MAPP).

Mission 1 (M1) MAPP is designed to carry lunar science instruments for missions lasting a single lunar day. M1 MAPPs fit into a CLPS lander payload volume of 44cm x 48cm x 35cm and provide 5 separate payload bays for instrument payloads up to 10kg. M1 MAPPs provide a peak payload power of 35W and have a maximum drive distance of 8km. The M1 MAPP Technology Demonstrator is currently undergoing TVAC, Vibe, EMI/EMC, and radiation testing, and will be ready for integration with a CLPS lander as early as Q2 of 2021.

NASA has also funded Lunar Outpost to develop the M1 MAPP into the Cryogenic-Operation, Long-Duration MAPP (COLD-MAPP), a 15kg rover platform designed to survive one or more lunar nights. As COLD-MAPPs have substantially longer mission durations, they can drive up to 20km. COLD-MAPP will be mission-ready in early 2022.

HL-MAPP Since the beginning of MAPP development, Lunar Outpost has maintained a focus on scalability and portability of critical M1/COLD-MAPP subsystems, which may be utilized directly in Lunar Outpost’s 300kg Heavy-Lift MAPP. HL-MAPP provides up to 120kg of payload accommodation and 85W of peak payload power for an extended mission and can travel up to 35km away from the lander. Another potential benefit is direct to Earth communications systems. HL-MAPP fits into a payload bay of 1.5m x 1.3m x 1.3m and will be mission-ready in late 2022.

Payload Accommodations. The Lunar Outpost MAPP reserves significant interior volume for prospecting, scientific, and commercial payloads. These payloads may be mounted internally or externally to the body, depending on payload requirements.

Figure 2: MAPP Payload Volumes

Figure 2 illustrates the 5 available payload spaces available aboard the rover; internal volumes are shown in blue (1443 cm$^3$) and red (1215 cm$^3$), and external accommodations are shown in green (820 cm$^3$) and orange (426 cm$^3$). A composite cover may be added to the top of the rover, allowing the purple payload volume (1105 cm$^3$) to be adapted for both internal and external payloads, as desired.
A NEXT-GENERATION LUNAR ORBITER TO SUPPORT LUNAR SCIENCE AND EXPLORATION. T. D. Glotch\textsuperscript{1}, \textsuperscript{1}Department of Geosciences, Stony Brook University, Stony Brook, NY, timothy.glotch@stonybrook.edu

Introduction: Over the last decades the lunar science community has used orbital data to make significant progress in addressing key lunar science and exploration goals, while defining many new high-priority scientific questions regarding the formation and evolution of the Moon. At the same time NASA’s key lunar orbital asset, the Lunar Reconnaissance Orbiter (LRO) is aging. NASA and the lunar science community should consider post-LRO lunar remote sensing strategies.

A large (Flagship or New Frontiers class) Next Generation Lunar Orbiter (NGLO) mission would address the last Planetary Decadal Survey objective of understanding the origin and diversity of terrestrial planets by studying the geochemistry and geology of the Moon at an unparalleled resolution compared to other lunar mission datasets. Also, NGLO would address the objective of studying the evolution of life on terrestrial planets by furthering knowledge about the composition and distribution of volatile elements on the lunar surface and better characterizing the past and present-day impact rates in the inner Solar System to better understand the original delivery of water to Earth. Key exploration goals, including identifying the nature and distribution of lunar volatiles (i.e., water, ice), mapping and characterizing potentially valuable lunar resources, and establishing a human presence on the Moon, also would be addressed by NGLO.

Notional Payload to Address Science Goals: The National Research Council Scientific Context for Exploration of the Moon (SCEM) report \cite{1}, Next Steps-Specific Action Team (SAT), and Advancing Science of the Moon SAT (ASM-SAT) developed scientific goals explicit to the study of the Moon. An advanced lunar orbiter such as the NGLO, with a payload consisting of imaging spectrometers spanning the ultraviolet (UV), visible/near-infrared (VNIR) and thermal infrared (TIR), a P-band radar sounder, and color stereo high resolution imagers would address many of these science goals, as shown in Table 1.

In addition to evaluating the progress made in achieving the eight scientific concepts of the SCEM report (and finding that none of the original SCEM goals were completed), the ASM-SAT \cite{2} also added three new concepts with additional science goals related to understanding (1) the lunar water cycle, (2) the origin of the Moon, and (3) lunar tectonism and seismicity, all of which would be addressed by NGLO.

Need for a Large Lunar Orbiter: NASA has recently invested in cubesat and small satellite development for lunar and planetary applications. These missions will provide valuable insights into the lunar volatile cycle and lunar geology but will generally have short timescales to end-of-mission. Further, power and mass requirements for cubesat and smallsat missions necessarily exclude certain classes of instruments, often preventing the acquisition of the highest possible precision, accuracy, and spatial resolution measurements. The NGLO notional mission includes instruments with large mass or power requirements to enable high precision and accuracy measurements of the lunar surface at spatial scales up to an order of magnitude better than those available from LRO and international lunar orbiters. The resulting unprecedented, foundational data set would advance consensus lunar scientific priorities and support landed missions over the next decade or more. NGLO would enable long-term landing site scientific and hazard characterization, act as a communications relay for landed assets, and could provide quick-response, high-resolution imaging of human and robotic activity on the lunar surface. Finally, NGLO would broaden participation in lunar and planetary science and train the next generation of leaders in extraterrestrial science and exploration.

Recommendation: The development of a large lunar orbiter with a potential lifetime of a decade or more would provide support and information that is essential to achieving near-future lunar exploration and science research goals. In the immediate term, NASA should fund a mission concept study to analyze trades between instrument suites, capabilities and observational modes, including the costs and benefits of different orbits and data acquisition plans.

References: \cite{1} National Research Council (2007). The scientific context for exploration of the Moon, \url{https://doi.org/10.17226/11954}. \cite{2} Lunar Exploration Analysis Group LEAG (2017), Advancing science of the Moon: Report of the specific action team,
FROM APOLLO TO ARTEMIS: HOW ANGSA HELPS PREPARING FOR FUTURE SAMPLE MISSIONS TO THE MOON AND BEYOND. J. Gross1,2,3, R.A. Zeigler1, F.M. McCubbin1, C. Shearer3,4, and the ANGSA Science Team. 1ARES, NASA Johnson Space Center, Houston (JSC) TX 77058, (juliane.gross@nasa.gov); 2Depart. of Earth and Planetary Sciences, Rutgers University, Piscataway NJ 08854; 3Lunar and Planetary Institute, Houston TX 77058; 4Dept. of Earth and Planetary Science, Institute of Meteoritics, University of New Mexico, Albuquerque, New Mexico 87131.

Introduction: The Apollo Program returned 381 kg of samples. Analyses of these samples have provided fundamental insights into the origin and history of the Earth-Moon system and our solar system. During Apollo some samples were collected or preserved in unique containers or environments and have remained unexamined by standard or advanced analytical approaches [1]. The Apollo Next Generation Sample Analysis (ANGSA) Program was designed to examine a subset of these special samples and to function as a sample return mission with site characterization, processing, basic characterization, preliminary examination (PE), and analyses utilizing new and improved technologies and recent mission observations [2]. Nine selected ANGSA teams are examining two distinct types of samples: (1) Apollo 17 double drive tube, 73001/2 consisting of an unopened vacuum sealed core sample (Core Sample Vacuum Container; CSVC 73001) and its unsealed but unstudied companion core 73002; and (2) Apollo samples that were placed in cold storage approximately 1 month after their return in the early 1970s [1]. Studying these unopened and specially curated samples could allow scientists to gain insight into the origin of the lunar polar ice deposits, as well as other potential resources for future exploration such as Artemis.

Many new curation and scientific tools such as X-ray computed tomography (XCT) [3], multi-spectral imaging [4], and gas extraction manifold with a piercing tool [5,6], that will be used to extract gas from 73001, are currently being developed and/or applied to the ANGSA core to benefit curation strategy, PE efforts, and ultimately sample allocation to the planetary science community [1,2]. Analyses of these samples with these new tools and technologies will maximize the science return from Apollo, as well as enable a new generation of scientists and curators to refine their techniques and help prepare future explorers for lunar missions within the next five years and beyond. As such the ANGSA Program links the first generation of lunar explorers (Apollo) with future explorers of the Moon (Artemis).

ANGSA 73001/2 samples: ANGSA has numerous science goals that fulfill Apollo mission goals and address new science concepts developed over the last 50 years [7]. A specific goal is to understand how effective the double-vacuum sealed containment of 73001 was at preserving the volatile record of lunar samples, which is paramount for preserving the core’s integrity and the meaningfulness of any subsequent analysis [7]. With future lunar missions likely to target the polar regions, and the international Mars Sample Return program in preparation, newly developed instruments such as the gas manifold and piercing tool, as well as protocols for extracting the volatiles that might still be present in 73001, will provide essential information for developing future sampling containers for Artemis and beyond.

ANGSA cold curated samples: Four science teams were selected to study cold and/or volatile-bearing samples collected during the Apollo program. The ANGSA samples that are stored cold have special storage and handling requirements that necessitate their processing in a -20°C environment [8]. Sample processing under cold conditions and meeting the Apollo materials and cleanliness requirements revealed some unique challenges in materials performance and PPE [9-11]. ANGSA provides excellent preparation for Artemis’ future cold sample processing efforts because lessons learned here will aid in the development and implementation of a cold sample processing facility, including curation procedures, needed to process the cold and volatile-bearing samples planned to be returned by Artemis missions [8].

Conclusion: Processing Apollo core 73001/2 and other future ANGSA samples, creating an informative PE catalog, and applying new and refined tool and technologies for sample analyses are invaluable activities that (1) will assist in the characterization of samples and (2) help us assess how well the lunar material has been collected and preserved. This will help us design future collection and curation procedures and will help to prepare for future human exploration and sampling missions such as Artemis.

Replicating or Exceeding the Imagery from Apollo for Artemis Missions. Rodney Grubbs, NASA Marshall Space Flight Center, Alabama Rodney.Grubbs@NASA.Gov

Introduction: If you ask a person their impressions of the Apollo Moon Program, most likely the response will include a reference to imagery. Imagery is the most powerful and effective way to engage the public for human exploration of space. As we now embark on a new chapter of human space exploration with the Artemis Program, the expectations for the quantity and quality of imagery present a host of challenges.

During Apollo, NASA had three sources of imagery: live television systems, motion picture film, and still frame film. The live television during Apollo was crude by today’s standards. The motion picture camera was similar to the 16MM cameras used in harsh environments on Earth. The still frame film camera was a very high-resolution professional class camera using 70MM film.[1] In the modern era, it is likely there will be no need to have separate cameras for motion imagery and still imagery. Modern cameras are capable of live and recorded motion imagery and high-resolution still imagery. But replicating the quality of the still imagery will be very difficult.

Comparing Analog to Digital: During Apollo, the motion picture and still imagery cameras used photographic film. The film was returned to the Earth, processed, and produced many of the iconic images and motion imagery. During Artemis, cameras will likely record the highest resolution on digital data cards, while simultaneously transferring lower resolution files or streams (in the case of motion imagery) to Earth while the mission is on-going.

While today’s motion imagery and television standards far exceed the quality of the Apollo era’s television and motion picture photography, replicating the quality of the 70MM still film camera with a digital equivalent will be very difficult. While it is difficult to compare the resolution of film with digital imagery, the imagery from the cameras used on Apollo is considered to be roughly 100 Megapixels [2]. While digital cameras capable of 100 Megapixel camera imagery exist, they would be very impractical to fly due to the large size of the cameras, lenses, and data sizes. Fortunately, electronic processing and other factors should allow for comparable, of not better, quality with smaller cameras that have image between 30 and 50 Megapixels.

Technical Challenges: Imagery data will by far exceed all other sources of data to be transmitted to Earth during Artemis missions. The primary enabling capabilities to support digital imagery from the moon will be: robust wireless communications (for imagery during EVA’s on the Moon’s Surface), large capacity solid state data storage, and high-bandwidth data links from the Moon’s surface to the Earth.

Artemis missions envision longer, more numerous, Extra Vehicular excursions on the Moon’s surface, that go much further away from the lander or a future base camp than Apollo missions. Scientists and ground controllers will need a steady stream of imagery data from the crew during these excursions. Should the astronauts stumble upon something unique or unexpected, an image beamed back to Earth quickly will enable quick decision making to determine whether to leave the sample, or pick it up and bring it back to the spacecraft for return to Earth. Wireless communications, either from the camera to a suit outfitted as a wireless access point, or directly to a relay or the spacecraft will be required to enable this real-time transmission.

Due to practical bandwidth constraints, any imagery transmitted to Earth during an excursion will need to be compressed to small file sizes or streams (in the case of video). The higher resolution imagery will need to be recorded on or nearby the camera. That will require very high-capacity solid state data storage. Files sizes for RAW still imagery can be up to 60 Megabytes per file. Less compressed Ultra High Definition video can consume 100 Megabytes per minute of recorded video. This recorded data will be the equivalent of the film from the Apollo missions, containing the high-resolution imagery that will be seen and shared for generations.

Probably the most critical enabler of imagery from the Moon will be the data links back to Earth. Imagery will require orders of magnitude more data than other sources of streaming data, such as voice, telemetry, guidance, command and control data. For example, heavily compressed streaming Ultra High Definition Television could require up to 10 Megabits-per-second of bandwidth. That compression is very vulnerable to jitter and missing data packets, so the entire communications system must be scaled for the requirement. Proxy still images using JPEG compression will still be large files, likely between 4 and 10 Megabytes of data per file.

Summary: We live in an era where cameras are everywhere—on our phones, in our doorbells, on our cars, on every street corner. The public will expect to be able to ride along with the crew when we return to the Moon. Imagery will be the primary method of engaging the public and maintaining their interest. Replicating the quality of imagery we had during Apollo can be done in the digital era, but care must be taken to make sure the enabling technologies are in place. It is much easier to build these technologies into the system during the design and planning phase, than to retro-fit the spacecraft later in development.

References:
[1] https://www.history.nasa.gov/apollo_photo.html
Introduction: The next five years of lunar science and exploration represent the beginning of a new era of human and robotic exploration of the Solar System, with an international armada of missions focused on the Moon, and missions addressing fundamental questions about our origin, evolution and our future. A major focus of this armada is exploration of the South Circumpolar Region (SCR) [1,2] with two major goals: 1) Assess the distribution, modes of occurrence, characteristics and abundance of polar volatile species, particularly water, and 2) obtain a representative sample of the Moon outside of the Apollo-Luna exploration region, with emphasis on obtaining a sample of South Pole-Aitken (SPA) Basin ejecta. Here we focus on the second goal, and outline 12 major themes and objectives for the next five years to optimize the chances for achieving this goal.

1) SCR is like Apollo 16, not like Apollo 15 and 17: Geologic goals and objectives at Apollo 15 and 17 were clear, very morphologically distinct, and assisted in traverse planning and mission operations. In contrast, the SCR is like Apollo 16 site geology: Astronauts Young and Duke quickly discovered that there were no highland volcanic plains, but instead the region was dominated by highland impact breccias of immediately unknown, and still today, uncertain provenance. Revisiting the Apollo 16 mission traverses and results will provide major insights into optimizing SCR exploration.

2) A Lot Has Happened Since the Formation of the SPA Basin: The SPA Basin is the oldest accepted impact basin, and thus SPA ejecta and related deposits have been subject to very significant destruction and reworking by over 4 Ga of impact cratering at all scales. Detailed geologic mapping [e.g., 3-4] is required to document the provenance of materials (redistribution by overlapping impact crater ejecta deposits) at any given point in the SCR, and to select landing sites and optimize scientific return.

3) Implications for Mobility: In order to ensure that a single impact crater ejecta deposit does not dominate the traverse region (minimizing science return), a minimum Apollo-style LRV capability (tens of km distance) is required.

4) Implications for Human-Robotic Partnerships: Because of the complexity of the SCR geology [1-4], and the subtlety of visible petrologic distinctions, ground-controlled roving robotic precursors, scouts and extrapolation missions (all with a full array of remote-sensing instruments) will be essential to scientific success.

5) Implications for Landing Site Selection: Due to the significant number of large craters (and thus extensive ejecta deposits) in the SCR, landing site selection must incorporate detailed geologic mapping of overlapping ejecta deposits [1-3], as well as landing safety considerations, in order to optimize mission success.

6) Implications for Mission Planning, Systems Engineering and Systems Integration: Engineers, scientists and operations planning personal must work shoulder-to-shoulder to ensure the type of science and engineering synergism (SES) that evolved in Apollo, and that optimized mission scientific success.

7) Implications for Traverse Scientific Instrumentation: Due to the likelihood that virtually all samples will be impact breccias, sophisticated traverse and hand-held remote sensing instrumentation will be necessary to provide immediate detection of key minerals and geochemical signatures to enhance sample selection and triaging.

8) Implications for CONOPS: Traverse goals and objectives will not be as clear-cut as on Apollo 15 and 17, and will require intensive systems engineering integration efforts to optimize scientific return and real-time and intra-EVA replanning.

9) Implications for Real-Time Science Support: Despite major advances in communications and video bandwidth, the optimal “situational awareness” will always be with the Astronauts on the ground [5]. This means that the Apollo ‘T3’ approach (Train ‘em, Trust ‘em, and Turn ‘em loose) should be the guideline for the real-time Ground Science Support Team and procedures should be developed for seamless updates and any real-time mid-course exploration corrections from ground-monitored remote sensing data or other updates.

10) Implications for Astronaut Training: The Apollo-like nature of the SCR means that a major pre-mission focus should be on intensive classroom, laboratory and field training of the Astronauts in lunar science and samples, sampling optimization procedures in impact-breccia-related terrains, and working shoulder-to-shoulder to ensure SES. Focus should be on 1) the optimization of handheld real-time sample characterization procedures, 2) seamless updates from the ground on data collected remotely, 3) obtaining a representative sample, and 4) ensuring time and openness to unanticipated discoveries (e.g., and obtaining pyroclastic glass on Apollo 15 and 17).

11) Implication for Sample Return Mass: The complexity of the SCR geology means that mission success and scientific return will be determined post-mission, after the samples are unpacked and analyzed in terrestrial laboratories. Thus, sample return mass for each mission must have a minimum of Apollo J-Missions (Apollo 17: >110 kg).

12) Implications for Feed-Forward to Mars: Procedures for human and robotic exploration of the SCR must always consider what lessons can be learned to optimize human Mars exploration, where immediate communications are not possible. Chief among these lessons will be: 1) optimizing crew scientific training and independence during EVAs, and 2) focusing debriefing and exploration replanning into periods between EVAs.

Beyond the next five years, we are also researching the needs for human long-term and short-term camping habitats using synthetic biology and mycotecture [6] and integrating them into design structures and reference missions.

A Legacy of Lunar Water Through SOFIA. C. I. Honniball¹, P. G. Lucey², and W. T. Reach³; ¹NASA Goddard Space Flight Center (casey.i.honniball@nasa.gov), ²University of Hawaii at Manoa, ³Universities Space Research Association, SOFIA.

Introduction: Through its unique instrument suite and operational altitude above 99.9% of Earth's atmosphere, the Stratospheric Observatory For Infrared Astronomy (SOFIA) has allowed for molecular water on the sunlit Moon to be detected unambiguously for the first time (Figure 1) [1]. This was accomplished using the H-O-H bending vibration at 6.07 µm that is unique to molecular water and does not occur in any other hydroxyl-bearing species. The H-O-H 6 µm band has been used for decades to detect and quantify water in geologic thin sections using FTIR spectroscopy [2-5].

![Figure 1: Spectra of high southern lunar latitudes showing strong 6 µm emission bands indicating the presence of H₂O.](image)

The detection of water on the sunlit Moon is of high importance for planetary and lunar science. At this time SOFIA, using the FORCAST instrument, is the only observatory capable of detecting and mapping the 6 µm water band on the Moon. Initial detections of water on the Moon with SOFIA were made at high southern latitudes in one region. Using FORCAST on SOFIA we have tentative approval from the SOFIA project for a 2-year Legacy campaign to map water on the sunlit Moon.

The goals of this Legacy project are to:

1. Address the origin of lunar water by characterizing its variation, mobility, and storage on the lunar surface.
2. Identify rare minerals and exposed lunar mantle material using the Christensen Feature and other spectral features in the 6 µm region.
3. Determine if other highly volatile compounds are present on the lunar surface.

Proposed Observations: For the Legacy project we will use two observing modes, one that samples a large fraction of the lunar surface at many lunar times of day and one that creates complete continuous maps of geologically interesting locations.

By sampling a large fraction of the Moon at many lunar times of day we can address goals 1 and 3. Scanning of the FORCAST slit across the Moon as a push-broom imaging spectrometer will be most efficient at gathering the large amounts of lunar locations needed to address compositional and latitudinal variations of water. With similar latitude and longitudes observed at many lunar times of day, the mobility of water and storage of water on the lunar surface can be addressed by measuring hourly diurnal variations. These observations are accomplished over multiple Earth nights where one Earth day advances the lunar time of day by about one hour.

Complete continuous mapping of volcanic deposits addresses all proposal goals. Continuous mapping of these locations will allow for maps of water and rare minerals (if detected) and may be used for Artemis landing site selection and resource utilization assessment. Goal 2 requires highly silicic features to be observed in order to determine if rare minerals are present from the Christensen feature and to determine if water is concentrated at these locations. Goals 1 and 3 require maps covering pyroclastic deposits to identify water sourced from the lunar interior.

Conclusions: Maps of water across the Moon at multiple lunar times of day, latitudes, and over a range of compositions will allow us to fully characterize the behavior and processes of water on the Moon. We will characterize the mobility of water and determine its correlation with solar wind intensity and other parameters that may indicate its formation mechanisms. Through SOFIA we will advance our understanding of water formation, storage, and retention on the lunar surface and extend this to other airless bodies. Maps created through the Legacy program will inform scientists on the availability of water as a resource and how to extract the water and may be used for landing site selection during the Artemis program.

Acknowledgments: Data that support the plot is publicly available from the SOFIA Data Cycle System at https://dcs.sofia.usra.edu and the Infrared Science Archive hosted by the Infrared Processing & Analysis Center (IPAC).


In the more than 50 years since the Apollo missions, thousands of scientists, operators, engineers, and managers have spent an enumerable amount of time and effort on a wide variety of missions to advance the boundaries of human knowledge, technology, and presence in our solar system. We stand on the cusp of the next giant leap in the story of humanity’s endless exploration of our world. In the next five years, we will establish a permanent presence on the moon by demonstrating the operational and scientific mission integration concepts required to do so. Space science operations specialists at NASA’s Marshall Space Flight Center (MSFC) in Huntsville Alabama, have spent those 50 plus years developing and evolving the methods necessary to accomplish this lofty goal.

NASA’s space science community has gathered essential lessons learned from the human and robotic missions to the Moon, Mars and beyond. Of preeminent importance from these, is the necessity to have well trained crews, scientist and operators who understand not only the scientific goals but also the operational methods that maximize the scientific returns. Over the past 20 years the Payload Operations and Integration Center (POIC) at MSFC has worked with the community of astronauts, scientists, international partners, commercial companies, and governmental representatives to train, integrate, operate and communicate the immense amount of information necessary to achieve innovative science aboard the International Space Station (ISS).

To accomplish the aspirational scientific goals of the Artemis missions, new methods for training crews, scientists, and operators are being developed that ensure efficient operations on the Moon that especially incorporate real-time feedback, high fidelity data, changes to science priorities, and in situ measurements. Having crews and operators who understand the science goals and scientists who understand the operational constraints is critical to the success of early Artemis missions.

In comparison to Apollo, Shuttle, Martian rover and ISS missions, the complex Artemis flight plans will require new and innovative integration techniques to be successful. Artemis science operations will span multiple programs, include international partners, various commercial interests and an exceedingly dispersed and diverse science team. In order to maximize science return and discovery potential, using a proven integration and operation model like that developed within MSFC’s Payload and Mission Operations Division (PMOD) will be crucial to overall mission success.

PMOD developed the following key tenants, called the Pillars of Payload Mission Operations to build upon NASA’s Foundation of Flight Operations. These attributes are necessary to maintain a permanent human presence in space and are indispensable to operating the scientific payloads essential to human spaceflight. Through these Pillars, NASA will help advance knowledge for the benefit of the world and all humanity.

**Preparation:** Understanding that total preparation is only possible when we embrace the highly dynamic and uncertain environment of conducting science off the Earth

**Proactivity:** Remaining passionately curious, we create our best advantage: anticipating issues before they arise

**Attentiveness:** Scientific investigations require the diligent application of awareness, as the payloads caretaker we are dedicated to their constant monitoring

**Rigor:** No detail is too small, no efficiency gained is insignificant, through persistent and exhaustive verification we create the potential for further discovery

**Collaboration:** We recognize and trust the inputs and expertise of our team members, especially the scientists we represent and the commercial partners we support

**Agility:** Never changing compulsively but creatively and consistently innovating in the pursuit of perfection; to achieve perfection we must embrace change

**Humility:** Seeking always first to serve so as to empower those around us to succeed
Introduction: NASA’s human lunar exploration plans under the Artemis program call for sending the first woman and first person of color to the surface of the Moon by 2024 and establishing sustainable exploration by the end of the decade. Working with both commercial and international partners, NASA will establish a permanent human presence on the Moon within the next decade to uncover new scientific discoveries and lay the foundation for private companies to build a lunar economy. Longer duration missions on the lunar surface or in lunar orbit can also serve as a test bed for technologies to support future Mars exploration campaigns. The agency will use what we learn on the Moon to prepare for humanity's next giant leap - sending astronauts to Mars. This LEAG presentation will provide an overview of the Surface Habitat, its benefits, and the challenges faced operating on the lunar surface.

Artemis Base Camp: NASA intends to establish a sustained lunar presence with the development of the Artemis Base Camp by the end of the decade. The base camp core elements – including the lunar terrain vehicle (LTV), Pressurized Rover (PR), Surface Habitat (SH), power systems, and in-situ resource utilization (ISRU) systems – leverage new international and commercial partnerships and national investment in systems needed to return to the Moon, establish sustained human exploration of the moon, and contribute directly to the first human mission to Mars.

Lunar Surface Habitat. Anchoring the long-term, human-led exploration at the lunar South Pole is the lunar Surface Habitat (SH). The SH is a fixed surface habitat offering a home base for astronauts, hub for communications, science facility, extravehicular activity (EVA) equipment repair site, waste processing facility, supply hub, surface operations base, and test bed for sustained surface presence and preparation for Mars missions. The SH will be self-sufficient for operations on the lunar surface, including providing its own power generation, energy storage to survive eclipse periods, and capability to communicate with surface assets, orbital assets, and directly with Earth ground stations. Two (2) crew will initially live in the habitat for ~30-day stays with crew swap-outs occurring mid-mission, in which the PR crew trades places with the habitat crew. During the swap-out, the habitat will nominally support 4 crew for a short period of time. Long-term, the SH will evolve to support up to four (4) crew for up to 60-day stays.

There are many operational and environmental challenges the SH will face and must be designed to endure for the safety of the crew and mission. Design considerations must consider the ability for the crew to safely outfit the SH in partial gravity following initial deployment on the surface, enable the crew to safely transfer logistics into and out of the SH, maintain nominal SH operation during long-duration uncrewed missions, mitigate the impacts of dust contamination and radiation on both internal and external systems and surfaces, and maintain nominal SH operation during 100hr+ eclipse periods.

Commercial Partnerships: While a suite of habitation concepts is currently under study within NASA, the agency is also working closely with U.S. industry through the Next Space Technologies for Exploration Partnerships (NextSTEP) activity to understand their concepts for commercially provided habitation capabilities as well as close coordination with our international partners to understand their desires for in-space and surface habitation.

Summary: The lunar Surface Habitat (SH) will anchor the long-term, human-led exploration at the lunar South Pole, enabling a sustained lunar presence. Utilizing the SH as a test bed for Mars analog missions will also ensure NASA and its partners can successfully pivot to eventual human missions to Mars.
OPTICAL MONITORING OF THE DUST ENVIRONMENT AROUND LUNAR EXPLORATION SITES.
R. Lolachi\textsuperscript{1,2,*}, D. A. Glenar\textsuperscript{1,2}, T. J. Stubbs\textsuperscript{1}. \textsuperscript{1}University of Maryland, Baltimore Co., Baltimore, MD, \textsuperscript{2}NASA Goddard Space Flight Center, Greenbelt, MD. *Corresponding author: rlolachi@umbc.edu

Abstract: The lunar dust environment and its impact on surface operations during the Artemis era are critical areas of study at this time. Lessons from the Apollo program showed that dust perturbed by human activities on the lunar surface can interfere with the operation of mechanical, thermal and optical systems, in particular the integrity of moving mechanisms and pressure seals\textsuperscript{1}.

Monitoring the local dust environment during surface activities by measuring the overlying dust loading will be an important capability. This could be accomplished at individual locations using elevated in situ dust detectors; however, a complementary, and arguably more comprehensive, approach would be to measure the intensity of scattered sunlight from dust in the environment surrounding an exploration site.

These measurements can be accomplished using modest cameras and will yield the abundance of dust along an observer line-of-sight. Observations along several look-directions can reveal the dust spatial distribution and can also constrain the average grain size by measuring the angular width of the forward scattering lobe. Perhaps most importantly, these measurements will be able to constrain spatial and temporal variations in dust ejection and deposition rates. Optical measurements of this type can be very sensitive, as demonstrated by the recent detection of faint FUV sunlight scattering by dust in the permanent impact-generated ejecta cloud surrounding the Moon\textsuperscript{2}.

Using a precomputed grid of scattering properties for realistically-shaped grains, we simulate spectral intensities for the scattering of sunlight by a plausible steady-state dust distribution (Fig. 1) around an exploration site to assess the feasibility of using commonly available wide-angle optics and commercial off-the-shelf (COTS) image sensors to create a simple notional dust monitoring camera. We model the dust detection sensitivity of cameras constructed using the PL1 (LEIA) imager aboard LICIACube (companion CubeSat on the NASA DART mission)\textsuperscript{3}, as well as sensors available from Hamamatsu and Ximea. Our present dust scattering grid spans UV to near-IR wavelengths and is computed for multiple grain shapes and sizes. Our results indicate that a simple camera can successfully detect a steady-state anthropogenically-raised dust cloud with a peak concentration of < 1 \(\mu\text{g m}^{-3}\) for a polar site on the Moon—well below what might be expected during surface activities on Artemis missions. Additionally, zodiacal light can be monitored and used as a periodic calibration source\textsuperscript{4}.


Figure 1 | (Left) Cross-section of the dust mass concentration model across the exploration site used in this study (Right) Astronaut, Surveyor spacecraft and Apollo Lander given for size comparison to vertical scale of model. The large difference between the vertical and horizontal scaling of the model means that an astronaut or spacecraft would experience an almost plane-parallel change in dust abundances. Our results indicate that during Artemis missions a COTS-based camera could even detect highly tenuous dust clouds produced by surface operations with peak mass abundances of <1 \(\mu\text{g m}^{-3}\) for a polar site on the Moon.

**Introduction:** Europe interest in space resources is growing. After several successful workshops on space mining and ISRU, the European Space Agency (ESA) and Luxembourg Space Agency (LSA) gathered the international community at the Space Resources Week 2021. The event started with a professional course, teaching state-of-the-art knowledge and challenges across the space resources value chain to 80 young and senior professionals. The course was then followed by a 4-day hybrid workshop. More than 1000 participants from 66 countries followed the workshop, with oral presentations and discussions of over 120 speakers.

Exploration missions update, space and terrestrial industry capability, and R&D progress were presented and actively discussed. Discussions about legal, regulatory and business aspects took also part during the workshop. The focus of the 2021 edition was utilization scenario. Groups with key experts across the value chain were organized to respectively debate the status of landing pad manufacturing, rocket refueling and sustainable infrastructure, understand the challenges and identify potential showstoppers. The authors want to share the lessons learnt during this international event.

**Utilization Scenarios:** Space Resources will only be useful if they serve a purpose. Processing regolith from the Moon and other rocks to produce rocket refuel or contribute to the manufacturing of a sustainable infrastructure are use cases often discussed in the community as being primary drivers for space resources. Yet, understanding the end user vision is required to insure that ISRU scientist and engineer are working on tackling the right challenges.

**Rocket refueling:** Representatives of large rockets manufacturer, Gateway and satellite refueling, propellant purification and storage and mining academia joined a panel to discuss their vision on the role of space resources for enabling refueling capabilities. They highlighted that no refueling demonstration of any cryogenic propellant (e.g., LOx/LH₂) had been done in space and that a first demonstration is needed from Earth propellant before considering the utilization of a propellant sourced from space materials. The quality of the propellant and the quality control before refueling are also open questions that would need to be answered as the technology to produce propellant in space advances. Moon propellant could either be sourced from lunar regolith or from polar water, would the latter be accessible. The economic viability would then drive the choice of a source over another.

**Sustainable Infrastructure:** Representatives from companies in space engineering, manufacturing technologies and architecture design, all involved in several space infrastructure concepts, provided their vision on the needs to develop sustainable infrastructures. Early-demonstration are expected to be critical to advance the field and understand better what can be sustainable. The existing technology and processes do not need a perfect understanding of the local resources to be demonstrated, the objective being to develop processes which are not dependent on specific soil properties. The sustainability does not only come from using local resources but by also showing that the processes do not produce any waste.
LUNAR EXOCAM - SURFACE MEASUREMENT OF LUNAR DUST PLUME MIGRATION

Jason Achilles Mezilis (1), Rex Ridenoure (2), Will Hovik (3), Kris Zacny (3), Dean Bergman (3), Jim Bell (4), Daniel C. Jacobs (4), Christopher McCormick (5), Matthew Adkins (6), Jnaneshwar Das (4), Harish Anand (5), Abdullah Masud (6), Lakshmi Gana Prasad Anturvedi (6), Darwin Mick (6), Katrina Davis (6); (1) Zanef Deksit Inc., Los Angeles CA info@zanefdeksit.com; (2) Ecliptic Enterprises Corporation, Pasadena CA; (3) Honeybee Robotics, Altadena CA; (4) School of Earth and Space Exploration, Arizona State University (ASU), Tempe AZ; (5) Interplanetary Initiative, ASU, Tempe AZ; (6) DREAMS Laboratory, ASU, Tempe AZ

ABSTRACT

The behavior of regolith plume migration in the lunar surface environment caused by lunar lander rocket propulsion remains largely unobserved. No sensor has directly measured the ejecta from lunar rocket engine plumes. With NASA’s forthcoming Artemis program focusing on lunar settlement in the coming years, a full characterization of these physical systems is essential.

Previous first-hand observations of Surveyor 3 by the Apollo 12 astronauts highlighted the adverse effects of regolith migration at a considerable distance from arriving spacecraft. By and large this is a well-recognized and concerning information gap in the lunar science community. Both design and proximity of landing areas and co-located physical structures will depend on lessons gathered from reliable regolith migration data.

“Lunar ExoCam” is a remotely deployed lunar payload that will eject during the final moments of descent of a lunar lander, for the purpose of safely landing a small camera / sensor module within the high-speed regolith dispersion cloud. Once ejected, this module will employ a 360° FOV high-definition video and particle-impact sensor suite for gathering in situ data to better inform future modeling efforts. This instrumentation set assures simplicity of ExoCam payload design, as no specific orientation or moving parts are required.

CURRENT DEVELOPMENT

In October 2020, Lunar ExoCam was awarded a grant under the NASA “Flight Opportunities” program. These funds will enable advancement of the system via an October 2021 test flight on board the Masten Space Systems Xodiac suborbital rocket, further elevating the ExoCam Technology Readiness Level and demonstrating overall payload effectiveness in terrestrial environment.

The NASA Flight Opportunities program provides for funded inclusion of an educational institution. Arizona State University is currently engaged with two individual teams developing and enhancing the overall scientific viability of the ExoCam payload (pictured below):

1. Team One is developing image enhancement tools for analysis of visual data captured in the 360° HD video format, including complex pre-visualization renders and post-launch analysis.

2. Team Two is developing a particle sensor [Fig.1] that will be affixed to the exterior of the video camera. Piezoelectric sensors will be mounted on all six outward faces without interfering with the dual-lens camera FOVs.

SENSOR OPERATIONS

Dropped near the landing site, the goal of this multi-angle particle sensor will be to measure size and frequency of particle impacts dispersed by the landing plume. These data, when combined with detailed analysis of the video captured by the video camera system, will help improve dispersion models that can be used to plan surface science exploration and protect emplaced lunar surface infrastructure.

REFERENCE

[1] https://www.nasa.gov/specials/artemis/
[3] https://go.nasa.gov/3sizpIC

Fig. 1 – Early development of the Lunar ExoCam 360° field-of-view HD video camera / particle-impact sensor suite
INTENSE PASSIVE COMMERCIAL X-RAY SOURCES FOR CHEMICAL AND ELEMENTAL ANALYSIS. C. G. Morrison, Astro Nuclear Engineer USNC-Tech, c.morrison@usnc-tech.com

Introduction: USNC-Tech is developing radioisotope technology initially focused on heat and electricity called the Chargeable Atomic Battery (CAB); however, the same technology can be used to generate source of passive x-rays much larger than that has been available in the past.

There are several types of analyses methods that have utilized x-rays derived from radioisotopes. The particle induced x-ray emission (PIXE) and alpha particle x-ray spectroscopy (APXS) are relevant. These systems have worked well. However, their scale is generally small. For example, the Mars Exploration Rovers utilized less than 50 milli-Curie sources of Cm-244 [1]. The amount of time required to complete a scientific analysis is heavily dependent upon the strength of the source. Most analyses complete by the Mars rovers took multiple hours to properly analyze. USNC-Tech’s CAB technology provides significantly higher activity - up to a multiple 10s of kilo-Curies. Different types of commercial radioisotopes are compatible with the radioisotopes as shown in Table 1.

### Table 1. Radioisotopes

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<tr>
<th>Precursor</th>
<th>Radioisotope</th>
<th>Half-life [yr]</th>
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</thead>
<tbody>
<tr>
<td>$^{6}$Li</td>
<td>$^{3}$H</td>
<td>12.3</td>
</tr>
<tr>
<td>$^{169}$Tm</td>
<td>$^{170}$Tm</td>
<td>129 days</td>
</tr>
<tr>
<td>$^{59}$Co</td>
<td>$^{60}$Co</td>
<td>5.7</td>
</tr>
<tr>
<td>$^{151}$Eu, $^{153}$Eu</td>
<td>$^{152}$Eu, $^{154}$Eu</td>
<td>11.0 (avg.)</td>
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About CABs: Chargeable atomic batteries are manufactured using natural non-radioactive precursor material embedded within an encapsulation material. The precursor material is then activated or "charged" inside a radiation source and packaged. This concept is known as a Chargeable Atomic Battery or CAB.

CABs can be manufactured in existing facilities and have a path toward a prototype using available technologies and facilities. For watt-scale batteries, the process can be demonstrated to a TRL of 6 with a ground demonstration and licensing in the next two years, focusing on a circa 2024 flight demo.

Science Applications: There could be multiple scientific use cases for the intense x-ray source offered by the CAB technology. An x-ray laser for example. The radioisotope could be modified with a pinhole collimated beam that could be directed at objects far away.

The intense x-ray beam could greatly reduce the spectroscopic scanning time for samples by a few orders of magnitude, enabling fast scanning of large numbers of samples. If the strong x-ray source is combined with a deep learning physics model, the composition of the ground up to several cm deep could be evaluated based on reflected x-rays and time of flight measurements. Remote sensing from a distance of meters or perhaps even km could be enabled.

Combining the intense x-ray source with other remote sensing methods such as visible light, infrared, and other neutron sources could offer a superior sensing technology for applications such as lunar water detection.

For lunar missions looking to survive the lunar night, passive heat generated by the x-ray source could be utilized to extend the mission lifetime.

Partners: USNC-Tech is looking for knowledgeable sciences to brainstorm possible novel sensing instruments enabled by the CAB technology. USNC-Tech would be interested in participating in upcoming science focused proposal calls such as PICASSO and the PRISM-2 call. Interested partners are encouraged to reach out to the author.

References:

LUNAR NIGHT SURVIVAL AND OPERATION UTILIZING COMMERCIAL RADIOISOTOPE HEATERS AND ELECTRIC GENERATORS. C. G. Morrison, Astro Nuclear Engineer USNC-Tech, c.morrison@usnc-tech.com

Introduction: Atomic batteries possess one million times the energy density of state-of-the-art chemical batteries and fossil fuels. Atomic batteries are enabling for locations that do not have access to the sun or other energy sources. Relevant use cases on the Moon include surviving the lunar night, exploring permanently shadowed regions, cave exploration and process heat for ISRU. USNC-Tech is maturing a patented (PCTUS2116982, PCTUS2116980) atomic battery technology and is actively engaging the government, science communities, commercial companies, regulatory agencies, and manufacturing partners to achieve a commercial product.

The challenges in production and the complexity of containing nuclear material have limited the application of atomic batteries. Traditional atomic battery solutions focus on the high-performance but expensive special nuclear material Plutonium-238. The cost, necessarily controlled nature, and limited supply of Pu-238 prevent widespread commercial use.

Atomic batteries are manufactured using natural non-radioactive precursor material embedded within an encapsulation material. The precursor material is then activated or "charged" inside a radiation source and packaged. This concept is known as a Chargeable Atomic Battery or CAB.

CABs can be manufactured in existing facilities and have a path toward a prototype using available technologies and facilities. For watt-scale batteries, the process can be demonstrated to a TRL of 6 with a ground demonstration and licensing in the next two years, focusing on a circa 2024 flight demo.

CAB Product: A CAB Unit is a cylindrical heterogeneous ceramic with an outer wall and a filling, as shown in Figure 2. The wall is composed of encapsulation material, and the filling is composed of an activation target material known as a precursor material. Multiple CAB units are integrated into a stack. The stack is integrated into a system that could include an x-ray shield, power conversion, thermal management, and aeroshell.

The encapsulation method is used with different types of isotopes. CAB units are tailored to meet the half-life, x-ray shielding, and power density needs of different science and commercial customers.

Table 1. Radioisotopes

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Science Mission Applications: USNC-Tech is developing a 1 to 100 W modular thermal heater unit to enable lunar night survival for landers, rovers, and science payloads as soon as 2024. We are also evaluating electric power conversion options looking at 1 to 5 watt thermoelectric systems and 40-100 W electric Stirling systems. We want to engage with science customers at LEAG to determine needs within the science community for these ideas.

Conclusions: CAB technology isn’t as high performance as Pu-238. However, CAB technology can provide many of the same benefits. Interested parties are encouraged to reach out to the author.
IN-SITU ARTIFICIAL SUBSTRATE WITNESS PLATES: GROUND TRUTHING SCIENTIFIC AND HUMAN OPERATIONS RELEVANT PROCESSES ON THE MOON. L. Morrissey1,2, P. Saxena2,3, J. McClain2, N. Curran2, and R. M. Killen2, 1CRESST II/SURA, Washington, DC 20005, USA, 2NASA GSFC, Greenbelt, Maryland 20771, USA, 3CRESST II/University of Maryland, College Park, Maryland 20742, USA

Introduction: Given the stark increase in lunar orbital and surface efforts by several countries, there is a pressing need to better understand several scientific and operational relevant surface processes. A NASA led effort to return astronauts to the Moon, Artemis, is an initial step to long-term sustainable human presence at the Moon. However, more research is needed on how lunar surface processes can interact with and modify these exposed structures. There is a pressing scientific need to establish how these processes contribute to lunar surface modifications before anthropogenic effects potentially permanently contaminate the surface. Current and planned efforts are leveraging familiar remote sensing and sample acquisition techniques to examine the nature of surface processes on the Moon. In this study, we discuss the potential value of a tool complementary to these techniques, in-situ artificial substrate witness plates. Witness plate studies in planetary science have been used to address targeted science questions as well as potential contamination of in-situ measurements on several missions [1-3]. In the case of the SWC experiments, flux variation between the different missions indicated that many key surface processes vary with location. Consequently, measurements that sample the Moon in different locations are needed to truly understand how these processes operate globally. Witness plates can simultaneously assess material performance as a function of time and location while also providing an important control for several lunar processes before increased human activity.

Artificial Witness Plates for the Future: In this study we investigated the potential of using an artificial substrate-based witness plate to capture location dependent lunar processes. These plates are low cost, low mass, and produce a low environmental footprint. They can capture processes relevant to science and operational objectives for a range of key locations. We explore 5 processes: 1) Water production and Transport 2) Solar Activity Related Effects 3) Micrometeorite Mass Flux and 4) Integrated Radiance. We outline key questions and signatures related to these processes and the locations on the Moon where their study is of high interest. Based upon this framework, we determine the ability and exposure time necessary to capture key parameters or bounds on these processes using a low mass, passive witness plate that can be placed on the surface and then analyzed later. Exposed plates will be fully characterized pre and post exposure, allowing for comparison of identical structures. Through modelling and calculations, we find that initially ‘perfect’ witness plates can be used to place important constraints and enable key measurements on relevant timescales such as a lunation or times similar to the proposed extent of the Artemis program. This analysis uses current instrumentation sensitivities, and these witness plates would be more diagnostic with increased instrumental sensitivity.

Model Witness Plates (Biscuits) and a Case Study: In addition to general analyses of potential witness plate substrates at a range of locations, we also conduct a case study using a hypothetical artificial substrate witness plate (which we title a “Biscuit”). Using SDTrimSP sputtering simulations we calculate the effect of solar wind (SW) weathering on an albite biscuit [4]. These dynamic simulations were used to determine the necessary exposure times for observable changes to the substrate’s mass and chemistry. Results demonstrated significant sputtering from albite due to SW impacts, with oxygen preferentially sputtered. After only 2 years of exposure simulations predict almost a 5% decrease in oxygen surface concentration, with .08 mg of albite lost after 10 years from a 20cm² biscuit. These instruments can provide a sustainable way of monitoring processes in key locations on planetary surfaces while also maintaining a low environmental footprint. While we specifically examine a customized version of these witness plates, we stress that all groups interested in planetary surfaces should consider these adaptable, low footprint tools for future exploration.

Fig. 1 Graphic Showing SW Impacts and Loss on an albite biscuit

CISLUNAR EXPLORERS: A STUDENT CUBESAT DEMONSTRATING LOW-COST TECHNOLOGIES FOR LUNAR EXPLORATION. Curran D. Muhlberger1, 1Cornell Ann S. Bowers College of Computing and Information Science, 107 Hoy Road, Ithaca, NY 14850, curran@cs.cornell.edu.

Introduction: Developed since 2014 by students in Cornell University’s Space Systems Design Studio, the Cislunar Explorers mission proposes to send a pair of 3U CubeSats to lunar orbit and demonstrate new technologies for water electrolysis propulsion and optical navigation in cislunar space. The vehicles showcase the results of a synergistic design process that reduces size and cost, paving the way for smaller missions to participate in lunar exploration. With water as the propellant, the architecture is suitable for missions leveraging in situ resource utilization, while water’s safety and simple storage requirements lend themselves to the constraints of nanosatellite platforms.

A symbiosis between subsystems makes water electrolysis propulsion viable on such small vehicles. Launching as a pair provides redundancy as well as a natural way to impart a spin during deployment. The spacecraft’s spin separates the electrolysis products (hydrogen and oxygen gas) from the liquid propellant while also reducing the hardware required for attitude determination and control—the moment of a single cold gas thruster and the fields of view of three cameras vary with rotation to cover all directions. Propellant slosh dampens out nutation, passively stabilizing the rotation axis. The water tank also acts as a natural heat sink for the avionics (keeping the propellant from freezing) and is an integral structural component.

Costs are also kept low by using off-the-shelf avionics, including a Raspberry Pi flight computer, Raspberry Pi camera modules, and hobbyist breakout boards for sensors. The flight software is written in Python, leveraging existing libraries to interface with sensors, which lowers the barrier of entry for new developers. The optical navigation system performs efficient rolling shutter correction and stereographic reprojection to maximize the accuracy of measurements made of the Earth and Moon, even when largely in shadow, with modest computational resources. Using the SurRender [1] image simulator, this system can be tuned and verified for other trajectories and camera sensors; preliminary results suggest translational accuracy within 100 km, sufficient for guidance into lunar orbit.

Competing successfully in NASA’s Cube Quest Challenge, Cislunar Explorers was originally manifested on Artemis 1. However, student-led missions present unique challenges, and difficulties during integration have forced a delay. The spacecraft are on track for completion within the next year, and the lessons learned [2] should help future small-scale lunar missions reduce cost and integration time. Through demonstration of water electrolysis propulsion and autonomous navigation on a small, low-cost platform, Cislunar Explorers hopes to broaden participation in orbital lunar science and encourage smaller lander concepts utilizing in situ resources for sample return.

Acknowledgments: The mission team would like to thank NASA’s Centennial Challenges program for supporting Cislunar Explorers through the Cube Quest Challenge, our payload partners at Los Alamos National Laboratory, our advisors from the National Space Society, and Airbus for use of their SurRender software. We are also grateful for the numerous students who have contributed to this project over the past 7 years.

An International Lunar Resource Prospecting Campaign.  C. R. Neal¹, A. Abbud-Madrid², and J. Carpenter³,
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**Introduction:** Resources that could be useful for sustaining humans on the Moon (and potentially for export off the Moon) have been known to exist for several years. However, understanding them and their use in enabling science, human exploration, and a vibrant cislunar economy remains rudimentary at best. Why is this and what is the critical next step that could build science, exploration, and commercial synergies?

**Resources vs. Reserves:** This semantic yet critical distinction is crucial in understanding the full scientific, exploration, and commercial potential of lunar resources. The USGS [1] defines resources and reserves as follows: **Resource:** a concentration of naturally occurring solid, liquid, or gaseous materials in or on the crust in such form that economic extraction of a commodity is regarded as feasible. **Reserve:** That portion of an identified resource from which a usable mineral or energy commodity can be economically and legally extracted at the time of determination.

The term “resource” in a lunar context has been used interchangeably with “reserve”, which has caused confusion. Based upon current knowledge and likely users, the only potential lunar reserve is oxygen from regolith as it is present in about the same proportion anywhere on the Moon. However, defining it as a “reserve” requires the economic and legal issues to be addressed.

**Economics:** The reserve definition implies that the resource can be extracted, refined, transported, and used at a profit (i.e., the value of the products is more than the cost of acquiring the products). This has not been achieved for any lunar resource because only the United Launch Alliance has placed a value on lunar-derived water (for rocket fuel) at $500/kg [2,3]. At this time, the true market value is not established so the economic potential of lunar resources cannot be evaluated.

**Legal Implications:** The Outer Space Treaty (OST) [4] has been interpreted to indicate use of lunar resources is prohibited or severely restricted. For example, Article I states: “The exploration and use of outer space, including the Moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries”. However, Article III states: “States Parties to the Treaty shall carry on activities in the exploration and use of outer space, including the Moon and other celestial bodies... in the interest of maintaining international peace and security and promoting international co-operation and understanding”. An International Lunar Resource Prospecting Campaign would therefore be compliant with the Outer Space Treaty.

The Artemis Accords [5] establishes a common vision via a set of principles, guidelines, and best practices for the governance of the civil exploration/use of outer space to advance the Artemis Program. Space resources are highlighted where the signatories:

- note that the utilization of space resources can benefit humankind by providing critical support for safe & sustainable operations;
- emphasize that extraction & utilization of space resources be executed to comply with the OST & in support of safe & sustainable space activities;
- commit to informing the Secretary-General of the United Nations as well as the public and the international scientific community of their space resource extraction activities in accordance with the OST;
- intend to use their experience under the Accords to contribute to multilateral efforts to further develop international practices and rules applicable to the extraction and utilization of space resources, including through ongoing efforts at the COPUOS.

**An International Lunar Resource Prospecting Campaign:** An international resource prospecting campaign is needed to understand the full economic potential of the Moon and comply with [4]. This has begun in an ad hoc fashion with the ISEC member missions to the lunar south pole to explore volatile deposits [6], but extensive cooperation between nations is lacking. This could be initiated either by the Artemis Accords or the ISEC, building on the work of LEAG [6]. Encouraging such international collaboration in lunar prospecting, international diplomacy is promoted. History shows us that international cooperation in space leads to an enduring program (e.g., ISS), whereas competition does not (e.g., Apollo). An international lunar resource prospecting campaign allows countries to participate in this exploration, regardless of economic status. Countries could contribute instruments, launch vehicles, rovers, etc., to ensure the same datasets are obtained for each site identified by orbital data (e.g., [7]). By sharing data obtained from this campaign (which will inform science, exploration, and commerce), commercial companies (& space agencies) will understand the reserve potential of lunar resources, such that a true market value can be determined and the reserve potential fully evaluated into the future. This allows lunar resources to be, for the first time, considered as essential for establishing a permanent human presence on the Moon and kick-starting the cislunar economy that would benefit society here on Earth.


Introduction: The Lunar Geophysical Network (LGN) mission will be part of NASA’s New Frontiers 5 call [1]. Work conducted as part of NASA’s Planetary Mission Concept Study initiative has further developed this mission [2]. The primary LGN goal is to understand the initial stages of terrestrial planet evolution, which is preserved in the Moon as seen from understanding the source region compositions of mare basalts.

Baseline Mission: Four identical landers will be put into lunar orbit together and deployed sequentially around the Moon. A dedicated relay satellite will communicate with a farside station. Nearside stations will use direct-to-Earth communication but can use the relay satellite if needed, for redundancy. The mission duration is 6 years (1 lunar tidal cycle) with a goal of 10 years. Each lander will carry identical instrumentation: both short period and very broad band seismometers, a lunar magnetotelluric sounding suite, heat flow probes, and laser retroreflectors. This allows landers to be re-directed in case of non-optimal deployment.

Objectives and Investigations: LGN has four science objectives that will be achieved through five investigations:

| Objectives: |
| 1. Evaluate the interior structure & dynamics of the Moon |
| 2. Constrain the interior and bulk composition of the Moon |
| 3. Delineate the vertical/lateral heterogeneities within the interior of the Moon as they relate to surface features and terranes |
| 4. Evaluate current lunar seismo-tectonic activity. |

| Investigations: |
| 1. Determine the size, state, and composition of the lunar core |
| 2. Determine the state and chemical/physical stratification of the lunar mantle |
| 3. Determine the thickness of the lunar crust and characterize its vertical and lateral variability |
| 4. Determine the thermal state of the lunar interior and elucidate the workings of the planetary heat engine |
| 5. Monitor impact events on the lunar surface. |

Landing Sites: Three nearside sites (PKT; Schickard Basin – SB; Mare Crisium – MC) and one farside site (Korolev Basin – KB) have been identified as candidates that best meet LGN science objectives [3]. These sites best enable definition of the structure of the lunar interior (SB & KB are favorably located for core phase observations from known deep moonquake nests) and span crustal thicknesses. The SB and KB sites are close to lobate scarps and could investigate shallow moonquake seismicity. Heat flow and magnetotelluric sounding will be determined from distinct terranes, both heat-producing (PKT) and without the crustal layer (MC). The deployed laser retroreflectors will significantly expand the current network (Apollo and Lunokhod sites) allowing much needed increased fidelity on ranging measurements to place better constraints on the Moon’s geodetic parameters.

CLPS and LGN: NASA has now selected multiple Commercial Lunar Payload Services (CLPS) landers to deliver science instruments to the Moon beginning in 2021, and continues to solicit new instruments annually. CLPS landers can currently carry ~35kg of total payload (LGN nominal payload mass is ~76kg) and survive for one lunar day (LGN requires a minimum of 6 years which is equivalent to ~76 full lunations); NASA is the marginal customer, meaning that CLPS landers primarily serve as delivery platforms rather than integrated science missions. While CLPS is an exciting model for lunar surface access, it is not yet proven, and the scope is very different – these missions do not replace the function of Discovery and New Frontiers to enable Decadal-level science investigations. Rather, CLPS missions can enable LGN by retiring key risks such as deployment strategies, lander noise characterization, and thermal and power performance. In the next few years, the repeated success of multiple new lander providers may eventually enable a mission like LGN to shop around and save on mission bus costs.

A 21-cm Cosmology Experiment on the Far Side of the Moon.

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The Lunar Surface Electromagnetics Experiment (LuSEE) will measure the radio-frequency sky between 50 kHz and 50 MHz from the Schrödinger basin. Of particular interest in this frequency band is redshifted 21-cm emission from the cosmic dark ages, which cannot be easily probed from Earth due to reflection from the ionosphere and interference from artificial sources. LuSEE will place constraints on the amplitude of the predicted trough in cosmic H I brightness at $z \sim 100$. Detection of this 50 mK signal amid the $10^4$ K galactic foreground will require exquisite systematics control and elaborate data processing. In anticipation of these challenges, we generated synthetic LuSEE data and evaluated the ability of foreground mitigation techniques to extract the cosmological signal.
ENVI RONMENTAL ANALYSIS OF THE BOUNDED LUNAR EXOSPHERE (ENABLE): ANALYTICAL CHEMISTRY IN EXTREME HIGH VACUUM (XHV).

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Introduction: The difference in scale between terrestrial sea level atmospheric pressure of our everyday experience and that at the lunar equator at local Midnight is approximately the same as the difference between the width of a microwave oven and the radius of a proton. From the opposite perspective, the difference in scale between pressure at the lunar equator at local Midnight and that at the seashore is about the same as that between the length of a school bus and the distance to Alpha Centauri.

Beneath the extreme high vacuum (XHV) of the lunar surface bounded exosphere (SBE)[1] are unexplored local and regional traps for native volatiles. During the coming prospecting and processing efforts for in situ resource utilization (ISRU), artificial contamination will unavoidably result from robotic and human operations at the lunar surface. It is therefore essential that signatures of contaminants be distinguished from those of important native volatiles through appropriate analytical techniques.

Pressure at the Lunar Surface: Quantitative pressure detection began at the lunar surface in November 1972 with the deployment of the Cold Cathode Gauge Experiment (CCGE) by the Apollo 12 (A12) astronauts[2]. Deployed and operating during lunar daylight, the CCGE successfully detected elevated background pressures at the lunar landing site due to artificial contamination, human activities that included depressurization (“depress”) of the A12 Lunar Module cabin, and a pressure saturation condition produced by the backpack of Commander “Pete” Conrad walking away from the sensor[3].

Lunar Mass Spectrometry: Mass spectrometry from the lunar surface began in December 1972 with deployment of the Lunar Atmospheric Composition Experiment (LACE) during Apollo 17[4]. Among its results, LACE successfully detected He, Ne and Ar in the lunar exosphere.

ENABLE: The Environmental Analysis of the Bounded Lunar Exosphere (ENABLE) project seeks to produce a prototype flightworthy mass spectrometer for use at the lunar surface. For this purpose we have selected a commercial off-the-shelf (COTS) quadrupole mass spectrometer (QMS) residual gas analyzer (RGA) as the basis for our prototype design.

The COTS unit is capable of pressure measurement over the nearly 15 order of magnitude range from terrestrial atmosphere to $1 \times 10^{-12}$ Torr. These pressure detection features include an integral Pirani gauge ($\geq 1 \times 10^{-3}$ Torr) and Bayard-Alpert ion gauge ($\leq 1 \times 10^{-2}$ Torr). Partial pressure detection by mass spectrometry is conducted with a Faraday cup at pressures below $5 \times 10^{-4}$ Torr with a lower sensitivity limit of $5 \times 10^{-12}$ Torr and a multiplier that can operate from $5 \times 10^{-6}$ Torr to $5 \times 10^{-14}$ Torr, thus covering over 15 orders of magnitude in pressure. Mass scanning can be conducted in 0.1 Da steps from 1 to 300 Da.

The instrument is capable of producing electron bombardment (EB) energies spanning a wide range (11 - 150 eV). Traditional EB energy used is 70 eV, but lower energies can be utilized to emphasize trace gas species over dominant majority gas species of lower mass that require significantly higher impact energies.

Data will be presented on the operation of the COTS QMS and how mass peaks of organic molecules can be amplified against those of major gas species. We will also cover the various mission platforms and lunar environment scenarios envisioned for ENABLE operations (Fig. 1), including as a detector for leaks, micrometeoroid swarms, overflying spacecraft, or for triangulation—along with a network of other MS instruments—to identify and analyze gas plumes from landing spacecraft, impactors, or surface vents.

Fig. 1. A future astronaut adjusts her ENABLE mass spectrometer as a colleague obtains a gas sample.

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THE LUNAR RECONNAISSANCE ORBITER IN 2021 AND BEYOND: STATUS AND FUTURE PLANS.

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Introduction: The Lunar Reconnaissance Orbiter (LRO) is in its 12th year of operations at the Moon. This duration enables fundamentally new science, observing changes to the lunar surface and environment over the human timescale. Additionally, the ability of LRO to respond to data acquisition requests in support of robotic and crewed missions to the surface, is a critical resource for the agency [1].

Landing Site Characterization: LRO data was envisioned to be used to support human and robotic missions to the surface. With over decade of observations, LRO has delivered over 1.3 Pb of data available for use in the PDS. This data volume includes maps of topography, slope, temperature, rock abundance, etc. [e.g.,2].

This new era of lunar surface exploration also enables a new age of coordinated lunar science between an orbital asset and surface assets. During Apollo, the best example of coordinated measurements between the surface and an orbital asset occurred with a comparison of surface magnetic fields by ALSEP and the deep space environment by Explorer 35 [3]. During this modern period of exploration, we may offer similar coincident measurements that benefit both LRO, CLPS landers, and Artemis operations.

Future of LRO: LRO is currently funded to operate through September 2022, however we have fuel onboard to support at least 6 more years of operations and are currently preparing an extended science mission proposal to extend operations until at least September 2025. During that time our orbit will continue to densify data coverage away from the poles (Figure 1, 2), we will continue to pass over areas within the “Artemis Zone” (poleward of -84º) (Figure 2).

Future Science for LRO: In addition to supporting future missions by characterizing landing sites and observing the effects of landing and surface operations, LRO will continue its science mission with a focus on volatiles [4], the thermal history of the Moon as expressed by volcanism and tectonics [5], and the evolution of the regolith [6]. The LRO science teams are actively developing new science questions that require additional data over the three years of our next extension. In the time frame of 2022-2025 we expect an unprecedented set of opportunities to connect our observations of the lunar surface and environment with in situ measurements from CLPS landers as well as the VIPER mission. These observations are a critical part of our preparation for future Artemis explorations of the South Pole.

Radiation Dosage From Solar Energetic Particles Around a Lunar Crater

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Introduction: The Moon has a harsh radiation environment that poses significant challenges to future science and exploration activities. Exposure hazards from space radiation are primarily due to galactic cosmic rays (GCRs) and solar energetic particles (SEPs) that are incident at the lunar surface from all directions. The Lunar Reconnaissance Orbiter’s (LRO) Cosmic Ray Telescope for Effects of Radiation (CRaTER) instrument has been observing space radiation around the Moon since 2009 [1]. The CRaTER observations show a steady GCR flux with intermittent SEP events that have much higher fluxes. During solar minimum GCRs have a higher flux, while SEP events are less common. On the other hand, during solar maximum the SEP events have a higher rate, but the GCR flux is lower. This is due to variations in solar activity. GCRs have characteristic energies spanning from 1 MeV to 10s of GeV [2]. SEPs, however, have much lower energy ranges of 50 keV to 100s of MeV.

![Illustration of how natural shielding from surrounding terrain effects radiation exposure at the lunar surface in and around a crater during a solar energetic particle (SEP) event. Inside the crater, the high elevation of the crater walls blocks SEPs incident at shallow angles.](image)

Figure 1: Illustration of how natural shielding from surrounding terrain effects radiation exposure at the lunar surface in and around a crater during a solar energetic particle (SEP) event. Inside the crater, the high elevation of the crater walls blocks SEPs incident at shallow angles.

The level of exposure at a given location on the Moon is dependent on the amount of space radiation incident from above the local horizon (Figure 1). This means that radiation dosage depends on the surrounding terrain for any location on the surface, so it can vary substantially from point to point. Here we consider the radiation exposure around simple lunar craters that are representative of the types of landforms that will be encountered by future landed missions (e.g., the Artemis program) [3]. Of particular concern will be radiation exposure to biological targets, such as astronauts, and to critical electronic systems.

Methods: We use Geant4 Monte Carlo simulations [4] to compute the dose response for spherical targets composed of water (H2O) and silicon (Si), as proxies for biological and electronic systems, respectively. These targets are surrounded by shells of aluminum of varying thickness to approximate the effects of shielding by space suits, rovers, and habitats. To determine the dose from SEP protons (e.g., in rad), we convolve the Geant4-computed dose responses with the fluence spectrum (integrated flux) for the infamous October 1989 SEP event [5]. This is widely regarded as the best event to use for predicting the worst case dose.

To determine the topographical effects, we created a 20 km diameter simple crater, similar to Shackleton Crater at the lunar South Pole. This provides a good proxy for the location of Artemis Base Camp 004, which is planned to be near the rim of Shackleton Crater. Measuring the local horizon for each location on a grid, we calculate the solid angle of the visible sky. This fraction can be multiplied by the dose computed from the Geant4 dose responses convolved with SEP spectrum. This gives the radiation dose received from SEP protons at each surface point.

Discussion and Conclusions: Radiation doses from sporadic, short-lived SEP events can be substantially larger than doses from the steady GCR background, thus resulting in acute radiation exposure. During the most extreme SEP events, such as those in October 1989 or August 1972, the radiation dosage at the lunar surface would be greater than the NASA astronaut 30-day radiation exposure limit [5]. However, such exposure can be significantly reduced by shielding from surrounding terrain. Therefore, for protection from SEP events, the shielding effects of surrounding terrain is an important consideration when selecting sites for permanent habitats, as well as for choosing routes and contingency planning during surface operations.

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**Introduction:** Permanently shadowed regions (PSRs) at the lunar poles maintain the thermal conditions necessary to harbor tens-of-meters thick deposits of nearly pure water ice for geologic time [1]. Such ice deposits have been unambiguously discovered by radar investigations within the PSRs of Mercury, however observations of the Moon’s PSRs have not resulted in the same level of certainty [2]. Models of ice delivery by ancient large hydrated impacts show that thick ice deposits could be buried and preserved below thick ejecta [3]. Therefore, if there are extensive ice deposits on the Moon, they may be buried below a > 1 m thick layer of regolith [4].

The Cosmic Ray Lunar Sounder (CoRaLS), a new orbital mission concept, will have the ability to detect and characterize subsurface ice deposits within the top 10-20 meters of lunar regolith, using the Askaryan effect of ultrahigh energy cosmic ray impacts, and may definitively discover or disprove the presence of extensive subsurface ice deposits in lunar PSRs.

**Askaryan Effect:** The lunar regolith is continually bombarded by cosmic rays, from GeV (10$^9$eV) up to ZeV energies (10$^{21}$eV). Due to the lack of a lunar atmosphere, ultrahigh energy cosmic rays (UHECR) (energies >10$^{18}$eV) enter the regolith unimpeded with their full energy. These cosmic rays produce strong secondary particle cascades within the regolith, extending for up to 10 meters at the highest energies. These particle cascades produce strong, coherent, wide-bandwidth, linearly-polarized radio pulses, demonstrated in numerous laboratory measurements over the last two decades; this emission process is known as the Askaryan effect [5]. Such UHECR-induced pulses are routinely observed in terrestrial atmospheric cascades by ground arrays, and have been observed by sub-orbital payloads from distances up to 700 km or more.

**Cosmic Ray Lunar Sounder (CoRaLS):** The cosmic ray-induced radio emission, created in the first few meters of the regolith via the Askaryan effect, will reflect off any subsurface ice layers (with lateral extent greater than ~5 m), including thin layers that are ~1 cm thick, as well as the regolith-bedrock interface. From its orbital altitude of ~25 km, CoRaLS’ dual-polarization interferometric radio receiver array can observe both the direct and reflected radio emission from these UHECR impacts.

Analysis of the direct and reflected radio signals (see figure), including the spectrum, amplitude, and polarization, allows for reconstructing the presence and properties of subsurface ice and bedrock layers.

These laboratory and Earth-based measurements, in conjunction with detailed full-wave electromagnetic simulations, confirm that such pulses will be observable by CoRaLS using existing radio receiver technology. The advantage of this technique over orbital active radar sounders is that the cosmic ray source acts as a high-quality dipole antenna embedded directly in the regolith very close to the targets of interest, avoiding both the decoherence, and surface clutter and losses, of a traditional active radar sounding design.

Over a two year mission, CoRaLS may be able to make ~600 independent detections of subsurface ice layers using roughly ~10,000 UHECR impacts and will be able to find and statistically characterize the subsurface ice distribution with ~1 km location resolution, characterize the depth and thickness distribution of a subset of well-measured ice layers, and measure the global lunar regolith depth distribution.

**References:**
[1] Paige D. A et al. (2010), Science, 330, 6003
Studies of In Situ Fissile Fuel from Lunar Resources
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Abstract: A nuclear reactor to power lunar habitats, science, and ISRU operations will dramatically increase productivity. Launching radioactive materials is controversial, so a new approach is called for. By using materials already extant on the lunar surface, it may be possible to produce the fissile fuel in situ. The key operations, to concentrate thorium, and then to transmute thorium into uranium, will become process steps having multiple additional scientific and engineering applications.

Two interesting natural phenomenon underpin the studies proposed herein. First, the surface concentration of thorium on the Moon is much higher than on Earth. Around certain craters, thorium has been excavated by meteorite bombardment, and may be 3-4 times more concentrated. Thorium is still a trace mineral, and will require further concentration. But Th is also very dense, so the means of density sorting of regolith can be used to concentrate other dense fractions, such as free iron.

The second phenomenon is the gamma ray fog, arriving isotropically from the deep sky. Although the origin of these gamma rays remains a mystery, they have been characterized by energy and flux. Beryllium exposed to these gamma rays becomes a neutron source. After passing through a graphite moderator, these neutrons will be captured by Th, which transmutes into U after a couple months as Pa. Such a neutron source on the moon can be used for several scientific purposes.

Hardware for testing density sorting and transmutation can be made very lightweight, just 10s of kg, and operated with modest tending (hours) by an astronaut or robot. Analytical equipment is minimal, such as a lab scale and a neutron scintillator and a few sample containers.

Density sorting methods adaptable to lunar gravity include momentum transfer and a hydrocyclone. Momentum transfer is simplest and easiest, and can use ferrous bullet particles to pass perpendicularly through a cascade of size-sorted regolith. Light fractions will be deflected further than dense fractions. Bins to capture outfall will be slightly concentrated on each pass, but can be readily fed back into the apparatus for another pass. Each pass concentrates by 2-5 percent, requiring 200-300 passes in order to achieve 95% purity. The first experiments on the moon need only run 20-30 times to demonstrate technical feasibility. With bullet particles collected from the bins by electromagnet, free iron, and Fe⁰-bearing agglomerates, can also be harvested at the same time.

Transmutation has no moving parts. Although it would be most satisfying to use concentrated lunar thorium, for the proof of concept, terrestrial Th will likely be used as the fertile source. The test apparatus can be self-contained, with no moving parts, and can operate without tending on the lunar surface. One embedded sensor would test for neutrons (scintillator with PMT, or microstructured semiconductor neutron detector) to characterize the n⁰ flux produced by gamma ray fog impinging on beryllium. A second sensor will test for the presence of uranium using X-ray fluorescence. Hand-held XRF sensors are readily available, and can test, over time, how the concentration of U increases as the following nuclear chemistry reaction runs to its completion:

\[
^{232}_{90}Th + n_0 \rightarrow ^{233}_{90}Th + \beta^- \rightarrow ^{233}_{91}Pa + \beta^- \rightarrow ^{233}_{92}U
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Detailed experimental plans are developed in this paper, and used to produce estimates of mass, volume, bandwidth, and operator attention for density sorting and transmutation. Results from such a test, on the Moon, could generate considerable interest in the development of a fission reactor for lunar operations where no radioactive materials are launched by rocket.

Future operations include the excavation needed to gather many tons of regolith in order to obtain meaningful quantities of Th, and chemical separation of uranium from protactinium and unchanged thorium (THOREX). Factors unique to the lunar surface are important to characterize, such as the influence of charged particles from the solar wind, which may require ionizers to prevent sticking or deflection. This work could lead to an ultra-safe baseload lunar reactor which now makes possible a very wide range of scientific, engineering, and human habitation endeavors on the Moon. As a further future development, such fissile fuel could be used to power nuclear thermal rockets, making it much easier and faster to reach Mars or main belt asteroid.
LRO INVESTIGATIONS OF VOLATILES PROCESSES AND THE SPACE ENVIRONMENT OF THE MOON. A. M. Stickle1, N. E. Petro2, C. M. Elder3, J. D. Stopar4, M. E. Banks5, J. W. Keller2 and the LRO Science Team 1Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Rd. M/S 200-W230, Laurel, MD 20723, angela.stickle@jhuapl.edu, 2NASA Goddard Space Flight Center, 3Jet Propulsion Lab/CalTech, 4LPI

Introduction: The Planetary Science Decadal Survey, Visions and Voyages [1] sets characterization of the lunar volatile cycle as a top priority for lunar exploration, seeking to address questions dealing with the sources of volatiles, if and how they migrate across the surface, and what is their ultimate fate. The Lunar Reconnaissance Orbiter (LRO) has been gathering data to address these questions for 12 years and, in that time, has revolutionized our understanding of lunar volatiles. Despite these advances, many fundamental questions remain unanswered. To address these questions, the LRO team is focused on new global-scale measurements characterizing diurnal variability and the exosphere and the space environment, as well as focused measurements of regions of high interest in the lunar poles, including polar craters.

The transport of volatiles across the surface of the Moon plays a critical role in the distribution of volatiles, both as a function of depth and of location on the surface. After several years of investigations by LRO and other spacecraft, major questions remain about how volatiles are transported and the role of the space environment in volatile production and evolution. Thus, LRO is investigating global volatile processes using a multi-instrument approach.

LRO is uniquely situated to study lunar exosphere processes [2-3] and the radiation environment surrounding the Moon. LAMP and CRaTER observations during this extended mission enable the first comparison of how the Moon’s atmospheric and radiation environments respond to the changing solar activity in two subsequent solar cycles. There is new evidence that the Sun is moving into a grand minimum, that is, a series of weak solar cycles, like the Maunder, Dalton, or Gleissberg minima [4-5]. Ongoing observations provide important information to understand and predict how this variability will affect the atmospheric and radiation environments.

Ongoing LRO Science: The LRO team is using a multi-instrument approach to address identified high-priority science questions in volatile science and the interaction of the lunar surface with the space environment. For example, LRO instruments are investigating the mobility of hydration as a function of local time, latitude and depth, as well as terrain type. Grava et al. [6] used LAMP observations to confirm that solar-derived alpha particles (He++) are the main source of lunar exospheric helium. Looper et al. [7] used CRaTER to show that, after a decline during the middle of the solar activity cycle, cosmic ray radiation intensity has risen back to exceed the historically high levels seen at the start of the mission. This suggests that the sun is not in another historic minimum, however more work remains to fully confirm.

The nature of PSRs and the presence or absence of volatiles is being investigated across the team. Studies by Jozwiak et al. [8] and Sefton Nash et al. [9] examined the large PSRs Cabeus and Amundsen to explore differences in water-ice signatures measured in these craters. Jozwiak et al. [8] combined observations from multiple instruments and suggests differences might be related to the nature and distribution of ices, and/or the different thermal and surface environment of the craters. Ongoing studies continue to evaluate this in detail.

Measurements from Diviner showed doubly-shadowed regions that are much colder than surrounding areas (micro-cold traps) within Amundsen [9]. Measured emissivity differences are thought to be from 1) The abundance of sub-FOV doubly-shadowed terrain with ultra-cool temperatures, and 2) The thermophysical gradient in the uppermost layers of PSR regolith that may be caused by a thin veneer of water ice.

Plans for ESM5: The LRO extended mission #4 is scheduled to end in September 2022. There are still many outstanding questions related to volatiles and the lunar exosphere which can be addressed by LRO in a fifth extended mission, which would span September 2022-September 2025. This time frame will see the landings of several Commercial Lunar Payload Services (CLPS) providers as well as the Artemis III South Pole landing, which will change the composition of the lunar exosphere. LRO is currently the only spacecraft orbiting the Moon capable of directly measuring the neutral lunar exosphere, and LAMP is well situated to study this environment in its pristine state. The LRO orbit will also be passing over Cabeus crater again, allowing more detailed analysis of Cabeus and how it compares to other PSRs. Diviner, LAMP, LROC, LOLA, and Mini-RF are poised to examine seasonal differences on volatile distribution and migration. The new solar cycle presents another opportunity to better understand the suns influence on the lunar exosphere and space radiation. LRO remains viable and ready to continue providing new insight into our Moon.

NEW LRO INVESTIGATIONS OF VOLCANISM, TECTONISM, AND THE LUNAR INTERIOR
J. D. Stopar1, M. E. Banks2, C. M. Elder1, J. W. Keller2, N. E. Petro2, A. M. Stickley4, and the LRO Team, 1Lunar and Planetary Institute, USRA; 2NASA Goddard Space Flight Center; 3Jet Propulsion Laboratory, California Institute of Technology, 4Johns Hopkins University Applied Physics Laboratory

Introduction: Data from LRO have formed the basis of much of our current understanding of lunar geology. As LRO finishes its fourth extended mission (ESM4), the LRO team is looking toward science objectives and future observations to address within the next five years. Key questions about interior and crustal processes, as well as volcanic and tectonic activities remain. Here we highlight some recent progress and possible objectives that LRO could address with another extended mission. Many objectives might be met using multiple instruments onboard LRO, or through comparison with data from other missions.

Recent and Ongoing Investigations: In ESM4, LRO collected data to investigate landforms with unusual compositions and/or physical properties, including the KREEP basalts of the Apennine Bench Formation that appear to be unique volcanic materials [e.g., 1]. Improved Christiansen Feature (CF) maps from Diviner thermal data and Kaguya near-IR data resulted in some silica-rich locations being recently identified [2]. Also being studied are the non-mare or light-toned massifs of possible silicic volcanism, such as the Lassell massif, among others [e.g., 3-4].

LRO data are also revealing the diversity, volumes, and timing of pyroclastic eruptions [e.g., 5-11]. As more data are collected, knowledge of many relatively small landforms, including ring-moat dome structures, irregular mare patches, and lunar pits, continues to evolve [e.g., 12-14]. Context for samples returned by the Chang’e-5 mission is provided by LRO and will aid detailed analyses [e.g., 15-17]. LRO data are also contributing to the determinations of young mare ages elsewhere [e.g., 18-19], and how the final mare eruptions were distributed and their composition. These and other investigations are revealing the complexity and range of magmatism on the Moon, from primary crust formation to later volcanic eruptions.

In ESM4, LRO also collected data to investigate the relationship of mafic rocks to primary crust formed from the lunar magma ocean [e.g., 20]. Possible exposures of mantle in basins, such as the South Pole-Aitken, are also revealing the Moon’s structure [e.g., 21-22]. Likewise, investigations of interior structure, magmatism, and any surface expressions continues to progress, including new insights into the magmatic processes associated with floor-fractured craters, which often host pyroclastic materials [e.g., 23-26]. Other studies include exploring the relationships between basins and later volcanic materials [e.g., 27-30].

Surface expressions of crustal stresses are also being analyzed, including seismic activity some of which might be ongoing, as well as regional extensional stresses related to basins [e.g., 31-34]. These and other investigations making use of LRO data demonstrate the wide-ranging value of collecting a cornerstone dataset, gathered over a decade-plus baseline.

Future Potential: Additional LROC, Diviner, Mini-RF, LOLA, CRaTER, and LAMP observations of compositional anomalies, exposures of primary crust or mantle, silicic exposures, volcanic materials, and tectonic features will aid further investigations into their origins, timing, composition, physical properties, and degradation over time. A fifth extended mission for LRO would span Sept. 2022 to Sept. 2025 and include the planned landings of several Commercial Lunar Payload Services (CLPS) providers as well as the Artemis III South Pole landing. Thus, LRO stands ready to collect new data needed to answer evolving science questions as well as provide additional orbital context for the forthcoming era of lunar exploration.

**LUNAR AUTONOMOUS ROBOTIC ROVER SYSTEM.** Tara Sweeney\(^1\), Racheal Schrock\(^2\), Judith Hoyt\(^3\), and Jose M. Hurtado, Jr.,\(^4\), Department of Earth, Environmental, and Resource Sciences, The University of Texas at El Paso, 500 West University Avenue, El Paso, TX 79968, \(^1\)tsweeney@miners.utep.edu, \(^2\)rgschrock@miners.utep.edu, \(^3\)jrchapman@miners.utep.edu, \(^4\)jhurtado@utep.edu.

**Introduction:** Artemis science and exploration will require the documentation of astronaut extravehicular activities (EVAs) on the lunar surface to be comprehensive, near-real-time, and representative of the advanced technological capabilities of the day. Lunar astronauts, mission control personnel, and members of the science support team will desire the still cameras, video cameras, lighting equipment, communications and navigations equipment, sensors, instruments, consumables, tools, etc. to be co-located with astronauts during an EVA to ensure astronaut safety and to accomplish the mission. Public engagement personnel and educators will desire access to the accumulated images, video, and data that can be presented to the public and students in a multitude of applications. These objectives can be met through the development of the Lunar Autonomous Robotic Rover System (LARRS), which will be able to follow the astronauts on EVA to document their activities and transport necessary equipment to support the EVA.

**Concept:** In this concept, a wheeled rover would accompany the astronauts on their EVA. The rover would be capable of either operating autonomously or driven by command from either an intravehicular crewmember (IVA) or from Earth. The rover would serve multiple EVA support functions, primarily as an imaging platform to record the events of the EVA from a standoff distance from the crew. To this end, the rover would be equipped with cameras to obtain still and video images as well as lighting to illuminate the astronauts’ work site. The rover’s mobility and automatic tracking capabilities of the cameras would allow the rover to follow the astronauts during their traverse to capture complete footage of the entire EVA. In addition, the rover could serve a logistical function as a tool and sample carrier for EVAs without a crew-capable pressurized or unpressurized rover. Additional capabilities that could be incorporated into the design are onboard stowage of emergency life support and power for spacesuits.

An additional perspective on EVA activities could be afforded by overhead views, similar to what is possible to capture with an uncrewed aerial vehicle on Earth. To obtain analogous aerial imagery, 2 or more autonomous rovers could be deployed to follow the EVA crew, each equipped with a mast and connected by a cable system between the masts. Along this cable, a small, gimbaled camera system could be deployed. The masts could host additional lighting to illuminate the astronauts’ traverse path and worksite. The masts could also serve as antenna for communications and navigation.

**Future Work:** Demonstrating the utility of documenting EVA activities and evaluating the impact, if any, obtaining that data has on EVAs requires analog field tests. At UTEP, we are anticipating an analog field test opportunity using a small, modified all-terrain recreational vehicle, equipped with a mast and representative equipment/technology as a concept of operations demonstration for the LARRS. The intention is to deploy the vehicle to the Kilbourne Hole maar crater in New Mexico. This venue is an identified training location for astronaut field training and lunar exploration projects.
**ELECTROSTATIC DUST ANALYZER (EDA) FOR MEASURING DUST TRANSPORT ON THE LUNAR SURFACE.** X. Wang\(^1\), Z. Sternovsky\(^1\), M. Horányi\(^1\), J. Deca\(^1\), I. Garrick-Bethell\(^2\), W. M. Farrell\(^3\), J. Minafra\(^4\) and L. Bucciantini\(^5\). \(^1\)University of Colorado, Boulder, USA, \(^2\)University of California at Santa Cruz, USA, \(^3\)NASA Goddard Space Flight Center, Greenbelt, Maryland, USA, \(^4\)NASA Ames Research Center, Moffett Field, California, USA, and \(^5\)French National Center for Scientific Research (CNRS), Paris, France (xu.wang@colorado.edu)

**Introduction:** Electrostatic dust charging and transport on the lunar surface is a longstanding problem. This electrostatic process has been suggested to explain several unresolved observations, including Apollo-era observations [1] of the lunar horizon glow, the high-altitude streamers, and the low-speed dust detections during terminator crossings by LEAM, as well as a recent observation of dust deposition on lunar rocks by Chang’e 3 [2].

However, a fundamental question of how dust particles obtain enough charge to become mobilized and lofted on the lunar surface remained unsolved for decades long. Recent laboratory studies [3-6] have revolutionized our understanding of this physical process and provided strong support for its occurrence on the surface of the Moon.

Dedicated in-situ measurements on the lunar surface are needed to unambiguously determine the ground truth of this electrostatic phenomenon. The Electrostatic Dust Analyzer (EDA), which is currently under development through the NASA DALI program, is aimed to quantify characteristics of electrostatically lofted lunar dust. The expected results from EDA measurements will provide insights into the role of electrostatic dust transport in shaping the surface physical properties of the Moon. Importantly, EDA measurements will assess potential risks posed by mobilized/lofted dust to human exploration, especially the long-term presence, on the lunar surface, and guide the development of dust mitigation strategies and methods.

Additionally, the expected lunar results will advance our understanding of this electrostatic process on all airless bodies across the solar system.

**EDA Instrument Development:** EDA measures the charge, size (mass), velocity and flux of lofted dust particles on the lunar surface. The instrument inherited the design from the Electrostatic Lunar Dust Analyzer (ELDA) [7]. The instrument sensor consists of two identical Dust Trajectory Sensor (DTS) units and a Deflection Field Electrodes (DFE) unit lying in-between the two DTS units (Fig. 1). The DTS consists of two wire electrode planes, each has seven wires. The DFE consists of three biased electrodes.

When a charged dust particle enters the instrument into a DTS unit, its charge is measured from induced charges on all the wires, and its velocity is determined from the time-shift of the charge signals between the two wire planes (Fig. 1). The dust particle will be then deflected by the electric field created in the DFE and exit through the second DTS on the other end of the instrument. The mass-to-charge ratio of the dust particle is then determined from its deflected trajectory, which can be reconstructed from measured charge signals as the particle passes through all four wire planes.

The instrument sensor with electronic boards is housed in a metal enclosure (Fig. 2). EDA can be tilted to optimized angles for dust collection. Depending on the relative position to the Sun, one of the doors will be opened to allow dust particles to enter the instrument. The EDA instrument has completed its final design and is currently in the production phase and to be tested in relevant environments to meet TRL 6 by early 2022.

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**Fig. 1** Cut-view of the EDA sensor module with examples of measured charge signals.

**Fig. 2** Overall view of the EDA instrument.

LUNAR SCIENCE AND EXPLORATION AT MARSHALL SPACE FLIGHT CENTER. R. C. Weber¹, J. Dankanich¹, N. Herrmann¹, ¹NASA Marshall Space Flight Center, Huntsville, Alabama (renee.c.weber@nasa.gov).

Introduction: Under the Artemis program for lunar science and exploration, the Agency is planning an ambitious path forward to the Moon. NASA’s Marshall Space Flight Center (MSFC) offers unique capabilities in propulsion, technology, engineering, science, and exploration, providing a rich environment for fostering new partnerships that will create and sustain a renewed human presence on the Moon. In the next five years, MSFC will execute multiple undertakings in fundamental research, payload development, lander technologies, environmental definition and test, and both surface and orbital missions.

Science Research: MSFC scientists maintain broad expertise in support of planetary remote sensing and in-situ data analysis and modeling, payload development, mission formulation, and laboratory work. Specific subdisciplines include: geophysical and interdisciplinary analysis and modeling of terrestrial planetary interiors; geological and geomorphological investigations of terrestrial planetary surfaces; and studies of the electrostatic charging, optical, and gas accretion properties of dust. Missions supported include Mars InSight, Venus VERITAS, VIPER, multiple CLPS missions, and LRO.

Science and Exploration Integration: Recognizing that science and exploration are mutually enabling, MSFC aims to integrate science subject matter experts into its human spaceflight, engineering, and technology programs and projects, to provide input into mission destinations and vehicle/payload requirements, evaluate performance, and assist in development efforts. Missions/programs supported include the Human Landing System, the Gateway, and the Solar Cruiser technology demonstration mission.

Propulsion and Lander Technologies: MSFC is an Agency leader in innovative advanced propulsion and lander technologies, including solid and liquid propulsion elements, green propellant thruster and feed system development, suppressed freezing point pressure feed thrusters, electric pump-fed engines, solar sails, electrostatic solar sails, nuclear propulsion concept studies, large cargo landers, and small lander technologies. Missions and programs supported include MAV, Mars Sample Return, Europa Clipper, Europa Lander, Lunar Flashlight, NEAScout, Solar Cruiser, TALOS, and the lunar CATALYST program.

Environmental Test: MSFC’s Space Environmental Effects (SEE) Test Capability maintains the most complete set of space environment test capabilities at any one location in the Agency. Most of our Space Environmental Effects (SEE) testing capabilities/facilities are unique within NASA and we customize every test to meet specific customer requirements. Over the years our SEE team has supported a range of activities including materials, component and instrument development testing as well as flight unit calibration and qualification.

Payload and Mission Development: MSFC scientists, technologists, and engineers are involved in the development of multiple lunar payloads and future mission concepts, the following of which are represented at this meeting:

Payload Node 1: LN-1 is an S-band Navigation beacon that will be delivered to the Moon's surface on Intuitive Machine's NOVA-C lander in early 2022. LN-1’s goal is to demonstrate navigation technologies that can support surface and orbital operations around the Moon, enabling autonomy which would decrease dependency on heavily utilized Earth-based assets like the Deep Space Network.

The Lunar Geophysical Network: LGN is a mission in development for NASA’s New Frontiers 5 AO, supported by MSFC scientists. LGN’s primary goal is to understand the initial stages of terrestrial planet evolution, through detailed lunar investigations.

Other instruments and payloads in development include the Kinematic Navigation and Cartography Knapsack (KNaCK) frequency-modulated continuous wave LiDAR sensor, and the Neutron Measurements on the Lunar Surface (NMLS) instrument onboard the CLPS 2022 Astrobotic Mission 1.

Mission Operation Development: MSFC applies decades of experience with science customers and instruments to continually advance mission operations capabilities for science and exploration. The Huntsville Operations Support Center (HOSC) implements the latest best practices and state-of-the-art distributed operations services to continuously improve ISS payload operations for thousands of remote teams and investigators. In the next few years, there will be parallel, ongoing human mission and payload operations in LEO, cislunar space, on the lunar surface, in-transit to Mars, and ultimately on and around Mars. As mission planning progresses, MSFC will support these missions by enabling multidisciplinary payload development, utilization, and maintenance; supporting infrastructure; and operations management and training.

Lunar Mobility as a Service in the Next Five Years: A Software Perspective. Taylor JL Whitaker1, Chris Rampolla2, Cedric Corpa De La Fuente3, Mike Provenzano4, Astrobotic Technology, 1016 N. Lincoln Ave. Pittsburgh, PA, {1Taylor.Whitaker, 2Chris.Rampolla, 3Cedric.Corpadelafuente, 4Mike.Provenzano}@astrobotic.com

Introduction: The next five years of Lunar surface exploration will play a major role in the preparation for and the eventual establishment of a persistent presence on the Moon. Though, it’s not humans that will be doing the initial exploration and experimentation, but rather robotic systems laying the foundation for permanent human presence. An increased understanding of the Lunar environment and infrastructure in terms of mobility, power, and surface structures are required to support a sustained presence, and robotic systems are an invaluable resource for this endeavor. A core requirement of any surface asset contributing to this effort is mobility.

Mobility as a Service (MaaS) is a familiar concept, here, on Earth as the proliferation of car-sharing and ride-sharing industries has virtually removed the need for individuals to rely on personal methods for transportation. However, simply attaching a payload to a rover destined for the Lunar surface, has up to this point not been possible. MaaS is at the core of Astrobotic’s CubeRover, a small rover platform with colossal benefits for surface exploration as its affordable, modular, and scalable. From academic sensors to robotic arms, the CubeRover platform can provide surface mobility for science applications, laying power cables, or even major structural construction.

Though CubeRover will be among the first to establish the MaaS model on the Lunar surface, it will not be the last and thus the eventual diverse ecosystem of surface assets was a vital consideration in the development of the platform. The CubeRover platform has given significant insights into this eventuality, especially regarding the software perspective.

A MaaS Software Ecosystem: Developing a MaaS software ecosystem in the context of establishing Lunar infrastructure extends beyond just the flight and ground software components of a single rover platform or even a single MaaS provider. Flight software (FSW) must facilitate the specific mission of a platform but should also maintain a high degree of adaptability to easily integrate into an environment of diverse Lunar assets. Ground software (GSW) must support the functionalities of individual platforms, but also enable higher-level management and coordination of fleets of assets.

Flight Software Architecture. FSW for a spacecraft is inherently tied to the craft’s mission and the available hardware resources, processors, sensors, actuators, etc., and can lead to large development overheads for recurring missions. FSW frameworks such as NASA’s core Flight System (cFS) [1] aid in this respect as NASA and community contributions enable a vast toolbox of functionalities to be leveraged and the modular framework reduces overheads in core software development to support the spacecraft and allows reuse across missions. Considering CubeRover is a mobility platform, FSW supporting CubeRover’s base functionality also requires that payloads be supported. Additionally, considering the range of complexity in possible payloads and use-cases, payload support can range from basic power supply and heat management to provisioning processing power for tighter integration of payload applications. The former case could easily be supported with a cFS framework and specific power and temperature management application plugins. However, the latter case shouldn’t impose the software framework used for the base functionalities of the platform on the payload developers, but rather allow software ecosystems such as ROS [2] to be supported alongside.

Astrobotic has approached the design of FSW such that core functionalities are isolated away from sandboxed payload functionalities with both hardware and software APIs providing an interface with the core system. This prevents CubeRover from requiring payload developers to concern themselves with the same rigorous qualifications needed to classify the platform as flight-safe and enables a larger range of supported payloads and missions. This segmentation of FSW drastically improves the modularity of the platform even beyond payload support, as high-level software systems can run safely with core applications.

Ground Software Architecture. The need for a front-end UI to control and monitor planetary assets is clear. But current open-source command and control solutions do not account for MaaS models that must handle significant increases in demand for data throughput of surface assets. Astrobotic aims to take an aggressive position in the nascent Lunar MaaS market by leveraging proven big-data technology that can handle high message throughput with built-in redundancy and structuring its ground services around it. This will make ground capabilities more attractive for payload customers who will require ever more demanding computational and data resources. Further, it guarantees the ability to scale gracefully without the need to re-architect the entirety of the ground segment to integrate new surface assets and missions.

References:

Introduction: The CRATER (Characterization of Regolith and Trace Economic Resources) instrument—a laser ablation mass spectrometer—enables rapid in situ analyses to determine mineralogy, organic inventory, trace element and isotopic fingerprints of lunar regolith and rock. CRATER includes the CosmOrbitrap™ mass analyzer, a version of the commercial Orbitrap™ adapted for spaceflight by a consortium of French laboratories [1], which provides unprecedented mass resolving power and mass accuracy for chemical analysis of planetary targets.

Support from NASA’s Development and Advancement of Lunar Instrumentation (DALI) program and the CNES Research and Technology program will enable the maturation of CRATER technology to reach TRL 6 (i.e., system demonstration in relevant environmental conditions) before the end of 2022. This competitive timeline renders the CRATER instrument ready for deployment on a commercial lunarlander or rover within the next few years [3].

Community-driven science goals: CRATER is suited to critically assess refractory and moderately volatile elemental abundances to provide ground truth constraints on their putative enrichment and depletion in the bulk silicate Moon, respectively. CRATER can detect organic molecules present in lunar surface materials that represent an abiotic inventory delivered by meteorites and comets, thereby providing an astrobiologic “blank”. As NASA and other global space agencies continue to look toward the Moon for future space exploration support, endogenous economic resources are important to identify. CRATER is capable of detecting viable economic resources in lunar phases.

Analytical Performance: Analytical strengths of the instrument include mass resolution (m/Δm > 100,000, FWHM at m/z 100) and mass accuracy (ppm level) that exceed previous flight capabilities [2], enabling the discrimination of molecular and elemental isobars. Expanded science benefits include fine laser attenuation control and active beam scanning to enable 2D chemical imaging across a 500 micron field of view [4], isotopic abundance precision (<1% 2σ) [5], and dual polarity modes (positive and negative ion detection). The CosmOrbitrap analyzer is capable of detecting organic and inorganic species simultaneously, providing inferences of contextual relationships.

Prototype Investigations: Metal alloys containing rock-forming elements have been analyzed for elemental and isotopic abundance accuracy and precision to understand systematic and random sources of error in this novel instrument concept. Through a series of experiments on lunar analog samples of increasing fidelity, the CRATER performance and scientific reach will be established.

Instrument design: CRATER’s low mass (8 kg) and power (40 W peak power) requirements make this instrument (Figure 1) ideal for spaceflight. A 213 nm, high power laser subsystem ablates/desorbs and ionizes the target. Generated ions are extracted and transmitted through a series of lenses that focus, steer, and inject the ions into the analyzer. The CosmOrbitrap employs image current detection of the ions’ axial oscillations, which inversely correlate to the square root of m/z.

![Figure 1. The lightweight and compact CRATER design enables versatile deployment options on an upcoming commercial lunar rover or lander concept.](image-url)

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