Continuous Lunar Orbital Capabilities
Specific Action Team (CLOC-SAT)
Community Update

Dr. Carle Pieters, CLOC-SAT Co-chair
Dr. Benjamin Greenhagen, CLOC-SAT Co-chair

21 July 2022
Orbital Capabilities as Part of an Integrated Strategy for Science and Exploration of the Moon

➢ Frequent question: What happens after LRO’s mission ends?
  - NASA will continue to have some presence in lunar orbit...
    - LRO and ARTEMIS currently operating
    - CAPSTONE, Artemis 1 cubesats, Lunar Flashlight, and Lunar Trailblazer soon
  - Gateway and Orion
  - Science questions remain that are best answered from lunar orbit
    - For example, recent lunar orbiter Discovery proposals
  - Orbital capabilities support surface investigations
    - Surface operations are significantly limited without orbital capabilities
  - Intentionally long-duration orbital capabilities provide new opportunities

➢ Better question: What is an integrated strategy for lunar orbital capabilities?

LRO has been in operation around the Moon since 2009 and has provided a wealth of information about the Moon
- >1.3 PB delivered to PDS
- 5th extended mission proposal approved in April 2022
CLOC-SAT Timeline to Date

• **February**
  - Community Kick-off February 15th

• **March**
  - CLOC-SAT member self-nominations closed March 4th
  - Full team established in late March

• **April – Mid-July**
  - White paper submissions closed April 8th
  - Information gathering by CLOC-SAT (reports, white papers, surveys, literature, etc.)
  - Evaluation and identification of information gaps
  - Request expert advice for specific areas
  - CLOC-SAT develops integrated strategy and recommendations from community input

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**Community Kickoff**

- 2.5 Hour Workshop held in February
- Present Scope of CLOC-SAT
- Community Topical Perspectives
  - Maria Banks, NASA GSFC
  - Brad Jolliff, Washington Univ.
  - Clive Neal, Univ. Notre Dame
  - Angela Stickle, APL
- Why, What, How Breakout Sessions
- Q&A
CLOC-SAT Members

- **Co-Chairs**
  - Ben Greenhagen, JHU/APL
  - Carle Pieters, Brown Univ.

- **Core Leads**
  - Mark Robinson, Arizona State Univ.
  - Julie Stopar, LPI
  - John Keller, NASA GSFC

- **SAT Members**
  - Tim Glotch, Stony Brook Univ.
  - Lauren Jozwiak, JHU/APL
  - James Tuttle Keane, JPL/Caltech
  - Paul Lucey, Univ. of Hawaii
  - Angela Stickle, JHU/APL

- **Ex Officios**
  - Amy Fagan, LEAG Chair
  - Kelsey Young, LEAG Human Exploration Chair
  - Brett Denevi, LEAG Science Chair
  - Ben Bussey, LEAG Strategic Roadmap Chair
  - Jose Hurtado, LEAG Technology Chair

SAT Members were selected from a community process:
- Community announcements to self-nominate
- Each candidate submitted a statement of interest and 2-page CV
- Reviewed by CLOC-SAT Chairs, Core Leads, and Ex Officios
- 13 Self-nominations
CLOC-SAT White Paper Topics

• **Community White Paper Submissions:**
  
  • The Case for Orbital Lidar Swath-Mapping at the Moon
  • A Case for Passive Microwave Wavelength Measurements From Lunar Orbit
  • Advanced UV Water Frost and Adsorption Signature Orbital Mapping Instrument Concepts
  • Characterization of Lunar Surface Thermal Environment and Physical Properties using Advanced Thermal Imagers
  • The Contribution of Active Spectroscopy to Orbital Remote Sensing of Lunar Volatiles
  • Cross-Over Infrared Spectroscopy: A New Tool for Remote Mineral Detection and Compositional Determination in the 4-8 μm Wavelength Range
  • Hydrogen Prospecting at the Lunar Poles: Orbital Mission Concept with Neutron Spectroscopy Measurements
  • Lunar Volatiles and Solar System Science
  • Lunar Volatiles Orbiters
  • The Need for Better Characterization of the Primary Anorthositic Crust with New Orbital Observations
  • The Next Lunar Orbiter: Some Observations and Programmatic Perspectives
  • Orbital Capabilities to Support Upcoming CLPS Lunar Surface Exploration
  • Why Radar Sounding is Crucial for Future Orbital Observatories
  • Why Orbital Magnetometer Instruments are Crucial for Future Improved Lunar Magnetic Observations
CLOC-SAT Timeline to Completion

• **Mid-July – Late-August**
  - Report structure, Principal Content, and Preliminary findings presented at Exploration Science Forum (July 19-21, Boulder, CO)
  - Revise report based on community feedback
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• **Late-August and Early Fall**
  - Draft Full Report presented at LEAG Annual Meeting (August 23-25, Laurel MD)
  - Two-week community response period
  - Revise report based on community feedback
  - Final Report delivered to LEAG and NASA
Report Structure

• Executive Summary
• Introduction and Rationale
• Science and Exploration Objectives and Needs [Why?]
• Implementation Approaches and Architectures [How?]
• Measurement Approaches and Traceability [What?]
• Traceability between Why, What, and How
• Example Mission Scenarios
• Summary
Science and Exploration Objectives and Requirements: Need for new investigations

- **Cumulative discoveries from lunar remote sensing as well as modern analysis of lunar materials (documented returned samples and meteorites) have opened entirely new questions regarding the Moon and its central role as a natural laboratory for planetary science.**
  - Current capabilities in spatial resolution and global coverage, along with with expanded spectral range, have enabled unanticipated discoveries and extended the range and detail of lunar crustal compositions, styles of volcanism, heat flow, and the nature of tectonism on this small planetary body. Improved resolution and coverage and full exploitation of available wavelengths will improve our understanding of fundamental processes that dominate the evolution of the lunar mantle and development of the crust.
  - Recent advances reveal a complex volatile system on the Moon, but the sources, transport mechanisms, sequestration, and loss of volatiles remains unclear.
  - The polar regions in permanent shadow are now known to host a wide range of volatile compounds. Furthermore, unexpected minerals (e.g. hematite) detected outside permanent shadow indicates that unanticipated chemistry occurs within the regolith far from the zones studied by Apollo. Unfortunately, coverage from existing spatial and spectral data are very limited, leaving significant questions unanswered.
Science and Exploration Objectives and Requirements: Need for new investigations

- The new era of human and *in situ* robotic exploration and sample return demands greatly improved characterization of potential landing sites in context to optimize the value of science return and to respond to the unique needs of exploration.
  - Compositional and physical characterization of landing sites requires orbital measurements at a scale of a few meters in addition to existing imaging, enabling the design of effective sampling strategies, and matching the mission resources and mobility to the characteristics of candidate landing sites.
  - LRO has shown that small impact features occur at the 10-meter scale much more frequently than was predicted. The exponential increase in impact flux with decreasing size demands hazard characterization for crews and long-lived surface assets. Furthermore, the recognition of widely distributed small young tectonic features increases the potential for seismic hazards.
  - Critical resources at rover scales, including water ice and carbon compounds, can be identified from orbit (as well as potentially hazardous volatile compounds such as hydrogen sulfide).
Science and Exploration Objectives and Requirements: Science Objectives Topics

- Provide a full inventory of igneous rock composition (including mantle materials) for surface missions
- Global characterization of the exosphere, especially water and hydrogen
- Global characterization of surface chemical reaction products, including oxides, organics, and hydrides
- Identification of surface ice deposits and their dynamics
- Detection and characterization of buried ice deposits
- Measure impactor flux at the exploration hazard scale
- Characterize ongoing tectonism and seismicity
- Characterize spatial variations of heat flow
- Characterize the structure of the regolith, including in PSRs
- Understand lunar magnetic fields and their connection to the plasma environment
Science and Exploration Objectives and Requirements: Example Preliminary Findings

- Compositional and thermophysical measurements should be obtained at sufficient spatial resolution to characterize individual boulders, minimizing mixing effects present in regolith and thus identifying targets for sampling.

- Mapping of volatile ices and organics in PSRs should feature sufficient sensitivity to detect dynamic changes due to temperature variation and other physical parameters such as sputtering and small impacts, and at sufficient resolution for traverse planning.

- Measurement of the three-dimensional and temporal structure of exospheric water is key to understanding volatile propagation across the surface.

- The distribution of surface hydroxyl and molecular water should be unambiguously separated, and their individual dynamics definitively characterized and linked to exospheric water and hydroxyl.

- A complete inventory of the energies and phases of outgoing hydrogen is required to evaluate the contribution of the solar wind to the volatile system.

- Detection and characterization of ice deposits at the 10-meter depth scale is essential for assessing the long-term viability ISRU of ice.

- Characterization of impactor flux at the centimeter to decimeter scale is essential to assess exploration impact hazards.

- Direct detection of strain products will improve understanding of lunar tectonism and better quantify the seismic hazard to surface operations.

- Spatially resolved measurement of heat flow improves understanding of the evolution of the lunar interior.
Implementation Approaches and Architectures: Orbital & Platform Topics / Findings

• **Different lunar orbits serve a variety of science and exploration objectives.**
  - **Circular polar orbits** enable global coverage with relatively high and uniform spatial resolution
    • Low orbits **must be maintained** with frequent station keeping maneuvers - which will eventually deplete propellant.
  - **Elliptical Frozen orbits** do not require station keeping, allowing an orbiter to remain active indefinitely.
    • Polar Frozen Orbits provide global coverage but with effective **spatial resolution limited** by the apoapsis.
    • These orbits require propellant only for momentum unloading and phasing maneuvers
  - **Distant orbits** include orbits around Lagrange Points (L1, L2) and Near Rectilinear Halo Orbits (NRHOs) such as envisioned for Lunar Gateway.
    • Orbits around Lagrange points provide near hemispherical coverage of the Moon, ideal for **communication stations** (e.g. far side comm from L2) and to observe impact flashes.
    • The **Gateway** NRHO provides access to the lunar surface (@ periapsis) and a **low-cost destination from Earth.**
Implementation Approaches and Architectures: Orbital & Platform Topics / Findings

- Both polar and equatorial orbits can be designed to be relatively circular or elliptical.
  - Polar orbits enable global or near global surface coverage.
  - Equatorial orbits enable high temporal coverage, often at the expense of spatial coverage.

- Continuous orbital presence at the Moon necessarily relies on a variety of platforms. No single platform or approach can meet all needs of science and exploration.
  - A LRO-class orbiter with state-of-the-art instrumentation is needed for long term coverage of the Moon with coordinated new and improved measurements.
    - A systematic replacement program is important to plan in order to take advantage of technical advances and to enable new discoveries to be addressed.
  - Intermediate orbiters (e.g. LADEE, GRAIL, Trailblazer) are well suited for focused short duration investigations that address compelling scientific objectives using the most advanced and capable instrumentation.
  - Cubesats (e.g. LunaH-Map and Lunar Flashlight) and other small platforms
    - ... are low cost with rapid development but enable high risk, high payoff investigations.
    - ... can involve constellations, tethered pairs and other configurations to be used to address unique science.
Implementation Approaches and Architectures: Operations & Ground Segment Topics / Findings

- A continuous lunar presence using state-of-the-art instrumentation and high resolution will require commensurate advances in communication capabilities
  - High data rate communication will be a common need by all stakeholders at the Moon and a strategy of shared resources and commitments should be implemented.
    - Communication infrastructure should provide global access to the Moon so that surface operations anywhere on the surface can be supported.
  - Development of advanced communication (e.g. laser-based) should be pursued. Preservation of lunar farside radio astronomy opportunities should be considered.

- The Planetary Data System must be appropriately upgraded to handle dramatic increases in lunar data to be archived.
  - Advanced communication capabilities and the Moon’s relative proximity will enable unprecedented data collection and transfer in order to fulfill scientific needs for high resolution measurements.
Measurement Approaches and Traceability: Breadth of Measurements

- **Appropriate and stable funding for maturation and flight-readiness of orbital instruments and measurements (e.g., DALI program) is essential for breakthrough advances that enable transformational science and increase breadth of measurements.**
  - Mature instrument designs define flight requirements, such as power, volume, mass, data, and orbit for planned architectures, implementations, and class of mission (large orbiter, small orbiter, cubesat).
  - **Examples requiring development to become flight ready in the near-future:** sounding radar (20-400 MHz), swath LIDAR at sub-meter scales, hyperspectral TIR (5-25 microns) imaging, ‘crossover’ IMIR (4-8 microns) spectroscopy, etc.
Measurement Approaches and Traceability: Key Measurements for Volatiles

• There are key measurement gaps in our ability to perform global assessment and monitoring of H-species, other volatiles, and organics on (and below) the lunar surface.
  • Near-term high-priority measurements include UV/VNIR/IMIR/TIR spectroscopy and imaging, orbital mass spectroscopy, multispectral laser reflectance and fluorescence, and neutron spectroscopy. Such data provide an essential framework for volatile cycles on the Moon.
  • By improving coverage, spatial resolution and depth range, detection of species present, and dynamic behavior expanded measurements address the composition, distribution, classification, and quantification of volatiles and the materials that host them (e.g., long wavelength radar and passive R/F detection)
  • Integrated measurements significantly aid in resource characterization and feed into resource uses and mission planning.
Measurement Approaches and Traceability: Measurements for Science and Exploration Topics

• There are significant gaps in our ability to provide global context, evaluate the full compositional range of lunar materials, and support missions that involve landing site evaluation, surface activities, and sample return.

  • Compositional measurements include high spatial resolution measurements (at 10-m scale or better) with high spectral resolution for key spectral features (e.g., VNIR/IMIR/TIR hyperspectral imaging).

  • Additional examples of valuable measurements include microwave sounding for information about near-surface properties and thermal state (upper 10s of m) and low-altitude magnetic field patterns for information about ancient lunar dynamo and local space weathering environment.
Measurement Approaches and Traceability: Measurements for a Dynamic Moon

- There are critical gaps in long-term monitoring (decadal-scale) measurements and imaging of the lunar surface including: documentation of primary and secondary impacts, small scale tectonic and landslide activities, surface changes caused by human activities, as well as natural changes linked to illumination variations, regolith chemistry, exosphere behavior, radiation and space weather.
  
- Temporal measurement needs include instantaneous, repeated (for validation), and measurements at different times of day to track variable solar illumination, temperature, phase angle effects, etc. over appropriate temporal baselines.
  
- Improved knowledge of variable surface environment, chemistry, and material properties is important for engineering design of surface hardware and mission and site architectures for long-duration activities including those within the polar regions (e.g., ISRU, power, and comm strategies that depend on a specific location).
  
- Additional example measurements: Extremely high-resolution imaging to document potentially hazardous impacts at 10-cm scales or better. Detection of strain displacements over a year baseline can be achieved by interferometric radar or swath mapping lidar at sub-meter spatial resolution. Microwave spectroscopy at or better than 10-km scales could provide spatially resolved measurement of heat flow similar to Apollo experiments.
Measurement Approaches and Traceability: Related Findings

- Several lunar orbital measurements are needed to address key science and exploration objectives at a few-meters scale or better.
  - Examples include high-resolution topography and composition for landing regions as well as time- and site-specific environmental conditions.
  - Sub-meter spatial resolutions in topography and image data are often requested for hazard and landing site assessments, but such data and measurements are not currently available.
- Next-generation orbital measurements include high spatial/spectral resolution data, targeted as well as global coverage, and long-term monitoring. This significant data return requires effective data management strategies.
  - Planned orbital measurements shape the architecture and implementation of missions (e.g., orbit geometry, altitude, duration, data volume, etc.) and the nature of data returned.
  - With multiple ongoing and future lunar activities (Artemis, CLPS, VIPER, and international instruments and missions), making data interoperable will maximize their benefits for all.
  - Coordinate data collection and storage strategies across missions.
Traceability between Why, What, and How

- The CLOC-SAT report will include a variety of figures and tables designed to synthesize the report, and provide traceability for stakeholders.

<table>
<thead>
<tr>
<th>SCIENCE OBJECTIVES</th>
<th>TRANSFORMATIVE INVESTIGATIONS</th>
<th>MEASUREMENT TYPES</th>
<th>MEASUREMENT PRIORITY FOR ACCOMPLISHING TRANSFORMATIVE INVESTIGATIONS</th>
<th>IS THIS A NEW MEASUREMENT TYPE AT THE MOON?</th>
<th>GLOBAL (average of all latitudes and longitudes)</th>
<th>LOCAL OR REGIONAL (if not present)</th>
<th>LOCAL-LOOK</th>
<th>TEMPORAL COVERAGE</th>
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</thead>
<tbody>
<tr>
<td>Understand the evolution of the interior of terrestrial planets through the lens of its surface deposits (cometary)</td>
<td>high-resolution (10m/pix) X-ray imaging spectroscopy</td>
<td>high-resolution hyperspectral mid-IR imaging (20m/pix)</td>
<td>X-ray mapping</td>
<td>[\textbf{X}]</td>
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Example Mission Scenarios

• The CLOC-SAT will refer to example mission scenarios that would address priority science questions. The intent is not to be prescriptive, but rather show possible avenues for accomplishing science for different assumptions (e.g., a capable large spacecraft, an armada of smaller spacecraft, etc.).
Summary

• **CLOC-SAT is a Community-Driven Activity Requested by LEAG**
  • Develop integrated findings that address questions associated with lunar orbital capabilities to carry lunar science and exploration forward during the next decade(s)

• **Community Input and Participation Solicited Throughout the Activity**
  • Public Kickoff
  • Self-nominated SAT Members from the Community
  • Community White Papers
  • Community Update at Artemis LSSW
  • Feedback on report structure, principal topics, preliminary findings (following NESF)
  • Feedback on full report (following LEAG)

CLOC-SAT Wants Your Feedback!
• Is the report structure appropriate?
• Have we missed priority topics?
• Are preliminary findings missing or inaccurate?
• Any other feedback?

Email: clocsat@gmail.com
• Responses requested by 7/29
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