CLOC-SAT

Continuous Lunar Orbital Capabilities

Specific Action Team

Final Report of the Continuous Lunar Orbital Capabilities Specific Action Team (CLOC-SAT)

Lunar Exploration Analysis Group (LEAG)
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Executive Summary

If the United States is to maintain science and exploration leadership at the Moon, continuous lunar orbital capabilities will be an essential component of NASA's plans in the coming decades. We now take for granted the ability to acquire before and after views of landing sites, watch international rovers as they traverse the surface, search for the causes of failed landing attempts, and obtain new data of future landing sites upon request (Figure E.1).

As we enter a period of extraordinary activity at the Moon (human and robotic, commercial and governmental, U.S. and international), we must develop a plan for maintaining critical lunar orbital capabilities over time. This is similar to how NASA and NOAA plan continuing Earth-observing capabilities that serve important scientific or communications purposes.

> **Continuity of Capabilities:** Continuous lunar orbital capabilities are essential for the United States and NASA to maintain a leadership role at the Moon during the coming decades of international science and exploration. Plans must be made now to ensure continuity. **(Overarching Finding 1)**

This report, commissioned by the Lunar Exploration Analysis Group (LEAG), details critical science and exploration objectives that require orbital capabilities and approaches for measurements and spacecraft implementation options. This report contains Topical Findings specific to individual chapters, as well as Overarching Findings that summarize the most pressing issues identified by the CLOC-SAT. A list of all findings is included in Appendix 2.

Transformative Investigations for Science and Exploration

The priorities for science and exploration at the Moon are described in a wide variety of NASA-generated and community-developed documents. The recent NASEM Planetary Science and Astrobiology Decadal Survey emphasizes the groundbreaking science possible at the Moon through a carefully crafted program "to reveal the history of major events and processes that have shaped the Earth–Moon system and the solar system." This LEAG report identifies a series of transformative investigations from lunar orbit, with traceability to these documents, centering on objectives related to 1) the state and evolution

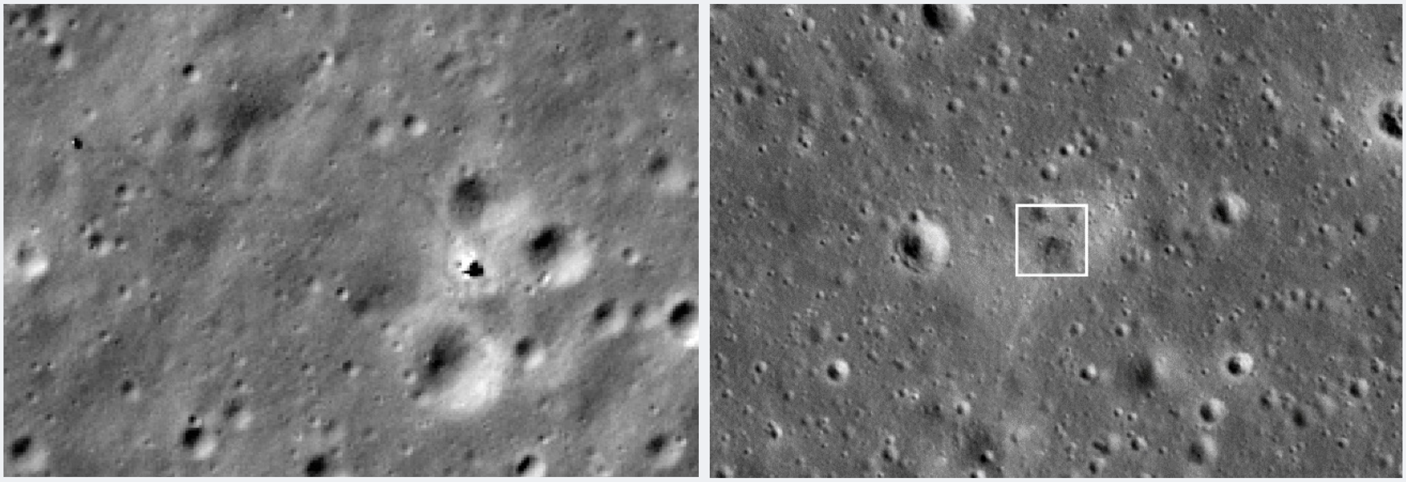

Figure E.1. Left: Site of the Chang'e 4 lander (with rover tracks to the left) on the farside of the Moon in 2019. Right: Impact location of the Beresheet lander that crashed in April 2019. Both images were obtained by the LROC-NAC camera on NASA's Lunar Reconnaissance Orbiter (LRO) launched in 2009 [NASA/GSFC/Arizona State University].

of the interior, 2) volcanism and magmatism, 3) tectonics, 4) impact processes, 5) regolith and space weathering, 6) composition, 7) special polar environments, 8) the volatiles system, and 9) the heliosphere and lunar plasma environment. For each of the transformative investigations, the implications for exploration are detailed; examples include related hazards for crew or equipment, engineering implications for surface assets, resource potential, and real-time activity monitoring.

Implementation Approaches

Many implementation approaches are possible to provide continuous lunar orbital capabilities. This report describes the pros and cons of various orbits and what can be accomplished with spacecraft of various classes. Many transformative investigations identified in this report are obtainable with a larger-scale, highly capable orbital platform with integrated instruments operating together for an extended time. Further, the synergistic results from complementary instruments working together are not easily reproduced with disaggregated approaches and discontinuous teams. The Lunar Reconnaissance Orbiter (LRO) is a major asset to science and exploration. As the spacecraft ages and its fuel is depleted, loss of such capabilities will leave an enormous hole in our abilities to carry out long-term science and exploration at the Moon.

> **Critical Need for Long-lived Integrated Orbiter Capabilities:** The demonstrated value of an LRO-class satellite with diverse instruments operating collaboratively at the Moon is a cornerstone of any science and exploration program that cannot be overstated. Plans for a next generation long-lived integrated orbiter with modern instruments that can replace the highly productive LRO (launched in 2009) are long overdue. **(Overarching Finding 2)**

However, the diversity of ongoing science and exploration objectives suggests a variety of implementation methods is also needed. In recent years NASA has recognized the necessity of complementary spacecraft with smaller SIMPLEx (LunaH-Map and Lunar Trailblazer), Discovery (GRAIL), directed (e.g., LADEE, CAPSTONE), and ‘missions of opportunity’ orbiters.

> **Diversity of Implementation Capabilities:** To meet lunar science and exploration orbital needs through the next decades, diverse orbits and implementation approaches ranging from small exploratory satellites to long-lived LRO-class satellites will be required. A single LRO-class satellite is unlikely to meet all science and exploration orbital needs alone. **(Overarching Finding 3)**

Measurement Approaches

A wealth of modern orbital measurements are available to address transformative science questions and exploration needs. This report provides examples of such measurements categorized by observable properties (e.g. fields and particles, surface composition, surface geology, and subsurface properties), and two integrated summary tables that link Why, What, and How for orbital measurements are provided for quick reference.

Among the measurements identified, several themes emerge. New orbital measurements with spatial resolutions on the order of a meter or better are essential to provide the means to characterize surface compositional or physical properties at scales relevant to landing sites. Such high-resolution data will maximize the return from both orbital and landed measurements by tying global- to local- or even individual rock-scale interpretations. In particular, m-scale compositional data would be invaluable for identifying high-priority sample sites. Furthermore, high-resolution observations acquired with a rapid repeat cadence would enable real-time monitoring of surface operations, such as tracking the traverses of surface assets or crew in time to adjust future EVAs and to give context to field data or samples soon after collection.

Landing-Site-Scale Capabilities: A variety of very high spatial resolution observations (~1 m-scale) are essential for characterizing landing sites and surroundings and monitoring temporal variations as exploration activities expand. To best support active crewed and robotic surface operations, these observations should also have capabilities for high temporal resolution. **(Overarching Finding 4)**

Specific measurements are needed at the global scale in order to provide context for local measurements and yield insights into high-priority science objectives that center on planetary processes and evolution. Some measurements are also needed over long temporal baselines so that the environmental changes that occur naturally and that result from exploration activities can be recorded.

Global Context Capabilities: High-quality global-scale data provide valuable context for addressing science questions and long-term mission planning. As modern orbital instruments are flown and global data for exploration and science investigations returned, new insight into and understanding of planetary-scale issues will result from orbital studies of the whole Moon. **(Overarching Finding 5)**

Long Temporal-Baseline Capabilities: Long temporal-baseline measurements enable critical monitoring of the surface and exosphere, including the effects of both natural and anthropogenic activities. **(Overarching Finding 6)**

The next generation of orbital instruments and spacecraft is poised to deliver transformative science and exploration as a result of recently developed capabilities or those currently in development. Ensuring that orbital technology development and instrument maturation proceed expeditiously will provide high value to expanding endeavors at the Moon. Many of the measurements described in this report will come from these new, highly capable instruments, yielding observations with a substantially larger data volume than those currently being collected. Therefore, high data rates must become standard to effectively realize the benefits of modern instruments. Similarly, as the need for data at high-spatial, high-spectral, and high-temporal resolution expands, in a situation analogous to current Earth-observing platforms, significant ground assets will be needed that include appropriate data archiving and access tools.

Next Generation of Orbital Capabilities: A new generation of technologies in spacecraft, instruments, and communications is emerging that can provide breakthrough capabilities to advance our knowledge of the lunar surface and exosphere and to enable robust communication and navigation support for assets on the surface and cis-lunar space. Technology development programs are essential to continue the development of advanced orbital instruments and spacecraft capabilities. **(Overarching Finding 7)**

Data Downlink and Access Capabilities: Lunar surface and orbital data acquisition and relay are not severely constrained by transmission distance, therefore robust data throughput (data rate) must become standard at the Moon in order to realize the potential of next-generation instrumentation. A holistic strategy for processing and archiving these large data sets is also needed. **(Overarching Finding 8)**

Next Steps

The next step is for stakeholders to incorporate the findings discussed in this report into an integrated lunar science and exploration strategy.

Orbital Capabilities as Part of an Integrated Lunar Strategy: An integrated lunar strategy should include a robust orbital remote sensing component to ensure maximum return from surface exploration and scientific activities. Appropriate and necessary orbital capabilities should be brought to bear on timelines that maximize their value to science and exploration. **(Overarching Finding 9)**

Such a strategy will benefit from cooperation between NASA's Science Mission Directorate (SMD), Exploration Systems Development Mission Directorate (ESDMD), and Space Operations Mission Directorate (SOMD). The overlapping objectives of these directorates, as well as NASA's integrated Moon-to-Mars Objectives call for coordination on orbital observations to optimize human-led science campaigns. NASA certainly has demonstrated success to draw upon. For example, the Planetary Science and Astrobiology Decadal Survey notes that "LRO is perhaps the most successful example of cooperation and mission performance in a joint SMD and human exploration project and represents a template for how to initiate and manage joint collaborations between science and human exploration directorates at NASA in the future."

The time has come. Development of next generation long-lived orbiters with modern capabilities should begin without delay. Ensuring both the continuity and diversity of lunar orbital capabilities into the decades ahead provides the necessary foundation on which to build long-term science and exploration endeavors.

1. Introduction

Orbital capabilities have been and continue to be an essential component of science and exploration of the Moon. Orbital data provide first-order information about the surface and its environment. Orbital spacecraft monitor and explore the character of the Moon with increasing detail and allow information from assets on the surface to be collected and transmitted to remote observers. These assets must be continually renewed and improved in order to provide information as needs arise and technology evolves and expands.

Recognizing that NASA's intrepid Lunar Reconnaissance Orbiter (LRO, launched 2009) has been providing a wealth of fundamental lunar information for well over a decade and that findings from the LEAG 2020 and 2021 Annual Meetings have emphasized the need to develop a long-term orbital strategy at the Moon, the Lunar Exploration Analysis Group (LEAG) formed a Continuous Lunar Orbital Capabilities Specific Action Team (CLOC-SAT) to investigate and identify opportunities and needs associated with the next generation of lunar orbiting spacecraft. The full Terms of Reference (TOR) and background for CLOC-SAT defined by LEAG are provided as an appendix. In brief, the TOR recognizes that a successor to LRO (and other smaller successors) is needed to address key near-term lunar science and exploration goals as well as to advance the state of knowledge about the lunar surface, including for several specific future landing sites. In the decades ahead, data from continuous lunar orbital capabilities are essential for strengthening and documenting detailed knowledge of the lunar environment and resources.

CLOC-SAT activities were initiated in February 2022, and additional CLOC-SAT members were solicited from the community with a diverse range of appropriate experience to accomplish these important tasks. A variety of opportunities for community involvement were incorporated into ongoing discussions, including a public web-based interactive Kickoff session on February 15, 2022, encouragement for community white paper submissions to the CLOC-SAT as well as submission of informal comments on capabilities during CLOC-SAT deliberations, and overview discussions of progress at the NASA Exploration Science Forum in July 2022 and LEAG community meetings in August 2022. Frequent announcements were made via the web-based Lunar-List soliciting community feedback as the report evolved. Weekly (and often twice a week) CLOC-SAT discussion sessions were held as information was collected and compiled. Final review of the report was provided by members of the LEAG Executive Committee. This CLOC-SAT report is a product of those interactions and discussions. The report provides a survey of lunar orbital measurements and discusses how modern and continuous lunar orbital capabilities are essential for expanding our integrated understanding of the lunar environment and potential resources, both of which are needed for serious science and exploration activities associated with the Moon throughout the years ahead.

There are three interwoven and deceivingly simple questions that drive and constrain the need for a new generation of lunar orbital capabilities: Why? How? What? Answers to each are framed by our limited current knowledge and quest for understanding, while moving forward is dependent on technical tools and resources available. There is no single answer. This report lays out the motivation and options for moving forward.

2. How to Use This Document

2.1 CLOC-SAT Report Structure

The record of the CLOC-SAT deliberations is primarily contained in this and the remaining four chapters. Chapter 3, Science and Exploration Objectives and Needs, addresses why continuous lunar orbital capabilities are needed and identifies specific investigations that could lead to a transformational understanding of the Moon and its environment. Chapter 4, Implementation Approaches and Architectures, addresses how we can use orbital capabilities and lays out different options for developing and supporting platforms capable of addressing the science and exploration objectives. Chapter 5, Measurement Approaches, addresses what measurement capabilities are required and suggests examples of the types of measurements that could facilitate the transformational science described in Chapter 3. This chapter (Chapter 2) provides an overview of links between the contents of Chapters 3, 4, and 5 and illustrates how a broad range of information is organized in this report. Since there are multiple implementation dimensions possible for the concepts discussed here, we summarize their relations as tensor tables.

It is important to reiterate that this report is a record of deliberations. There may be areas that are covered in greater or lesser detail, which is not intended to indicate preference or prioritization. In order to truly demonstrate that a given measurement or architecture can address a given transformative investigation would require detailed study—which is beyond the scope of this report. The discussion focus is broadly inclusive, but it is recognized there may be alternative, innovative solutions not identified here. This report is also not a review paper and as such the references herein are limited to specific documents and figures mentioned in the text.

There are necessarily many acronyms used throughout the discussion. Each is defined at first mention in the text and a list with definitions is provided as an appendix for reference. Portions of the electromagnetic spectrum and measurement techniques are abbreviated with common labels which are defined in Appendix 3 (FUV, UV, VIS, NIR, IMIR, TIR, INSAR: see also Tables 5.3a, b). Similarly, a glossary of common measurement techniques used throughout this report is also provided as an appendix.

The two tables described in sections 2.2 and 2.3 below are designed to show the traceability between science themes and transformative investigations (the “Why” described in Chapter 3 of the report), implementation constraints (the “How” described in Chapter 4 of the report), and example measurement types (the “What” described in Chapter 5 of the report). Observation altitude is divided into two categories: “low-altitude” indicates lunar orbits with an altitude typically 100 kilometers or less while “distant orbit” indicates orbits with a higher altitude, such as halo orbits or orbits about the L1 or L2 Lagrange points. Spatial coverage is divided into three categories: “Global” indicates that near global coverage (or at least, hemispheric coverage) is required; “Polar” indicates that coverage is required poleward of 80°N/S; “Local or Targeted” indicates that coverage is required for specific non-polar regions. Temporal coverage that requires “Long-Term Monitoring” particularly over timescales of months to years is also identified. The two tables contain the same information, but organized differently. The tables are not intended to be prescriptive, but rather demonstrate the breadth of untapped science opportunities from lunar orbit, and illustrate the range of possible instrument and implementation options.

2.2 Investigation-Driven Traceability

An expected use case is to show traceability from investigations to measurement approaches and implementation approaches. Table 2.2 provides the Investigation Traceability Tensor (ITT) which has similarities to a conventional science traceability matrix (STM). However, through focusing on specific

Table 2.2: Investigation Traceability Tensor (ITT)

Table 2.2 and Table 2.3 are also available in Microsoft Excel (xlsx) format on the LEAG website: https://www.lpi.usra.edu/leag/reports/

WHY		WHAT	HOW					
			ALTITUDE		COVERAGE			
SCIENCE THEMES	TRANSFORMATIVE INVESTIGATIONS	EXAMPLE MEASUREMENT TYPES	Low Altitude	Distant Orbit	Global	Poles	Local/ Targeted	Long-term Monitoring
The state and evolution of the interior of the Moon (3.3.1)	Map global heat flow	Microwave radiometry (5.5.2)	■		■			
		IR radiometry (5.5.3)	■		■			
	Determine state of inner core	Time-dependent gravimetry (5.5.4)	■		■			■
Lunar Volcanism and Magmatism (3.3.2)	Determine the composition of silicic features	TIR imaging spectroscopy (5.3.2)	■				■	
		Gamma ray spectroscopy (5.3.6)	■				■	
	Determine the nature of irregular mare patches	VIS imaging (5.4.1)	■				■	
		Radar imaging (5.4.2)	■				■	
		Radar sounding (5.5.1)	■				■	
	Characterize the structure of mare pits and lava tubes	VIS imaging (5.4.1)	■				■	
		VIS imaging spectroscopy (5.3.1)	■				■	
		NIR imaging spectroscopy (5.3.1)	■				■	
		Radar sounding (5.5.1)	■				■	
		IR radiometry (5.5.3)	■				■	
		Microwave radiometry (5.5.2)	■				■	
		Gravimetry (5.5.4)	■				■	
	Characterize the nature of localized pyroclastic deposits	VIS imaging (5.4.1)	■				■	
		VIS imaging spectroscopy (5.3.1)	■				■	
		NIR imaging spectroscopy (5.3.1)	■				■	
Lunar Tectonics (3.3.3)	Measure surface strain	INSAR* (5.4.3)	■		■		■	■
		Repeat laser altimetry (5.4.5)	■		■		■	■
		Repeat VIS imaging (5.4.3)	■		■		■	■
	Constrain mass wasting events	VIS imaging (5.4.1)	■		■		■	■
		Repeat laser altimetry (5.4.5)	■		■		■	■
		INSAR* (5.4.3)	■		■		■	■
Understanding the Impact Process (3.3.4)	Determine present-day impact rate	Impact flash monitoring (5.4.4)		■	■			■
		Repeat VIS imaging (5.4.3)	■		■			■
		Repeat laser altimetry (5.4.5)	■		■			■
		INSAR* (5.4.3)	■		■			■
	Determine secondary impact rate	Impact flash monitoring (5.4.4)		■	■			■
		Repeat VIS imaging (5.4.3)	■		■			■
		Repeat laser altimetry (5.4.5)	■		■			■
		INSAR* (5.4.3)	■		■			■
	Elucidate cold spot crater formation	IR radiometry (5.5.3)	■				■	
		VIS imaging (5.4.1)	■				■	
The Lunar Regolith and Space Weathering (3.3.5)	Determine structure of regolith and megaregolith	Radar sounding (5.5.1)	■		■			
		Microwave radiometry (5.5.2)	■		■			
	Determine the products of space weathering	UV imaging spectroscopy (5.3.1)	■		■			
		VIS imaging spectroscopy (5.3.1)	■		■			
		NIR imaging spectroscopy (5.3.1)	■		■			

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WHY		WHAT	HOW					
SCIENCE THEMES	TRANSFORMATIVE INVESTIGATIONS	EXAMPLE MEASUREMENT TYPES	ALTITUDE		COVERAGE			Long-term Monitoring
			Low Altitude	Distant Orbit	Global	Poles	Local/ Targeted	
The Composition of the Moon through the Lens of its Surface Deposits (3.3.6)	Determine chemical inventory of the Moon	Gamma ray spectroscopy (5.3.6)	■		■			
		Neutron spectroscopy (5.3.6)	■		■			
		X-ray spectroscopy (5.3.5)	■		■			
	Determine mineralogical inventory of the Moon	UV imaging spectroscopy (5.3.1)	■		■			
		VIS imaging spectroscopy (5.3.1)	■		■			
		IMIR imaging spectroscopy* (5.3.3)	■		■			
		TIR imaging spectroscopy (5.3.2)	■		■			
	Characterize ultramafic lithologies	UV imaging spectroscopy (5.3.1)	■		■		■	
		VIS imaging spectroscopy (5.3.1)	■		■		■	
		NIR imaging spectroscopy (5.3.1)	■		■		■	
		IMIR imaging spectroscopy* (5.3.3)	■		■		■	
		TIR imaging spectroscopy (5.3.2)	■		■		■	
		Active reflectance spectroscopy (5.3.7)	■		■		■	
Special Polar Region Environments (3.3.7)	Determine composition of surface and near surface PSR volatiles	Active reflectance spectroscopy (5.3.7)	■			■		
		NIR imaging spectroscopy (5.3.1)	■			■		
		IR radiometry (5.5.3)	■			■		
		UV imaging spectroscopy (5.3.1)	■			■		
		Active fluorescence spectroscopy* (5.3.8)	■			■		
		Neutral and ion mass spectroscopy (5.2.3)	■			■		
		Neutron spectroscopy (5.3.6)	■			■		
		Dust analyzer	■			■		
	Characterize the abundance of volatiles over various timescales	Active reflectance spectroscopy (5.3.7)	■			■		■
		NIR imaging spectroscopy (5.3.1)	■			■		■
		IMIR imaging spectroscopy* (5.3.3)	■			■		■
		IR radiometry (5.5.3)	■			■		■
		UV imaging spectroscopy (5.3.1)	■			■		■
		Neutral and ion mass spectroscopy (5.2.3)	■			■		■
	Determine the distribution of volatiles at depth	Microwave radiometry (5.5.2)	■			■		
		Radar sounding (5.5.1)	■			■		
		Cosmic ray radio frequency sounding* (5.5.1)	■			■		
	Characterize chemical processing products of regolith	Active IR reflectance spectroscopy (5.3.7)	■			■		
		VIS imaging spectroscopy (5.3.1)	■			■		
		NIR imaging spectroscopy (5.3.1)	■			■		
		IMIR imaging spectroscopy* (5.3.3)	■			■		
		Active fluorescence spectroscopy* (5.3.8)	■			■		
		Neutral and ion mass spectroscopy (5.2.3)	■			■		
The Lunar Volatile System (3.3.8)	Determine the four-dimensional behaviour of exospheric volatiles	Neutral and ion mass spectroscopy (5.2.3)	■		■			■
		FUV spectroscopy (5.3.4)	■		■			■
		NIR spectroscopy (5.3.1)	■		■			■
		IMIR spectroscopy* (5.3.3)	■		■			■
		TIR spectroscopy (5.3.2)	■		■			■
	Fully characterize lunar surface hydration	FUV spectroscopy (5.3.4)	■		■			■
		NIR spectroscopy (5.3.1)	■		■			■
		IMIR spectroscopy* (5.3.3)	■		■			■
		TIR spectroscopy (5.3.2)	■		■			■
		Active reflectance spectroscopy (5.3.7)	■		■			■
Heliosphere and the Lunar Plasma Environment (3.3.9)	Determine the three-dimensional structure of lunar magnetic anomalies	Plasma package (5.2.1)	■	■	■	■	■	■
		Electric and magnetic field (5.2.2)	■	■	■	■	■	■

Table 2.3: Measurement Traceability Tensor (MTT)

WHAT	WHY		HOW					
			ALTITUDE		COVERAGE			
MEASUREMENT TYPES	TRANSFORMATIVE INVESTIGATIONS	SCIENCE THEMES	Low Altitude	Distant Orbit	Global	Poles	Local/ Targeted	Long-term Monitoring
Active fluorescence spectroscopy* (5.3.8)	Determine composition of surface and near surface PSR volatiles	Special Polar Region Environments (3.3.7)	■			■		
	Characterize chemical processing products of regolith		■			■		
Active IR reflectance spectroscopy (5.3.7)	Characterize chemical processing products of regolith	Special Polar Region Environments (3.3.7)	■			■		
Active reflectance spectroscopy (5.3.7)	Characterize ultramafic lithologies	The Composition of the Moon through the Lens of its Surface Deposits (3.3.6)	■		■		■	
	Determine composition of surface and near surface PSR volatiles	Special Polar Region Environments (3.3.7)	■			■		
	Characterize the abundance of volatiles over various timescales		■			■		■
	Fully characterize lunar surface hydration	The Lunar Volatile System (3.3.8)	■		■			■
Cosmic ray radio frequency sounding* (5.5.1)	Determine the distribution of volatiles at depth	Special Polar Region Environments (3.3.7)	■			■		
Dust analyzer	Determine composition of surface and near surface PSR volatiles	Special Polar Region Environments (3.3.7)	■			■		
Electric and magnetic field (5.2.2)	Determine the three-dimensional structure of lunar magnetic anomalies	The Lunar Volatile System (3.3.8)	■	■	■	■	■	■
FUV spectroscopy (5.3.4)	Determine the four-dimensional behaviour of exospheric volatiles	The Lunar Volatile System (3.3.8)	■		■			■
	Fully characterize lunar surface hydration		■		■			■
Gamma ray spectroscopy (5.3.6)	Determine the composition of silicic features	Lunar Volcanism and Magmatism (3.3.2)	■				■	
	Determine chemical inventory of the Moon	The Composition of the Moon through the Lens of its Surface Deposits (3.3.6)	■		■			
Gravimetry (5.5.4)	Characterize the structure of mare pits and lava tubes	Lunar Volcanism and Magmatism (3.3.2)	■				■	
IMIR imaging spectroscopy* (5.3.3)	Determine mineralogical inventory of the Moon	The Composition of the Moon through the Lens of its Surface Deposits (3.3.6)	■		■			
	Characterize ultramafic lithologies		■		■		■	
	Characterize the abundance of volatiles over various timescales	Special Polar Region Environments (3.3.7)	■			■		■
	Characterize chemical processing products of regolith		■			■		
IMIR spectroscopy* (5.3.3)	Determine the four-dimensional behaviour of exospheric volatiles	The Lunar Volatile System (3.3.8)	■		■			■
	Fully characterize lunar surface hydration		■		■			■
Impact flash monitoring (5.4.4)	Determine present-day impact rate	Understanding the Impact Process (3.3.4)		■	■			■
	Determine secondary impact rate			■	■			■
INSAR* (5.4.3)	Measure surface strain	Lunar Tectonics (3.3.3)	■		■		■	■
	Constrain mass wasting events		■		■		■	■
	Determine present-day impact rate	Understanding the Impact Process (3.3.4)	■		■			■
	Determine secondary impact rate		■		■			■
IR radiometry (5.5.3)	Map global heat flow	The state and evolution of the interior of the Moon (3.3.1)	■		■			
	Characterize the structure of mare pits and lava tubes	Lunar Volcanism and Magmatism (3.3.2)	■				■	
	Elucidate cold spot crater formation	Understanding the Impact Process (3.3.4)	■		■		■	
	Determine composition of surface and near surface PSR volatiles	Special Polar Region Environments (3.3.7)	■			■		
	Characterize the abundance of volatiles over various timescales		■			■		■
Microwave radiometry (5.5.2)	Map global heat flow	The state and evolution of the interior of the Moon (3.3.1)	■		■			
	Characterize the structure of mare pits and lava tubes	Lunar Volcanism and Magmatism (3.3.2)	■				■	
	Determine structure of regolith and megaregolith	The Lunar Regolith and Space Weathering (3.3.5)	■		■			
	Determine the distribution of volatiles at depth	Special Polar Region Environments (3.3.7)	■			■		

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WHAT	WHY		HOW					
MEASUREMENT TYPES	TRANSFORMATIVE INVESTIGATIONS	SCIENCE THEMES	ALTITUDE		COVERAGE			Long-term Monitoring
			Low Altitude	Distant Orbit	Global	Poles	Local/ Targeted	
Neutral and ion mass spectroscopy (5.2.3)	Determine composition of surface and near surface PSR volatiles	Special Polar Region Environments (3.3.7)	■			■		
	Characterize the abundance of volatiles over various timescales		■			■		■
	Characterize chemical processing products of regolith		■			■		
	Determine the four-dimensional behaviour of exospheric volatiles	The Lunar Volatile System (3.3.8)	■		■			■
Neutron spectroscopy (5.3.6)	Determine chemical inventory of the Moon	The Composition of the Moon through the Lens of its Surface Deposits (3.3.6)	■		■			
	Determine composition of surface and near surface PSR volatiles	Special Polar Region Environments (3.3.7)	■			■		
NIR imaging spectroscopy (5.3.1)	Characterize the structure of mare pits and lava tubes	Lunar Volcanism and Magmatism (3.3.2)	■				■	
	Characterize the nature of localized pyroclastic deposits		■				■	
	Determine the products of space weathering	The Lunar Regolith and Space Weathering (3.3.5)	■		■			
	Characterize ultramafic lithologies	The Composition of the Moon through the Lens of its Surface Deposits (3.3.6)	■		■		■	
	Determine composition of surface and near surface PSR volatiles	Special Polar Region Environments (3.3.7)	■			■		
	Characterize the abundance of volatiles over various timescales		■			■		■
	Characterize chemical processing products of regolith		■			■		
NIR spectroscopy (5.3.1)	Determine the four-dimensional behaviour of exospheric volatiles	The Lunar Volatile System (3.3.8)	■		■			■
	Fully characterize lunar surface hydration		■		■			■
Plasma package (5.2.1)	Determine the three-dimensional structure of lunar magnetic anomalies	The Lunar Volatile System (3.3.8)	■	■	■	■	■	■
Radar imaging (5.4.2)	Determine the nature of irregular mare patches	Lunar Volcanism and Magmatism (3.3.2)	■				■	
Radar sounding (5.5.1)	Determine the nature of irregular mare patches	Lunar Volcanism and Magmatism (3.3.2)	■				■	
	Characterize the structure of mare pits and lava tubes		■				■	
	Determine structure of regolith and megaregolith	The Lunar Regolith and Space Weathering (3.3.5)	■		■			
	Determine the distribution of volatiles at depth	Special Polar Region Environments (3.3.7)	■			■		
Repeat laser altimetry (5.4.5)	Measure surface strain	Lunar Tectonics (3.3.3)	■		■		■	■
	Constrain mass wasting events		■		■		■	■
	Determine present-day impact rate	Understanding the Impact Process (3.3.4)	■		■			■
	Determine secondary impact rate		■		■			■
Repeat VIS imaging (5.4.3)	Measure surface strain	Lunar Tectonics (3.3.3)	■		■		■	■
	Determine present-day impact rate	Understanding the Impact Process (3.3.4)	■		■			■
	Determine secondary impact rate		■		■			■
Time-dependent gravimetry (5.5.4)	Determine state of inner core	The state and evolution of the interior of the Moon (3.3.1)	■		■			■
TIR imaging spectroscopy (5.3.2)	Determine the composition of silicic features	Lunar Volcanism and Magmatism (3.3.2)	■				■	
	Determine mineralogical inventory of the Moon	The Composition of the Moon through the Lens of its Surface Deposits (3.3.6)	■		■			
	Characterize ultramafic lithologies		■		■		■	
TIR spectroscopy (5.3.2)	Determine the four-dimensional behaviour of exospheric volatiles	The Lunar Volatile System (3.3.8)	■		■			■
	Fully characterize lunar surface hydration		■		■			■
UV imaging spectroscopy (5.3.1)	Determine the products of space weathering	The Lunar Regolith and Space Weathering (3.3.5)	■		■			
	Determine mineralogical inventory of the Moon	The Composition of the Moon through the Lens of its Surface Deposits (3.3.6)	■		■			
	Characterize ultramafic lithologies		■		■		■	
	Determine composition of surface and near surface PSR volatiles	Special Polar Region Environments (3.3.7)	■			■		
	Characterize the abundance of volatiles over various timescales		■			■		■
VIS imaging (5.4.1)	Determine the nature of irregular mare patches	Lunar Volcanism and Magmatism (3.3.2)	■				■	
	Characterize the structure of mare pits and lava tubes		■				■	
	Characterize the nature of localized pyroclastic deposits		■				■	
	Constrain mass wasting events	Lunar Tectonics (3.3.3)	■		■		■	■
	Elucidate cold spot crater formation	Understanding the Impact Process (3.3.4)	■		■		■	
VIS imaging spectroscopy (5.3.1)	Characterize the structure of mare pits and lava tubes	Lunar Volcanism and Magmatism (3.3.2)	■				■	
	Characterize the nature of localized pyroclastic deposits		■				■	
	Determine the products of space weathering	The Lunar Regolith and Space Weathering (3.3.5)	■		■			
	Determine mineralogical inventory of the Moon	The Composition of the Moon through the Lens of its Surface Deposits (3.3.6)	■		■			
	Characterize ultramafic lithologies		■		■		■	
	Characterize chemical processing products of regolith	Special Polar Region Environments (3.3.7)	■			■		
X-ray spectroscopy (5.3.5)	Determine chemical inventory of the Moon	The Composition of the Moon through the Lens of its Surface Deposits (3.3.6)	■		■			

measurement techniques and prescribed mission architectures, the ITT shows how investigations can be addressed with a broad range of measurement and implementation approaches. The ITT serves as a roadmap to the content presented in Chapter 3, Science and Exploration Objectives and Needs.

The investigations identified in the ITT (and Chapter 3) were derived though deliberations of transformative investigations that could only be completed with new or enhanced datasets beyond those currently available. Therefore all included investigations are considered to be of high priority.

2.3 Measurement-Driven Traceability

Another expected use case is to show traceability from measurement approaches to investigations and implementation approaches. Table 2.3 provides the Measurement Traceability Tensor (MTT). In this approach, the same information as in the ITT are arranged to emphasize measurements and to demonstrate how specific measurement approaches map to one or more investigations. The MTT serves as a roadmap to the content presented in Chapter 5, Measurement Approaches.

The measurements identified in the MTT (and Chapter 5) were derived though deliberations of the measurements required to address specific transformative investigations identified in Chapter 3. These measurements are therefore necessarily either new or enhanced datasets beyond those currently available; however, there are likely other (conventional or otherwise unknown to the CLOC-SAT) approaches that could also be employed. Exclusion from these tables and text is not intended to reflect on the general importance of any specific measurement approach.

2.4 Implementation-Driven Traceability

The capabilities described in Chapter 4, Implementation Approaches and Architectures, lend themselves toward an extremely diverse range of investigations and measurements. Therefore the CLOC-SAT determined that a traceability tensor from this perspective was not practical. In its place, this report provides brief examples of combinations of orbits and orbiter capabilities within the narrative text of Chapter 4. These examples are illustrative only and intended to demonstrate how capabilities described herein can be used. The CLOC-SAT is not a science definition team and these examples are not intended to be viewed as priorities endorsed by the CLOC-SAT.

2.5 Additional Resources

The CLOC-SAT Report contains appendices to be used as additional resources.

Appendix 1: Acknowledgements

This report exists because of community support. Here we acknowledge individuals who contributed to development of the CLOC-SAT report beyond the members of the CLOC-SAT team and ex officios. These knowledgeable community leaders should be seen as valuable additional resources for the contents of this report.

Appendix 2: List of All Findings

For convenience, a complete list of findings are provided in Appendix 2. The findings are listed in the order first mentioned in the text and are not in a prioritized order. Overarching findings are presented first and followed by topical findings.

Appendix 3: List of Acronyms

A complete list of all acronyms used throughout the report is provided.

Appendix 4: Glossary

For clarity, a subset of common terms and techniques included in the report are defined in the Glossary.

Appendix 5: References

The CLOC-SAT Report is not a review paper and does not contain the same types of references that would be expected of that type of manuscript. Rather, the references included in Appendix 5 focus on specific documents relevant to the text.

Appendix 6: Alphabetical List of White Papers

Community members were invited to contribute topical White Papers. The CLOC-SAT received

13 White Papers in support of a broad range of investigations, measurements, and architectures. The full list of White Papers is presented in Appendix 6. The full text of the indicated White Papers is available on the LEAG website, https://www.lpi.usra.edu/leag/reports/.

Appendix 7: CLOC-SAT Terms of Reference (TOR)
The full text of the TOR defined by the LEAG Executive Committee to establish the CLOC-SAT are provided in Appendix 7.

3. Science and Exploration Objectives and Needs

3.1 Introduction and Scope

The 21st century has seen a revolution in the scientific exploration of the Moon with astounding new insights gleaned from recent missions, including the first sample return and rover missions since the 1970's. The near future will feature additional landed missions through the Commercial Lunar Payload Services (CLPS) and international programs and Artemis exploration that will provide unprecedented new data aimed at key science questions, including new questions raised this century. While in situ exploration and especially sample return are unique in the value of their contributions, orbital measurements enable extrapolation of landed investigations to regions across the Moon. In addition, some areas of lunar science are best addressed from lunar orbit, such as the state of the exosphere.

In this section we introduce science and exploration objectives that orbital measurements can uniquely address, that have the potential to yield transformative results, are technically feasible in the coming decade, and make significant contributions to the unique needs of exploration science. We note that this report includes guidance from prior reports, especially the most recent Decadal Survey, and community responses to the CLOC-SAT's aims.

3.2 Traceability to Strategic Documents

Several community documents discuss in detail the importance of lunar science and exploration which are relevant to the CLOC-SAT report. These include:

- The 2022 NASEM Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032 (Decadal Survey)
- The 2007 NRC The Scientific Context for Exploration of the Moon (SCEM), and the 2018 LEAG review and update, Advancing Science of the Moon (ASM-SAT)
- The 2020 NASA Artemis III Science Definition Team (SDT) Report
- The 2016 LEAG Lunar Exploration Roadmap (LER)

Although each was written for a different purpose, there is consistency across them all. Summarized in Table 3.2 below are the ways that different CLOC-SAT themes and issues are discussed. Each of these reports independently highlights a common list of key science issues that are addressed with lunar exploration.

In addition, the recently released NASA document "Moon to Mars Objectives" has numerous goals and objectives directly relevant to the aims of the CLOC-SAT. Examples include:

- **Lunar/Planetary Science Goal:** Address high priority planetary science questions that are best accomplished by on-site human explorers on and around the Moon and Mars, aided by surface and orbiting robotic systems.
- **Science Enabling Obj. 6**: Enable long-term, planet-wide research by delivering science instruments to multiple science-relevant orbits and surface locations at the Moon and Mars.
- **Applied Science Obj. 1:** Characterize and monitor the contemporary environments of the lunar and Martian surfaces and orbits, including investigations of micrometeorite flux, atmospheric weather, space weather, space weathering, and dust, to plan, support, and monitor safety of crewed operations in these locations.
- **Applied Science Obj. 2:** Coordinate on-going and future science measurements from orbital and surface platforms to optimize human led science campaigns on the Moon and Mars.
- **Lunar Infrastructure Obj. 2:** Develop a lunar surface, orbital, and Moon-to-Earth communications architecture capable of scaling to support long term science, exploration, and industrial needs.

TABLE 3.2: CLOC-SAT science and exploration topics as identified across relevant strategic reports.

CLOC-SAT Topics	**2022 Decadal Survey**	**SCEM / ASM-SAT Concepts**	**Artemis III SDT Objectives**	**LER Science, Sustainability Objectives**
3.3.1 The state and evolution of the interior of the Moon	Q3.3; Q3.5; Q5.1; Q5.2; Q5.6; Q8.2; Q8.3	SCEM/ASM 2c. Determine the size, composition, and state (solid/liquid) of the core of the Moon. SCEM/ASM 2d. Characterize the thermal state of the interior and elucidate the workings of the planetary heat engine.	1a. Formation of the Earth-Moon System 1b. Differentiation: Magma Oceans, Crust and Mantle	Sci-A-5: Understand lunar differentiation Sci-A-8: Determine the stratigraphy, structure, and geological history of the Moon
3.3.2 Lunar Volcanism and Magmatism	Q3.3; Q3.5; Q4.3; Q5.2; Q5.3; Q8.2; Q8.3; Q9.1; Q10.3	SCEM/ASM 5a. Determine the origin and variability of lunar basalts. SCEM/ASM 5c. Determine the compositional range and extent of lunar pyroclastic deposits. SCEM/ASM 5d. Determine the flux of lunar volcanism and its evolution through space and time.	1c. Volcanism: Partial Melting, Eruptions, Flows, Compositions	Sci-A-6: Understand volcanic processes Sci-A-8: Determine the stratigraphy, structure, and geological history of the Moon
3.3.3 Lunar Tectonics	Q5.2; Q5.3; Q5.6; Q8.2	ASM New Concept: Lunar tectonism and seismicity	1d. Tectonism: Deformation of the Crust and Thermal History	Sci-A-8: Determine the stratigraphy, structure, and geological history of the Moon
3.3.4 Understanding the Impact Process	Q2.4; Q3.1; Q3.2; Q4.1; Q4.2; Q4.4; Q5.5; Q9.1; Q12.4	SCEM/ASM 1e. Study the role of secondary impact craters on crater counts. ASM 1d. Assess the recent impact flux. SCEM/ASM 6c. Quantify the effects of planetary characteristics (composition, density, impact velocities) on crater Formation and morphology. SCEM/ASM 6d. Measure the extent of lateral and vertical mixing of local and ejecta material.	1e. Impact Processes: Basins and Craters, Mixing of the Crust 3b. Understand changes to the Earth-Moon bombardment rate	Sci-A-7: Understand the impact process Sci-A-8: Determine the stratigraphy, structure, and geological history of the Moon Sci-B-1: Understand the impact history of the inner Solar System as recorded on the Moon.
3.3.5 The Lunar Regolith and Space Weathering	Q4.1; Q5.5; Q6.5; Q8.3	SCEM/ASM 3e. Determine the vertical extent and structure of the megaregolith. SCEM/ASM 7b. Determine physical properties of the regolith at diverse locations of expected human activity. SCEM/ASM 7c. Understand regolith modification processes (including space weathering), particularly deposition of volatile materials. ASM New Concept: The lunar volatile cycle	1e. Impact Processes: Basins and Craters, Mixing of the Crust 1f. Moon as a Natural Laboratory for Regolith Processes and Weathering 2d. Understand regolith modification processes	Sci-A-4: Understand the dynamical evolution and space weathering of the regolith Sci-A-7: Understand the impact process Sci-B-2: Regolith as a recorder of extra-lunar processes

3.3.6 The composition of the Moon through the lens of its surface deposits	Q2.4; Q3.1; Q4.4; Q5.1; Q5.3; Q5.5; Q8.3; Q12.1; Q12.2	SCEM/ASM 2a. Determine the thickness of the lunar crust (upper and lower) and characterize its lateral variability on regional and global scales. SCEM/ASM 3a. Determine the extent and composition of the primary feldspathic crust, KREEP layer, and other products of planetary differentiation. SCEM/ASM 3b. Inventory the variety, age, distribution, and origin of lunar rock types. SCEM/ASM 3c. Determine the composition of the lower crust and bulk Moon. SCEM/ASM 3d. Quantify the local and regional complexity of the current lunar crust.	1b. Differentiation: Magma Oceans, Crust, and Mantle	Sci-A-5: Understand lunar differentiation Sci-A-8: Determine the stratigraphy, structure, and geological history of the Moon Sci-A-9: Understand formation of the Earth-Moon system.
3.3.7 Special Polar Region Environments	Q3.1; Q3.6; Q4.3; Q5.5; Q6.1; Q9.1; Q10.3, Q11.1	SCEM/ASM 4a. Determine the compositional state (elemental, isotopic, mineralogic) and compositional distribution (lateral and depth) of the volatile component in lunar polar regions. SCEM/ASM 4b. Determine the source(s) for lunar polar volatiles. SCEM/ASM 4c. Understand the transport, retention, alteration, and loss processes that operate on volatile materials at permanently shaded lunar regions. SCEM/ASM 4d. Understand the physical properties of the extremely cold (and possibly volatile rich) polar regolith. ASM-SAT New Concept: The lunar volatile cycle	2a. Determine the compositional state and distribution of the volatile component in polar regions 2b. Determine the source(s) for polar volatile deposits. 2c. Understand the transport, retention, alteration, and loss processes that operate on volatile materials in PSRs. 6k. Study and assess effects on materials of long duration exposure to the lunar environment.	Sci-A-3: Characterize the environment and processes in lunar polar regions and in the lunar exosphere
3.3.8 The Lunar Volatile System	Q3.3; Q3.6; Q4.3; Q5.3; Q5.5; Q6.1; Q6.5; Q10.3; Q12.4	SCEM/ASM 4a. Determine the compositional state (elemental, isotopic, mineralogic) and compositional distribution (lateral and depth) of the volatile component in lunar polar regions. SCEM/ASM .4c. Understand the transport, retention, alteration, and loss processes that operate on volatile materials at permanently shaded lunar regions. SCEM/ASM 8a. Determine the global density, composition, and time variability of the fragile lunar atmosphere before it is perturbed by further human activity. SCEM/ASM 8d. Learn how water vapor and other volatiles are released from the lunar surface and migrate to the poles where they are adsorbed in polar cold traps ASM New Concept: The lunar volatile cycle	2a. Determine the compositional state and distribution of the volatile component in polar regions 2b. Determine the source(s) for polar volatile deposits. 2c. Understand the transport, retention, alteration, and loss processes that operate on volatile materials in PSRs. 2e. Learn how water vapor and other volatiles are released from the surface and migrate to the poles.	Sci-A-1: Understand the environmental impacts of lunar exploration Sci-A-3: Characterize the environment and processes in lunar polar regions and in the lunar exosphere Sci-A-4: Understand the dynamical evolution and space weathering of the regolith Sci-A-6: Understand volcanic processes

3.3.9 Heliosphere and the Lunar Plasma Environment	Q6.5; Q8.3	SCEM/ASM 8a. Determine the global density, composition, and time variability of the fragile lunar atmosphere before it is perturbed by further human activity. SCEM/ASM 8b. Determine the size, charge, and spatial distribution of electrostatically transported dust grains and assess their likely effects on lunar exploration and lunar-based astronomy. SCEM/ASM 8c. Use the time-variable release rate of atmospheric species such as 40Ar and radon to learn more about the inner workings of the lunar interior.	5b. Heliophysical Investigations using the Moon 7k. Understand lunar dust behavior, particularly dust dynamics	Sci-A-1: Understand the environmental impacts of lunar exploration Sci-A-3: Characterize the environment and processes in lunar polar regions and in the lunar exosphere Sci-C-2: Heliophysical Investigations using the Moon.

3.3 Science and Exploration Objectives

In this section, we present brief backgrounds and areas of strategic research that could yield transformative science advances through new measurements that are significant improvements over the datasets currently available, measurements that are feasible, and in many cases multiple approaches that are now possible. Example measurement technologies are presented in Chapter 5, whereas measurement goals and objectives are presented and supported here.

3.3.1 The state and evolution of the interior of the Moon

Our knowledge of the lunar interior has been revolutionized by precise measurements of the Moon's gravity field, shape, and moments of inertia. The Gravity Recovery and Interior Laboratory (GRAIL) mission produced the highest resolution global gravity field model for any planetary body, with a resolution of 3–5 km (although the quality varies globally). The LRO Lunar Orbiter Laser Altimeter (LOLA) instrument provided a comparably high-resolution global shape model; this model was merged with the JAXA SELenological and ENgineering Explorer (SELENE) Terrain Camera stereo image-based shape model, increasing the spatial sampling to 60 m. Stereo images from LRO Lunar Reconnaissance Orbiter Camera (LROC) provide topography at an order-of-magnitude better resolution, albeit with less spatial coverage. Laser ranging to retroreflectors on the surface of the Moon have also provided critical constraints on the Moon's interior structure, including measuring dissipation within the Moon. The combination of these datasets provided substantial insights to the lunar interior, from the thickness, structure, and porosity of the crust, to the formation of lunar impact basins. Nonetheless, there are still outstanding questions about the Moon's interior (core and mantle). Gravity measurements have also hinted at tantalizing structures just at or below the resolution of the global gravity field, including intrusive magmatism, and lava tubes below the mare surface.

Heat flow is another fundamental geophysical parameter for any object as it uniquely probes the interior through the presence of internal heat sources (Fig. 3.3.1). Apollo measurements of heat flow enabled estimates of the bulk composition of the Moon through the influence of heat-producing elements. In addition, recent results from the microwave sounder on Chang'E-1 and -2 showed that heat flow could be derived from passive microwave measurements. The Chang'E work added this critical geophysical parameter to the global maps of gravity and topography. We note that the existing microwave data are at a frequency higher than optimal for estimating heat flow. The new global heat flow map showed that the Procellarum KREEP Terrane (PKT), which exhibits regional anomalous concentrations of radioactive elements at the surface, is accompanied by enhanced heat flow, illustrating how the expression of heat producing elements characteristic of the PKT is not superficial. LRO Diviner Lunar Radiometer (Diviner) observations also demonstrated an ability to remotely estimate heat flow by measuring temperatures in a few permanently shadowed regions (PSR) that are doubly or triply shadowed from direct sunlight where surface temperatures are as low as 20K and where flux is dominated by heat flow from the interior. These polar observations enable a heat flow estimate far from the Apollo heat flow measurements in the PKT. Remote measurements would place local heat flow measurements by the proposed Lunar Geophysical Network (LGN) into global context.

Transformative investigations

Map global heat flow to provide context for ground truth provided by surface measurements

Remote mapping of heat flow at a spatial resolution at or better than 10 km with sensitivity similar to Apollo heat flow measurements would reveal buried heat sources and allow modeling of igneous bodies at depth. These data would also supply constraints on the bulk and regional composition across the Moon. Spatially-resolved orbital heat flow data would complement surface heat flow measurements acting as ground truth and extend the surface measurements carried out by planned CLPS missions at Schrödinger and Crisium basins as well as the proposed LGN to encompass the entire Moon. At 10 km resolution the detailed structure of the PKT anomaly and many smaller thermal anomalies are likely to be detected, reflecting buried intrusive igneous activity. For example, does the putative buried rift system around the PKT, suggested by GRAIL-derived gravity anomalies, have a residual heat flow signature that might reveal its origin?

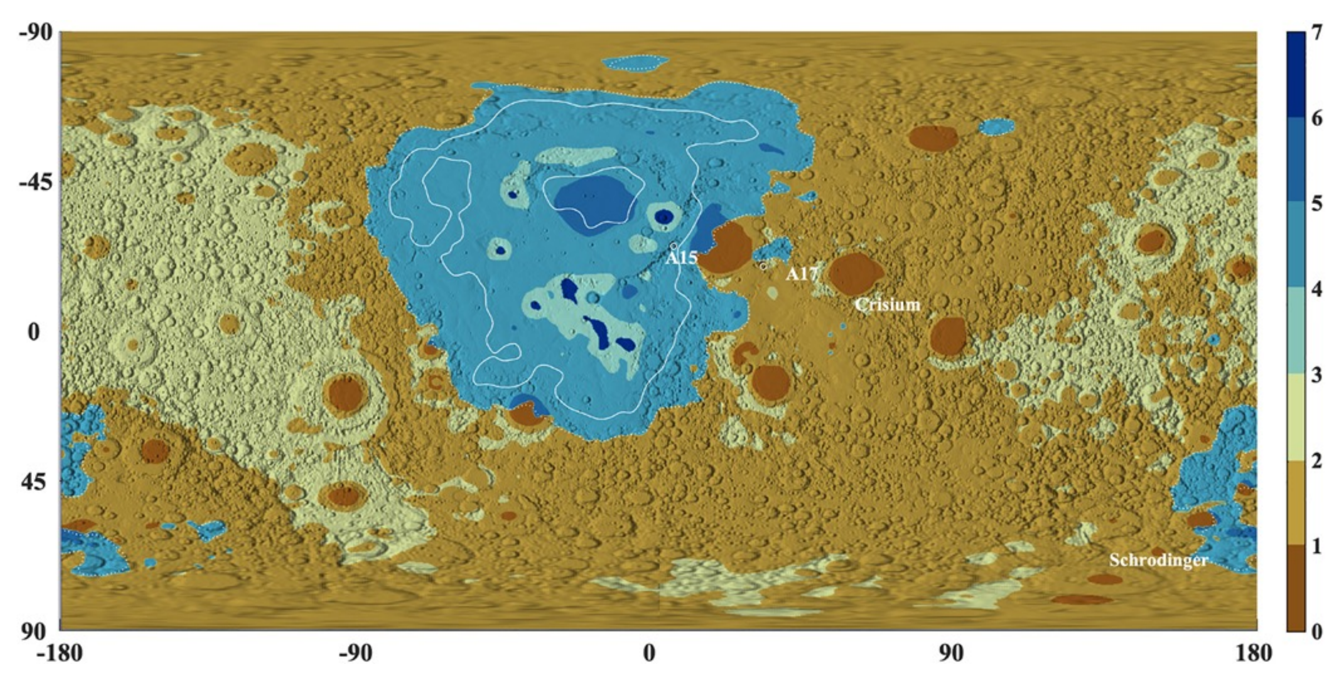


Figure 3.3.1: Seven anticipated Lunar Heat Flow Provinces. This map was created through analysis of available surface elemental abundances and crustal thickness to classify areas predicted to have observable differences in heat flow. Highest heat fluxes are expected for the dark blue units (7) while lowest heat fluxes are expected for the light beige units (3) found largely on the farside. Figure from Siegler et al. 2022a.

Example measurements: microwave radiometry (§5.5.2), infrared radiometry (§5.5.3)

Determine the state of the Moon's solid inner core

Despite the extreme resolution of the Moon's gravity field from GRAIL, the nature of its deepest interior is still uncertain. Analysis of available seismic, gravity, and laser ranging data suggest that the Moon may have a solid inner core and a fluid outer core–although key details (e.g., size, density, composition) remain uncertain. One untapped method for probing the Moon's core is by measuring the time-dependent gravity field of the Moon to high precision. As the Moon orbits the Earth, the inner core is expected to librate differentially from the rest of the bulk Moon. As the core moves, it would result in a weak, periodically varying gravity field at the surface. GRAIL could not directly detect the core using this method, as GRAIL was optimized for high spatial resolution.

Example measurements: time-dependent gravimetry (§5.5.4)

Implications for Exploration

Obtaining heat flow measurements is particularly salient for landed missions near PSRs, as is planned for Artemis III. Predictions of ice at depth have significant uncertainties depending on the local heat flow. Due to the complex lighting environment at the poles, a significant fraction of heat flow is lateral and, in some cases, will be negative at the surface as heat flows through the subsurface from illuminated regions into PSRs. This heterogeneous lateral heat flow may be a significant control on the distribution of subsurface ice. Local surface heat flow measurements will require regional context from orbit to reduce ambiguities in data interpretation.

Findings

- **Finding 3.3.1a:** Global, high-resolution (~10 km) measurements of heat flow are required to understand the geophysical evolution, structure, and composition of the Moon, and to place ground truth measurements into global context.
- **Finding 3.3.1b:** Regional heat flow measurements at the poles are required to support interpretation of Artemis III and other surface polar data, and to better understand the distribution of buried ice.
- **Finding 3.3.1c:** Time-dependent gravity measurements may provide a unique method for probing the Moon's core, complementary to landed geophysical measurements.

3.3.2 Lunar Volcanism and Magmatism

This century has seen a transformation in the understanding of the styles and diversity of lunar volcanism. The compositions of spectrally distinct domes and other features long suspected to be the result of constructional silicic volcanism have been confirmed by orbital infrared spectroscopy, and the inventory of silicic material has expanded considerably with the ability to remotely estimate silica content. Orbital spectroscopy of pyroclastic deposits show they vary widely in hydration, indicating a highly variable water content of their source regions. Some show evidence for the presence of spinel, with unknown implications for their emplacement process. High resolution imaging has revealed the presence of a large number of "irregular mare patches" (IMPs), which have apparent collapse features with highly unusual morphologies that suggest potential violent volatile outgassing, and crater counts and spectral properties suggesting extreme youth. The anomalous nature of these features suggest they may feature similarly anomalous physical properties, which calls into question the ability to judge the antiquity of these features. It has been proposed that their nature may not permit preservation of small craters or allow evolution of spectral properties in the same manner as typical lunar material, leading to the opposing suggestion that IMP features are ancient, and not the result of recent volcanic activity. Deep pits in the maria discovered from orbit are thought to be skylights into lava tubes, and these have been suggested to be sites for astronaut habitats, and their value as a scientific resource has only begun to be recognized.

Transformative Investigations

Characterize the compositions and distributions of silicic features

Remote sensing has identified numerous volcanic structures and craters that have anomalously silica-rich compositions compared to common lunar volcanic materials. Similar compositions on Earth are the result of hydrous magmas and plate tectonics, the latter of which the Moon lacks. Therefore a greater understanding of these features is required for a complete picture of lunar interior evolution, crust building, and surface volcanism. Volcanic activity on the Moon was volumetrically and compositionally dominated by basaltic mare volcanism. In contrast to the mare, the silicic dome features are discretely located, have steep slopes of 15-30°, low ultraviolet to near-infrared reflectance, and low TiO_2 and FeO abundances. Furthermore, a likely silicic pluton has been exposed by Aristarchus crater, suggesting even more widespread occurrences of silicic material than are seen at the surface. The silicic nature of these features were confirmed by LRO Diviner data based on the thermal infrared silicate Christiansen feature (CF) position, and most silicic lunar features also seem to exhibit elevated thorium abundances. While silicic compositions have been confirmed by Diviner, its limited spectral resolution has prevented detailed characterization of the lithologies of these features and therefore an understanding of their relationship, if any, to rare felsite/granite samples in the Apollo collection. Furthermore, the coarse spatial resolution of orbital GRS data prevents detailed characterization of the chemistry (especially Th abundance) of these features.

Example measurements: TIR imaging spectroscopy at <10 m resolution (§5.3.2), IMIR imaging spectroscopy at <10 m resolution (§5.3.3), GRS measurements at <50 km resolution (§5.3.6)

Determine the nature of irregular mare patches

Understanding of irregular mare patches (Fig. 3.3.2) will greatly improve with planned new data, but these would still benefit from much higher resolution imaging as their properties are so anomalous. The sharpness of contacts in these features has been used as an argument for their young age; better imaging would enable testing this hypothesis. If these features are due to recent lunar volcanic activity, this has profound implications for the thermal evolution of the Moon and would cause a re-examination of existing thermal models and the state of the lunar stress field.

Example measurements: ~10 cm resolution visible imaging (§5.4.1), radar imaging (§5.4.2), subsurface radar sounding (§5.5.1)

Characterize the nature and structure of mare basalt volcanism from lava tubes and mare pits

The existence of lava tubes on the Moon has been hypothesized since the discovery of lunar pits, rilles, and other features. Analyses of GRAIL gravity data have suggested the presence of enormous (~1 km wide, 100s m deep, ~10s of km long) empty lava tubes. At one of those locations (Marius Hills), the SELENE Lunar Radar Sounder observed radar reflections consistent with a 50 km long lava tube. Lava tubes are intrinsically interesting as a record of lunar volcanism, and their potential as radiation- and thermal-shielded environments for human exploration. While the current lava tube detections are tantalizing, they are not conclusive. There may be multiple methods for verifying and characterizing these structures, including radar sounding, ultra-high resolution gravity measurements, or thermal measurements. LRO imaging has shown clear layering in the walls of some mare pits that are likely skylights into lava tubes; higher resolution imaging may detect soil horizons between flows, and higher resolution compositional measurements could probe the history of mare volcanism using these natural drill holes.

Example measurements: Imaging at 10-cm scale (§5.4.1), multispectral imaging or imaging spectroscopy at ~1 m resolution, radar sounding (§5.5.1), infrared radiometry (§5.4.6 & §5.5.3), microwave radiometry (§5.5.2), high-resolution gravimetry (§5.5.4)

Characterize the nature of localized pyroclastic deposits

Pyroclastic deposits are important recorders of lunar mantle conditions, including volatile content, and the discovery of water in pyroclastic deposits has led to new understandings about the nature of volatiles in the lunar interior. The majority of pyroclastic deposits are

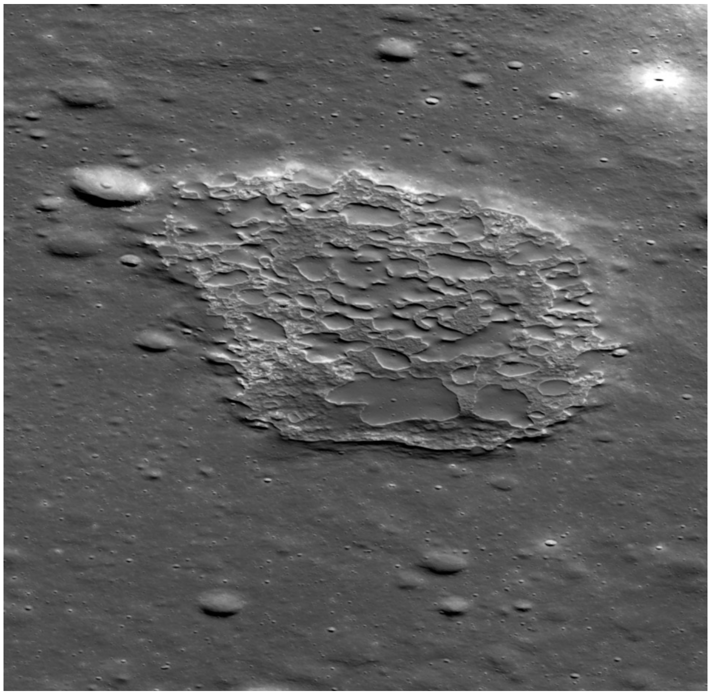


Figure 3.3.2: Oblique view of the Ina D caldera irregular mare patch (IMP) feature. The smooth mound surfaces, steep slopes, and bright floor have all contributed to a hypothesis that this feature represents volcanic activity less than 100 million years old. [LROC NAC M1108203502LR]

characterized as localized (<1000 km^2) and surround a central vent depression. However, all of the pyroclastic deposit materials in the lunar sample collection are sourced from larger, regional-scale pyroclastic deposits, and the relationship with the original eruption vent is unknown. The lack of context for these samples therefore constrains the understanding of volatile evolution in the mantle and mantle heterogeneities. Current remote sensing datasets do not have the spatial resolution to characterize the majority of localized deposits. Increased spectral and imaging resolution is required to identify characteristics of localized deposits and map new deposits along known fractures. Further studies of localized pyroclastic deposits could expand the understanding of the evolution of water in the lunar interior, and serve as additional locations for in situ resource utilization, not just for water, but also for Fe and potentially Ti.

Example measurements: imaging at 10-cm scale (§5.4.1), multispectral imaging or VIS and NIR imaging spectroscopy at ~1 m resolution (§5.3.1)

Implications for Exploration

Lava tubes may provide long term shelter or habitation on the Moon, and improved measurements would facilitate site evaluation, and address issues regarding possible disturbance to their scientific value by extensive operations. The unusual nature of irregular mare patches makes them an intriguing target for exploration, but their geotechnical properties are the subject of vigorous debate, complicating the ability to plan surface operations. In addition, the hydration state of pyroclastic materials is essential to know with high confidence, given the interest in thick pyroclastic deposits for processing large quantities of regolith for resources.

Findings

- **Finding 3.3.2a:** Determining the nature of irregular mare patches would better constrain the thermal evolution of the Moon.
- **Finding 3.3.2b:** Additional measurements should be undertaken to complete detection and mapping of mare pits and lava tube distributions to better understand the utility of these features to future exploration activities and astronaut habitation.
- **Finding 3.3.2c:** Increased spectral and imaging resolution is required to characterize localized pyroclastic deposits, map new deposits along known fractures and determine their hydration states.
- **Finding 3.3.2d:** Thermal-infrared imaging spectroscopy and high spatial resolution GRS measurements are required to fully characterize the compositions and distribution of silicic features on the Moon.

3.3.3 Lunar Tectonics

LROC images documented small thrust faults throughout the highlands, including cross-cutting relationships with relatively fresh craters indicating ongoing tectonism. Discoveries of landslides that occurred during the LRO mission show a spatial correlation between the landslides and thrust faults, suggesting significant seismicity associated with these newly created features. Some wrinkle ridge thrust faults show boulder fields at their margins, indicating these may also be active.

Transformative Investigations

Determine the extent of present-day tectonic activity through direct measurements of surface strain

The ability to measure surface deformation on the Earth has revolutionized terrestrial geology and geophysics, and has the potential to do the same for the Moon (Figure 3.3.3). Measuring surface displacements (i.e. strain) can reveal accumulating stress, and can be used to probe subsurface structure and the processes shaping the Moon today and in the past. Orbital measurements of deformation at regional or global scales would provide context for local surface measurements, like those enabled by the LGN.

Example measurements: Interferometric synthetic aperture radar (§5.4.3), repeat laser topography (§5.4.5), repeat m-scale visible imagery (§5.4.3)

Determine the magnitude, extent, and distribution of present-day mass wasting on the Moon, and its relationship to lunar tectonism and seismicity

Mass wasting events are a tracer of seismicity. The relationship between mass wasting and the distribution of recognized faults may provide the beginnings of maps of lunar seismicity, especially including correlation with fresh or very recent impact craters that may also trigger mass wasting events.

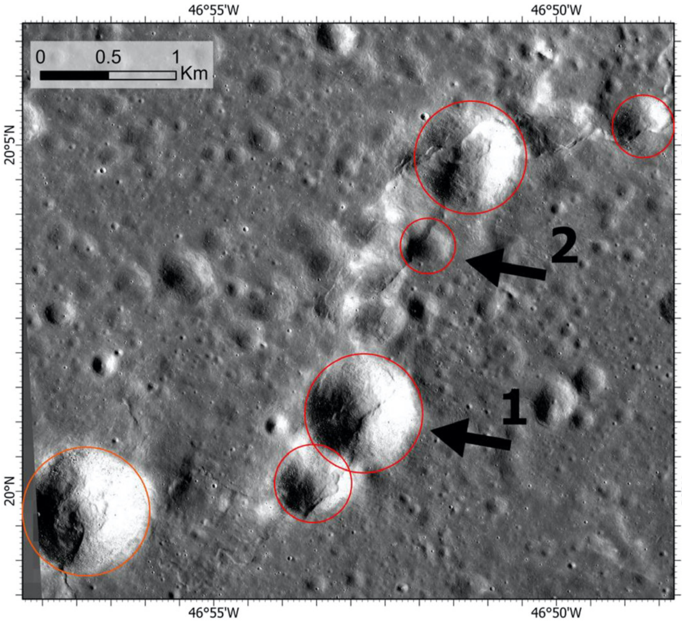


Figure 3.3.3: Tectonically degraded lunar craters. (1) A degraded crater crosscut by both parallel wrinkle ridge scarps and (2) crater deformation by a single wrinkle ridge scarp [LROC NAC M1219258635RE]. Red circles represent tectonically deformed impact crater rims. Figure from Nypaver and Thomson, 2022.

Example measurements: m-scale visible imagery (§5.4.1), repeat laser topography (§5.4.5), interferometric synthetic aperture radar (§5.4.3)

Implications for Exploration

Recent studies have suggested that seismicity is a significant hazard to crew and infrastructure; evidence for ongoing tectonism underscores that potential. New observations can directly measure displacements of the surface and infer where stress is accumulating. This improved understanding of the spatial aspect of the seismic hazard would support habitation siting and inform standards for infrastructure to mitigate seismic hazards.

Findings

- **Finding 3.3.3a**: Measurements of accumulating stress should be carried out to understand the contemporary tectonic environment and better characterize the seismic hazard.
- **Finding 3.3.3b**: Detection of mass wasting events as a result of ongoing lunar seismicity should be continued.

3.3.4 Understanding the Impact Process

One of the most startling discoveries enabled by LRO was the identification of newly formed small albedo markings termed “splotches.” These are identified through temporal analysis, comparing LROC NAC images with similar lighting separated by time intervals of varying durations. The occurrence rate of these features is far higher than is reasonable for a primary impactor population, whereas the size-frequency distribution is consistent with a secondary crater population. Thus these features are thought to be predominantly the signatures of secondary cratering. The frequency of secondaries cannot at this time be extrapolated from primary impact rates with confidence. A key missing piece of information is how many secondaries a given primary impact might produce, including the influence of the target site.

Transformative Investigations

Determine the present-day impact rate through direct observation of new impacts and detection of m-scale and larger surface changes

Continuous lunar observations address this need by coordinating two types of observations (Figure 3.3.4). Distant orbital monitoring of impact flashes (both day and night) shows precisely the time and location of primary impacts on the Moon, and flash spectroscopy could constrain the nature of the impactor. These new images, using the LROC NAC legacy dataset as a baseline, can then be targeted to detect craters and "splotches" that can be directly associated with a newly observed primary impact event. The Decadal Survey noted the value of impact flash monitoring and detection of new craters by directing this strategic study area: "Determine the present-day lunar impact rate and better understand the nature of impact mechanics by ... observations of impact flashes and fresh impact craters." Direct detection and localization of new impacts also supports surface seismic measurements including the LGN.

Example measurements: impact flash monitoring (§5.4.4), repeat high-resolution visible imagery (§5.4.3), repeat high-resolution laser topography (§5.4.5), interferometric synthetic aperture radar (§5.4.3)

Determine the secondary impact rate at small spatial scales

It is a safe assumption that the frequency of small secondary impactors, on the order of a cm to tens of cm, is higher than observed splotches, as impacts follow a power law distribution. Extrapolating downward from the splotch statistics is fraught as secondary material production at this scale may be critically dependent on regolith properties at the primary impact site. Direct detection of secondaries associated with specific primary impacts will enable better understanding of the ability of primaries to produce secondaries and the influence of target on this efficiency.

Example measurements: mpact flash monitoring and spectroscopy (§5.4.4), repeat high-resolution visible and radar imagery (§5.4.3), repeat high-resolution laser topography (§5.4.5), interferometric synthetic aperture radar (§5.4.3)

Determine the process that creates observable differences in regolith thermophysical and photometric properties around impact craters < 1 Ma

The freshest lunar impact craters exhibit significantly lower nighttime regolith temperatures, termed cold spots, extending to ~50-100 crater radii, well beyond the visible ejecta. In a similar way, phase ratios of visible images before and after impact events show subtle surface texture disruptions well beyond 500 crater radii. The processes that alter surface regolith density to depths of 10s cm to produce cold spots and their relationship to the extended surface disruptions are unknown, but are likely associated with distal ejecta emplacement. Additional higher spatial resolution infrared observations and temporal visible image pairs are required to understand this fundamentally important class of lunar impact cratering phenomena.

Example measurements: infrared radiometry (§5.4.6), high-resolution visible imagery (i.e., temporal pairs; §5.4.1)

Implications for Exploration

The existence of likely secondaries with higher formation rates than anticipated raises the importance of impact hazards to crew and infrastructure. While splotches are certainly at the scale of a significant hazard, their absolute rate makes the likelihood of interacting with an active mission small. However, secondaries that produce features far smaller than the few-meter scale of splotches still constitute a significant hazard. It is likely that the frequency of cm-scale secondary impactors is higher than observed splotches suggesting these events may be a serious potential hazard. The cost of misestimating this hazard is potential loss of crew, thus direct measurement of the secondary impactor rate at the cm size range is a critical need. Real time detection of impacts can provide important advance warning of potential secondary impacts for surface operations.

Findings

- **Finding 3.3.4a**: Direct detection of new impacts as they occur can enable characterization of the impact process as it develops, and constrain the composition of the impact products through flash spectroscopy.
- **Finding 3.3.4b**: Continuous monitoring at the >1 m-scale is required to refine the measurements of the primary and secondary flux and detect new impacts at the <<1 m-scale.
- **Finding 3.3.4c** Real time detection of impacts can provide a direct measurement of the secondary impact hazard for surface operations.
- **Finding 3.3.4d:** Determination of the secondary impact rate at << 10-m scale is required to understand the relationship between secondaries and primaries, and to define impact hazards.
- **Finding 3.3.4e:** Additional measurements are required to constrain the unknown process of cold spot formation, a fundamental product of lunar impact cratering that fades on the scale of ~1 Ma.

3.3.5 The Lunar Regolith and Space Weathering

The 21st century has seen significant strides in understanding the lunar regolith. Multi-frequency radars have revealed subsurface structures at the

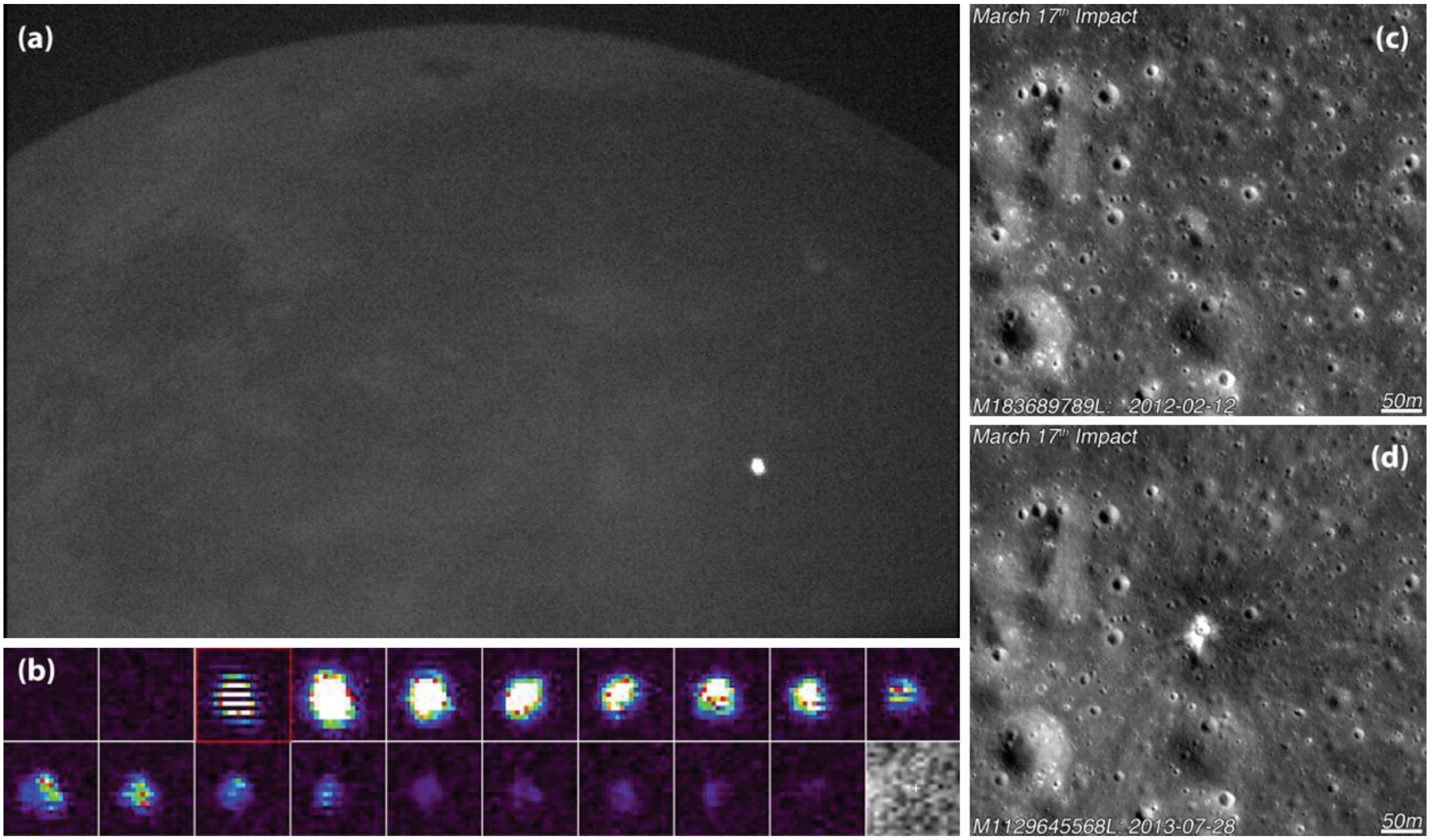


Figure 3.3.4: Earth observed impact flash and orbital surface imagery. A large lunar impact flash was observed on March 17, 2013. (a) Full field-of-view of the brightest frame. (b) Sequence of successive cropped video frames. LROC NAC images (c) before and (d) after the impact site. Figure from Suggs et al. (2014)

largest scales, including buried mare basalts under Orientale ejecta and rocky ejecta blankets at shallow depths below a pulverized ejecta upper layer. At finer scales, the Diviner data have shown the average compaction of the upper few cm varies across the Moon, and that this parameter correlates with crater age. Transmission electron microscopy (TEM) imaging revealed the relationship between nanophase iron and the host of spectral effects associated with space weathering at the micro-scale. Additionally, experiments revealed how tightly lunar regolith samples bind to water and how the regolith and space weathering forms a chemical reactor for production of water. Extensive methane in the lunar exosphere is also attributed to this reactor, raising the possibility that other compounds, including carbon dioxide, ammonia, alcohols, silanes, and carbides, could be produced in the regolith.

A significant recent discovery is the presence of ferric iron oxides at high latitudes despite the highly reducing nature of the Moon. This occurrence further demonstrates the unique nature of space weathering and the difficulty of predicting its character. A more oxidizing environment is possibly aided by an oxygen-rich “Earth wind” that occurs during the Moon’s passage through the magnetotail.

The Decadal Survey noted the importance of the regolith and space weathering explicitly in their direction for strategic research such as: (a) “Investigate the role of space weathering processes on airless rocky bodies using high-resolution imaging and spectroscopy of planetary surfaces…”; and (b) “Assess processes producing lunar regolith heterogeneity by measuring the thickness variations, and vertical and lateral compositional variability of the lunar regolith, using geophysical profiling, high-resolution multi-spectral imaging…”

Transformative Investigations

Determine the three-dimensional structure of the regolith and megaregolith

Multi-mission multi-frequency radar measurements reveal subsurface structures associated with impact cratering and other processes that are obscured at the surface by regolith formation and rock breakdown. However, global data are limited to the SELENE radar that had modest range resolution and was insensitive to the upper 200-m of the regolith. Those measurements are complemented by data from surface ground penetrating radar (GPR) and Apollo sounding measurements. The boundary between the regolith and megaregolith is virtually unmeasured, especially among the major terranes, so understanding how the developing crust evolved with respect to the impact flux is very poorly known. Improved understanding of regolith structure to km depth globally and near landing sites specifically can affect site and traverse selection and inform sample analysis.

Example measurements: radar sounding (§5.5.1), microwave radiometry (§5.5.2)

Determine the products of space weathering and chemical evolution in the regolith

When lunar regolith was first examined in laboratories it was apparent that profound physical and chemical alterations were associated with exposure to the space environment (Figure 3.3.5), including formation of nanophase iron, agglutinates, and unique minerals associated with vapor deposition. Remote sensing has added hydroxyl and water as well as hematite and other iron oxides to the inventory of phases produced by space weathering processes. Other compounds that might occur are silanes and carbides produced in the illuminated Moon from solar wind plasmas. Remote detection of a wide range of candidate compounds will inform the boundaries of the chemistry of interaction between the regolith and the space environment.

Example measurements: UV, VIS, NIR, and TIR (§5.3.1–§5.3.2) imaging spectroscopy for products of solar wind interactions

Implications for exploration:

The structure of the regolith below sampling sites is immediately relevant to the understanding of samples on the surface. For example, is a site over a buried rocky ejecta blanket, or a rock-poor section distant from the regolith/megaregolith boundary? Detection of iron oxide absorptions at high lunar latitudes reveals a correlation between the oxide chemistry and water content that strongly suggests the presence of hydrated oxides. This material occurring on illuminated surfaces may provide a uniquely accessible water source for in situ resource utilization (ISRU). As yet undiscovered compounds may provide more efficient processing of key elements and chemical feedstock.

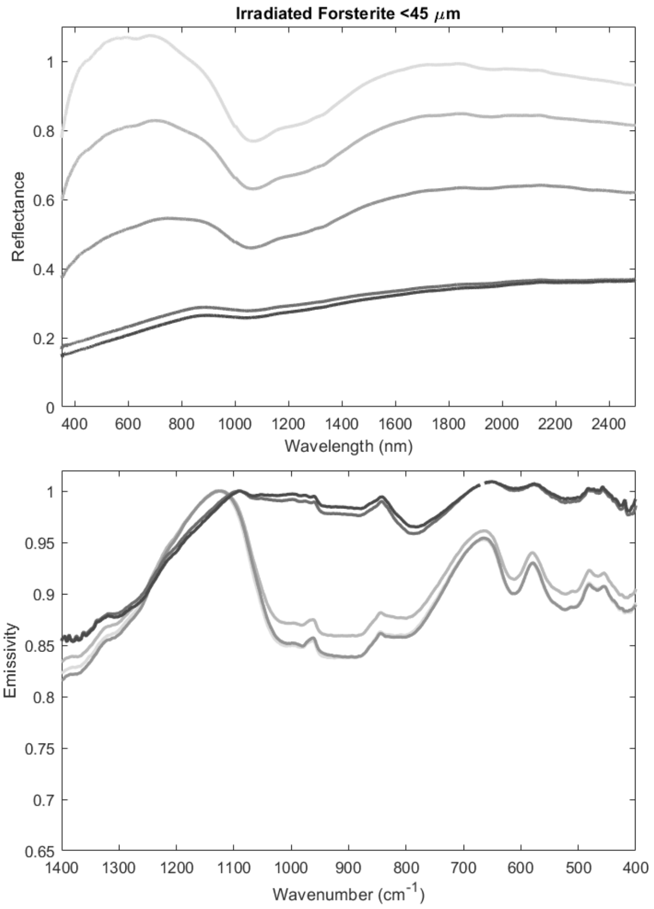


Figure 3.3.5: Spectral effects of simulated space weathered minerals. Significant differences in spectral shape and band depths are clearly visible in both the VNIR (top) and TIR (bottom) for progressively laser irradiated olivine samples from unaltered (light gray) to heavily altered (black).

Remote assessment of regolith depth, density, grain size, slopes, and rock and dust hazards can provide inputs to predictive models of surface development, and linkages to evolving groundtruthed geotechnical properties can improve predictability. Remote measurements support capabilities to manufacture, construct, and/or deploy structures, including for habitation, that can provide service and safety for extended time frames in the deep-space environment.

Findings

- **Finding 3.3.5a:** Mapping the structure and composition of the regolith and the upper megaregolith can improve our understanding of how the Moon has responded to the cratering flux.
- **Finding 3.3.5b:** Characterizing the products of chemistry in the lunar surface with mineralogic sensors extends the understanding of the range of potential reactions that may occur, and provides constraints on what reactions are possible.
- **Finding 3.3.5c:** Newly discovered compounds may provide resources for ISRU, such as carbon at the poles, and recoverable water in hydrated iron oxides.
- **Finding 3.3.5d:** Remote characterization of surface physical properties can improve landing site selection, resource evaluation, and siting of exploration infrastructure.

3.3.6 The composition of the Moon through the lens of its surface deposits

Quantitative space-based compositional remote sensing of the Moon enabled significant contributions to lunar science, beginning with the Clementine orbiter and Galileo flybys (Fig. 3.3.6). These spacecraft provided the first global multispectral coverage of the Moon enabling detailed mapping of mineralogy, chemistry, and surface exposure. The invaluable contribution of direct elemental detection of major and key trace elements by Lunar Prospector (Fig. 3.3.6), Kaguya, and LRO provided especially important insight given the crucial role of the rare element-rich lunar KREEP component that is an indicator of the presence of a magma ocean. Elemental mapping of thorium at relatively low resolution revealed the unique nature of the portion of the lunar nearside now called the PKT, and enabled (with FeO) the definition of the major geochemical terranes on the Moon.

The value of comprehensive global compositional coverage was also proven by the unanticipated discoveries of spinel-rich deposits, hematite and other iron oxides at high latitudes, water-rich and water-poor pyroclastic deposits, silica-rich domes and crater deposits, and impact basin rings enriched in olivine. The spinel discovery spawned a rich area of research in the interaction of intrusive magma with the anorthosite crust. High latitude iron oxides show that complex and unanticipated chemistry is occurring on the surface. The hydration state of pyroclastic materials shows that the interior of the Moon is heterogeneous with respect to volatile content. Silica-rich features extend the range of lunar volcanic processes. The distribution of olivine-rich and pyroxene-poor exposures at basin rings correlates with results of hydrocode models that have suggested that some rings sampled the mantle.

Transformative Investigations

Determine the chemical inventory of the Moon with high-quality, contiguous, global geochemical measurements at <30 km resolution, and targeted measurements with ~10 km resolution

Geochemical sensors, despite having relatively low spatial resolution, provide invaluable insights into the evolution of the Moon principally through direct sensing of trace elements or key elemental ratios. Existing data allow chemical anomalies to be directly associated with regional or hemispheric units, and by inference with specific geologic features through modeling, but low spatial resolution inhibits more detailed analysis. For example, many silicic anomalies are associated with thorium anomalies, but abundances are model-dependent (requiring spatial unmixing) and the compositions of smaller geologic units are unconstrained. Very low orbits and improved measurement techniques can provide drastically improved spatial resolution that can revolutionize the understanding of the origin and evolution of lunar geologic features.

Example measurements: High-resolution gamma ray (§5.3.5), neutron (§5.3.5), and X-ray spectroscopy (§5.3.6).

Determine the mineralogical inventory of the Moon with high-quality, contiguous, global compositional measurements at <50-m resolution

Some of the discoveries made with mineralogic remote sensing could have been made with targeted approaches based on morphology or other non-compositional indicators, but global coverage provided the key to many of the unanticipated discoveries. For example, recently recognized spinel deposits show no morphological indicators that would have caused them to be targeted. Additional keys to these discoveries were the transition from multispectral imaging (targeted to capture specific spectral features defined prior to the mission) to imaging spectroscopy, and extending wavelengths from the visible across the near-infrared, intermediate infrared, and thermal-infrared that provide a much broader range of compositional sensing and enabled serendipitous discovery in unexplored terrain.

While existing data are extremely useful, the improvements in data quality (sensitivity and calibration) and wavelength coverage exemplified by the potential of Lunar Trailblazer for select regions on the Moon should be extended to contiguous coverage of the entire lunar surface to produce a comprehensive assay of lunar mineralogy and chemistry.

Example measurements: UV, VIS, NIR, IMIR, and TIR (§5.3.1–§5.3.3) imaging spectroscopy at the <50-m scale

Determine the composition of the lunar mantle through definitive detection and characterization of exposures of ultramafic lithologies

Current datasets and petrologic models permit a wide range of compositions, structures, and styles of evolution of the lunar mantle, yet no unambiguous samples of the mantle are known. Hydrocode models suggest that many basins should have excavated mantle material and exposed it in some of their rings. Some rings (e.g. in Crisium and Humorum) show anomalous olivine concentrations suggesting an olivine-rich upper mantle, whereas an ultramafic exposure on a ring of Imbrium basin suggests a pyroxene-rich upper mantle. The general dominance of the mafic assemblage by orthopyroxene in the highlands may also reflect the presence of a pyroxene-rich upper mantle, sampled during the intense bombardment of the crust.

Direct detection of ultramafic materials by remote mineralogic analysis would provide high-value candidates for in situ and sample return analysis. The ~100 m resolution of current high fidelity mineralogic data may be limiting these detections. Investigations at the Ries crater in Germany show remnants of target material occur at small sizes, but also that large blocks of original target are common; these blocks can be larger than 20 m and preserve the lithology of the target rocks without mixing. This suggests that if basins have exposed mantle material, blocks of this material may be exposed at the surface at sizes resolvable from orbit with measurements at ~10 m scale. The value of extremely high spatial resolution compositional studies has been amply demonstrated by photometrically calibrated single scattering albedo imaging by the LROC NAC. While a single wavelength has limited compositional leverage, existing studies show how quantitative photometry at the 1-2 m scale enables significant advances. This extremely high resolution capability should be extended to multispectral imaging to the extent technically feasible.

Example measurements: UV, VIS, NIR, IMIR, and TIR (§5.3.1–§5.3.3) imaging spectroscopy at the ~10 m scale, multiband high resolution multispectral imagery or active laser spectroscopy at the ~1 m scale

Implications for exploration

The next phase of lunar exploration strongly emphasizes in situ analysis and sample return, as

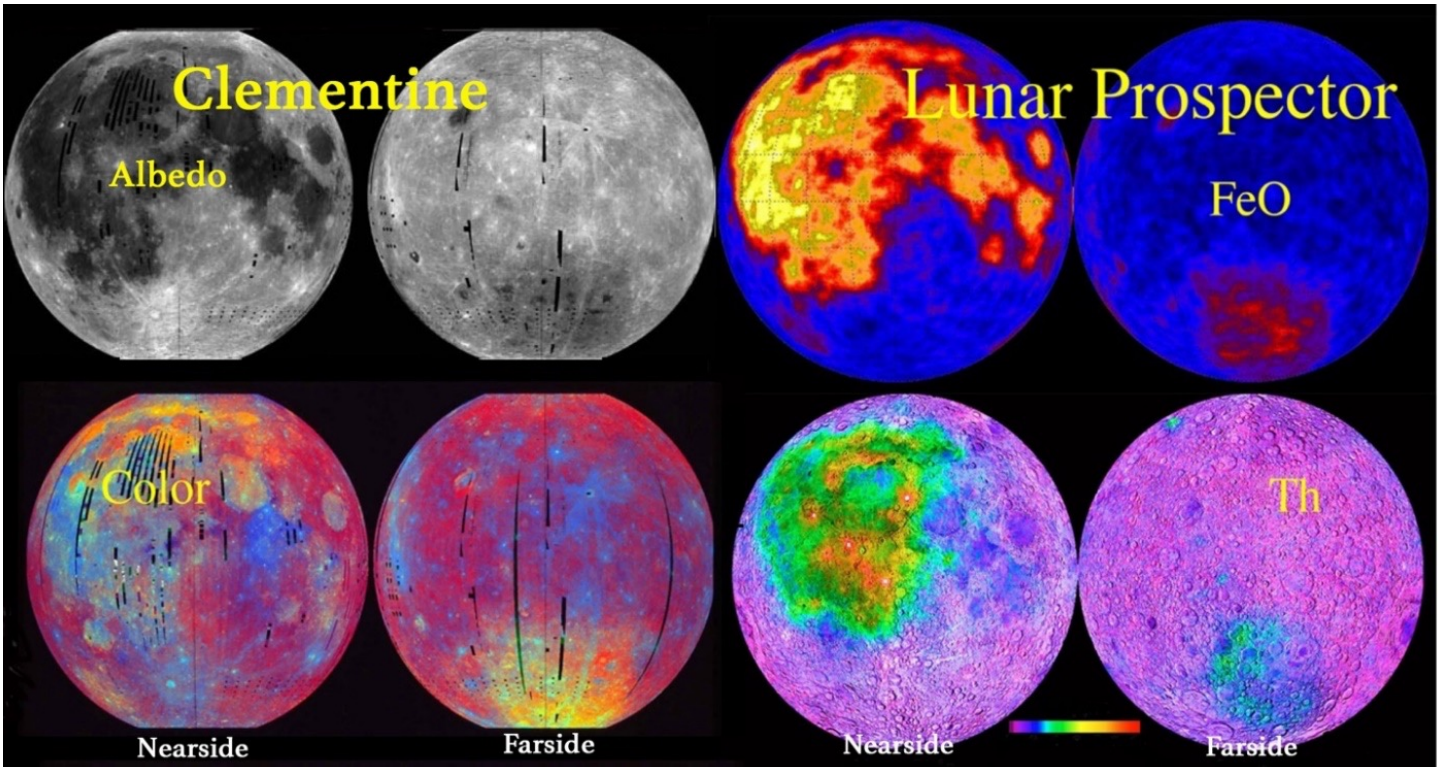


Figure 3.3.6: Clementine (initiated by DOD) and Lunar Prospector (NASA's first Discovery mission) were spacecraft that obtained lunar data during the end of the last century. These early global compositional data remain some of the most widely used today.

shown by many of the strategic research objectives outlined in the Decadal Survey. Improved remote sensing can make critical contributions to these new efforts. With spectroscopy at the 1 to 10 m scale, landing site selection and traverse planning can be guided by direct knowledge of mineralogy and bulk composition of individual rocks and boulders targeted for efficient collection of the highest priority samples. Current compositional data sets, and those to be collected by missions in development, do not have the spatial sampling to resolve any but the largest rocks and features present. For example, in a search for exposures of lunar mantle that ultramafic compositions would reveal, existing data lack the resolution to identify such materials definitively at the 1-10 m scale. At present, only a single site, on a ring of the Imbrium basin, has been suggested to be composed of an ultramafic rock type. With mineralogy and chemistry at ten times better spatial resolution than available now, it is highly likely that the list of mantle candidate exposures will greatly expand.

The principal advantages of high resolution compositional analysis are two-fold. First, all soils are mixtures whereas some rocks are primary products of lunar igneous processes. In typical highlands the majority of observable rocks are likely breccias, and hence also mixtures, but in well-chosen geologic settings, outcrops or boulder-sized examples of primary compositions are almost certainly present (for example, extensive exposures of "purest anorthosite"). It is also feasible that thermophysical measurements at this very high resolution may be able to distinguish breccias from more competent igneous rock based on their thermal properties. Second, the ability to characterize the mineralogy of outcrops or boulders and the deposits of very small craters can greatly enhance the efficiency of robotic or human field geology by pre-defining or classifying sampling target candidates. For example, the recognition that a boulder is largely ultramafic would place that object high on the list for sampling.

Findings

- **Finding 3.3.6a**: Significantly improving the resolution of geochemical sensing (e.g., Th, K/Th, Mg/Fe ratios) to <30 km globally, and locally to 10 km resolution will result in significant advancements.
- **Finding 3.3.6b**: Completing the compositional inventory of the Moon with high quality contiguous global compositional measurements at <50 m resolution is essential to ensure the mineralogic diversity of the Moon is captured and documented.
- **Finding 3.3.6c**: Direct measurements of the compositional nature of the lunar mantle through detection and characterization of ultramafic lithologies at ~10 m scale would place strong constraints on models of the evolution of the lunar interior and provide high value candidates for in situ investigation or sample return.
- **Finding 3.3.6d**: Compositional imaging of the Moon at ~1-10 m resolution is a priority to support surface operations.

3.3.7 Special Polar Region Environments

The lunar polar regions at high latitudes contain unique local environments as an interplay between solar illumination and topography. Permanently shadowed regions (PSRs) are special polar environments that feature some of the most intriguing conditions in the Solar System. Owing to the Moon's low obliquity, craters and other depressions near the poles receive no direct sunlight and as a result achieve extremely low temperatures. A related special polar environment comprises some regions adjacent to PSRs that receive some illumination over various timescales, but can still feature very low, PSR-like temperatures at shallow depths (Figure 3.3.7). These surfaces constitute a potential lunar permafrost zone with subsurface volatile stability. Small PSR's, called micro-cold traps, occur at scales of 10s of cm to 10s of m and are ubiquitous in the polar regions owing to lunar roughness at all scales. These features are a unique resource because their lifetime is proportional to their scale owing to the power law dependence of the impact flux that drives landscape evolution. Thus measurement of micro-cold trap volatiles over a range of scales provides insight into volatile inputs and evolution over the past several million years.

LRO Diviner has measured surface temperatures below 30K in the depth of the lunar winter, though most PSR surfaces are warmer but do not exceed about 125K. These conditions may give rise to a priceless scientific resource as the PSR surfaces and cold near-surface regions act as cold traps to capture compounds flowing through the lunar volatile system. Volatiles trapped a billion years ago or more may be preserved under the ejecta of larger polar craters, providing an accessible record of volatiles delivered to the Earth-Moon system preserved nowhere else.

The lunar PSRs are also a natural laboratory for observing the interaction of volatiles with a silicate surface, providing a testbed for understanding processes that occur broadly across the Solar System and beyond, from the poles of Mercury to dust grains in interstellar space. They also allow direct observation of the interaction of an ice-bearing or icy surface with the space environment, and allow the study of ice reacting to micrometeoroid impact, UV irradiation, and solar wind sputtering. These sequestered volatiles also provide an accessible natural example of how organic synthesis might occur in icy surfaces from irradiation by galactic and solar cosmic rays.

Volatiles are known to be present on PSR surfaces, widespread in the regolith, and buried at shallow depths. Lunar Prospector and the LRO Lunar Exploration Neutron Detector (LEND) both found hydrogen in the upper m of the polar regolith, and modeling suggests these deposits are primarily confined to PSRs, though their chemical form is unknown. Spectrometers on LRO, SELENE, and Chandrayaan-1 detected patchy water ice at the surface, and the Lunar Crater Observation and Sensing Satellite (LCROSS) excavated ice-bearing regolith from Cabeus crater. Ice-related anomalies may also have been detected by radar, and inferred from the presence of anomalously shallow polar craters.

The abundance and distribution of polar volatiles in the surface and near-surface environments where they are potentially stable is central to the viability of ISRU at the poles. The selection of the Volatiles Investigating Polar Exploration Rover (VIPER) mission, which is predicated on determining the nature of polar volatiles, demonstrates this value to NASA. However, results of rover missions are, by their nature to date, a sample of a small area. And current orbital observations are of insufficient resolution to both reveal the distribution and concentration of sequestered volatiles and place rover data in context. Direct detection of surface and buried volatiles from orbit with higher spatial resolution, depth, and fidelity than current data offer, as well as contiguous coverage, is essential.

Transformative Investigations

Determine the composition and spatial distribution of surface and near-surface volatiles (hydrogen, water-ice, carbon dioxide, etc.) for all permanently shadowed regions and surroundings at the astronaut and rover scales, <100 m

While the ensemble of current data offers compelling evidence for surface and shallow buried volatiles, individual detections of surface volatiles have high false negative and positive rates and are limited to water ice, whereas measurements of shallow buried volatiles are largely confined to hydrogen and have low resolution and no sensitivity to the chemical phase of hydrogen. New orbital measurements are needed. Surface volatile detections must feature much lower uncertainties, and in addition to water ice include CO_2, ammonia, and potentially hazardous compounds such as HCN and H_2S. Data should enable mapping at the 100 m scale or better to support traverse planning. Detection and mapping should also include organics and adsorbed methane.

Measurements of shallow buried volatiles should be able to resolve at least the largest PSR and potential permafrost regions and feature some sensitivity to depth distributions of volatiles.

Example measurements: active infrared spectroscopic imaging (§5.3.7), NIR imaging spectroscopy, infrared radiometry (§5.4.6), UV imaging spectroscopy (§5.3.1), active fluorescence spectroscopy (§5.3.8), neutral and ion mass spectroscopy (§5.2.3), neutron spectroscopy (§5.2.3), mass spectroscopic dust analyzer (§5.2.3

Determine the abundances of volatiles, especially water ice, at diurnal, seasonal, and processional timescales

Dynamics of volatiles in the PSRs are inferred from evidence of surface water ice coupled with the short modeled lifetime on the surface due to the many loss mechanisms. This implies that volatiles are renewed on short timescales and should exhibit significant mobility with temperature variations over the timescales experienced in PSRs.

Example measurements: active infrared spectroscopy (§5.3.7), FUV (§5.3.4), NIR, (§5.3.1), IMIR (§5.3.3), and TIR (§5.3.2) spectroscopy, infrared radiometry (§5.4.6), neutral and ion mass spectroscopy of activated molecules (§5.2.3)

Determine the distribution of volatiles to depths >10 m to distinguish between hypotheses for volatile emplacement, and address the viability and sustainability of volatiles as a resource

Recent work has shown that the impact and volcanic contribution of volatiles to the lunar environment over the past few billion years may have given rise to thick ice deposits sequestered below protective ejecta blankets of polar craters. Monte Carlo modeling shows the expected thicknesses and depths are highly variable owing to the stochastic nature of the source and sequestration processes. Testing of these hypotheses requires probing PSR and surrounding surfaces to depths of 10 m or more, and 100s m, while less accessible, would be especially valuable to understanding the extent of sequestered volatiles.

Example measurements: microwave radiometry (§5.5.2), radar sounding (§5.5.1), cosmic ray radio frequency sounding (§5.5.1)

Determine the abundance and distribution of products of chemical processing in the lunar regolith, including organics and iron oxides in polar regions, and their relationship to volatiles, to define their scientific and resource potential

The dark materials that cover many ice deposits on Mercury are inferred to be organic lag deposits synthesized by, and then carbonized by, radiolysis of ices in cold traps. Carbon, hydrogen, oxygen and nitrogen-bearing ice deposits on the Moon may form similar compounds that are a scientific and exploration resource. The methane in the lunar atmosphere must also cold trap (adsorb) within the PSRs; though too volatile to condense, adsorbed methane may provide a feedstock to produce more refractory organics from radiolysis. Detection and mapping of organic and other compounds in a natural environment where silicates and volatiles are exposed to the space environment, will place strong constraints on models of synthesis.

Example measurements: active infrared spectroscopy (§5.3.7), VIS and NIR (§5.3.1) and IMIR (§5.3.3) imaging spectroscopy, infrared radiometry (§5.4.6), active fluorescence spectroscopy (§5.3.8), neutral and ion mass spectroscopy (§5.2.3)

Implications for exploration

The utility of maps of surface and shallow buried volatiles are obvious both for planning in situ resource utilization, especially of potential ice deposits, and in situ sampling for scientific analysis or sample return. Mapping the distribution of potentially hazardous compounds will reduce risk to crew. Direct measurement of volatile mobility in PSRs can also inform potential hazards, and constitute a recoverable scientific and exploration resource, and ISRU resource if fluxes are high enough.

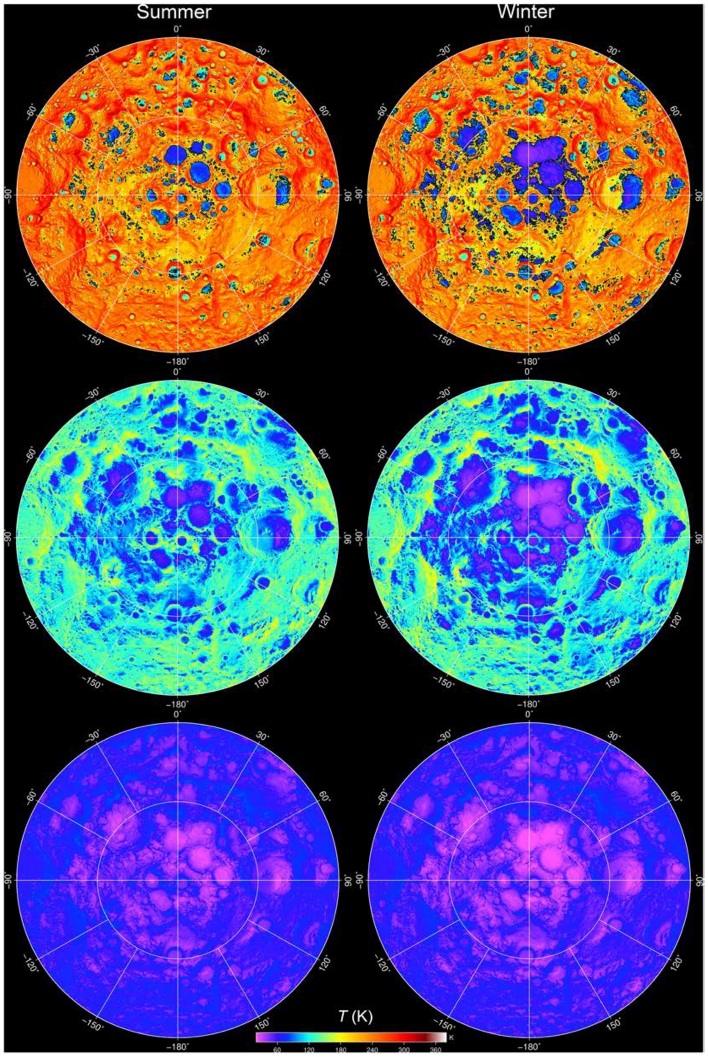


Figure 3.3.7: South pole seasonal temperature variations. LRO Diviner temperature measurements have revealed an extreme thermal environment with significant differences caused by seasonally-varying illumination. Maps are provided for the south polar region to 80°S latitude of maximum (top), average (middle), and minimum (bottom) temperature during summer (left) and winter (right). Figure from Williams et al. 2019.

Findings

- **Finding 3.3.7a**: Key measurements enabling a more complete global assessment and monitoring of hydrogen-species, other volatiles, and organics on and below the lunar surface are vital for understanding the lunar volatile system as well as the sources of volatiles.
- **Finding 3.3.7b**: High priority science and exploration objectives remain regarding the distribution of surface and near-surface volatiles. Water-ice, carbon dioxide and potentially hazardous volatiles like HCN should be mapped within all PSR surfaces and surroundings at rover-accessible scales (<100 m) with context of surface temperature and temperature history.
- **Finding 3.3.7c**: Additional integrated measurements of volatiles and organics are also highly beneficial as context for and inputs into resource identification, planning for systems that make use of the Moon's resources, as well as inputs into architectures for surface activities.
- **Finding 3.3.7d**: Neutron measurements of hydrogen with sufficient spatial sampling to resolve larger PSRs would provide key validating measurements for other methodologies, and provide a bridge between the near-surface and more deeply buried volatiles.
- **Finding 3.3.7e**: Measuring the isotopic composition of ejecta lofted into lunar orbit from contemporary natural impacts could provide the isotopic composition of sequestered volatiles.
- **Finding 3.3.7f:** The dynamics of water-ice at diurnal, seasonal and precessional timescales should be characterized with measurements sensitive to abundances well below 1%, ice layer thicknesses much less than 1 μm, and include measurements at the coldest locations.
- **Finding 3.3.7g**: Searches for buried water ice should be conducted to depths of 10 m or greater to test emplacement hypotheses and to address the viability and sustainability of the water-ice resource.
- **Finding 3.3.7h:** Evidence should be sought in the exosphere for volatiles activated by loss mechanisms.
- **Finding 3.3.7i:** The presence and distribution of methane and more complex organics should be evaluated (prior to significant human activity) to define their scientific and resource potential and hazards.

3.3.8 The Lunar Volatile System

The lunar volatile system comprises the interaction between volatile elements and compounds and the lunar surface, and encompasses the sources, transport, sequestration and loss of volatiles from the lunar environment (Fig. 3.3.8). Volatiles introduced from space, principally the solar wind and large and small impacts, or from the lunar interior can be promptly lost to space, trapped in the regolith, or conveyed across the surface as the lunar exosphere (or atmosphere in some cases). A portion of these mobile molecules can be permanently trapped at the lunar poles. And a degree of recycling must occur, as volatiles trapped in the regolith and polar sinks can be released by subsequent impacts.

Only a few aspects of this system are well understood. While the behavior of noble gases is well explained by models, very little is known about the behavior of other elements and compounds. Overall, hydrogen is probably the best known. Maps of regolith and polar hydrogen are available, and LRO Lyman Alpha Mapping Project (LAMP) has made great strides in understanding exospheric hydrogen, though key energy ranges of atomic and molecular neutral hydrogen remain unmeasured.

The Decadal Survey explicitly recognized the importance of the connection between surface and exospheric volatiles such as: (a) “Derive the sources of exospheric volatiles by measuring the distribution, composition, and abundance of surface volatiles .... on solid bodies including the Moon....”; (b) “What role does the space environment play in forming and liberating the volatiles contained within surface bounded exospheres like that at the Moon and Mercury?”; and (c) “Fundamental questions remain, however, regarding the transport, retention, physical and chemical alteration, and loss processes operating on such deposits [PSRs] over seasonal, diurnal, and precessional timescales.”

Transformative Investigations

Determine the 4-dimensional spectral, spatial and temporal behavior of volatile species in the exosphere, including composition and abundance, that are produced from space-surface interactions and anthropogenic sources

In the exosphere, the principal measurement of water is from the Lunar Atmosphere Dust and Environment Explorer (LADEE) neutral mass spectrometer (NMS) that operated in near equatorial lunar orbit for seven months in 2013-2014. Water was occasionally detected, associated with meteor showers, but the water background eluded detection. Knowledge of the abundance and distribution of water in the exosphere is vital to understanding the transport of water through the lunar system. Once introduced into the exosphere, a water molecule can escape to space thermally, be ionized and swept away by the solar wind, or if gravitationally bound, impact the surface. The fate of water molecules that interact with the surface is poorly constrained and may dissociate on contact. If this is the typical outcome of the surface interaction, then water is largely unable to propagate across the surface and stock the cold traps and their collection area may be limited to the immediate polar regions. Even if dissociation is not favored, the bond energy of the silicate surface (also not well understood) may be high enough to prevent release. Estimates of binding energy from LRO LAMP UV observations suggest it is relatively high, but allows release at temperatures above about 320 K. However, the abundance of water in the exosphere implied by the LAMP observations are in conflict with the upper limits imposed by the LADEE NMS measurements, underscoring the critical importance of additional exospheric measurements.

Example measurements: temporal data of neutral and ion mass spectroscopy (§5.2.3), supplemented by coordinated FUV (§5.3.4), NIR, (§5.3.1), IMIR (§5.3.3), and TIR (§5.3.2) spectroscopy, infrared radiometry (§5.4.6)

Characterize the abundance, distribution, and temporal variability of hydration, including hydroxyl and molecular water, across the lunar surface

Our understanding of the behavior of surface hydration is incomplete, and aspects of existing data are enigmatic. Hydration on the illuminated surface has been detected in both the UV and infrared. In the UV and the NIR near 3 μm, the spectral features observed may be due to either hydroxyl or molecular water, and in both cases the intensity of the spectral features vary with surface temperature, both diurnally and with latitude. The relationship between feature intensity and temperature differ between the NIR and UV wavelengths, but this may be due to the much lower intensity of the infrared absorption that allows probing both the surface and interiors of grains.

The NIR measurements are plagued by the need to separate reflected solar and emitted lunar thermal emission, and there is no consensus on how to carry out this separation, leading to major differences in interpretation of the temperature, latitude and diurnal behavior. A new approach that is immune to thermal emission, such as active infrared spectroscopy or advanced UV spectroscopy may be able to solve this problem.

In addition, the existing UV and NIR measurements do not currently differentiate water from hydroxyl, while intermediate infrared (IMIR) measurements across 6 μm capture the H-O-H bend of water uniquely, and airborne observatory measurements have detected emission from this feature and some of its variation. Furthermore, water bands farther into the TIR may be available with sufficient spectral resolution. This work demonstrates the technical capability to identify molecular water as distinct from hydroxyl and additional NIR, IMIR, and TIR multispectral imaging or imaging spectroscopy will help better constrain the abundance, distribution, and temporal variability of the species.

Example measurements: FUV (§5.3.4), NIR, (§5.3.1), IMIR (§5.3.3), and TIR (§5.3.2) spectroscopy, infrared radiometry (§5.4.6), laser reflectance spectroscopy (§5.3.7) measured at different times of the lunar day.

Implications for exploration

Exploration and science are particularly synergistic in this research area. Understanding the volatile system results in understanding the location of resources and their sustainability. In addition, volatiles introduced into the environment from spacecraft traffic (where location and masses of volatiles are well known) are natural experiments that can be used to robustly understand the transport, sequestration, and loss of volatiles, in particular water and CO_2. Appropriate surface and orbital assets can directly measure the evolution of these volatile plumes and how effectively, for example, ballistic migration operates for both of these species. Near polar landing sites, rocket exhaust will cold trap onto PSR surfaces, providing an opportunity to watch a freshly emplaced volatile deposit evolve with temperature, solar wind sputtering and UV irradiation.

Findings

- **Finding 3.3.8a**: The critical constraint of water abundance in the exosphere makes confirming and extending beyond the LADEE NMS dataset essential. This should be carried out as soon as is practical before the exosphere is further altered by extensive spacecraft traffic.

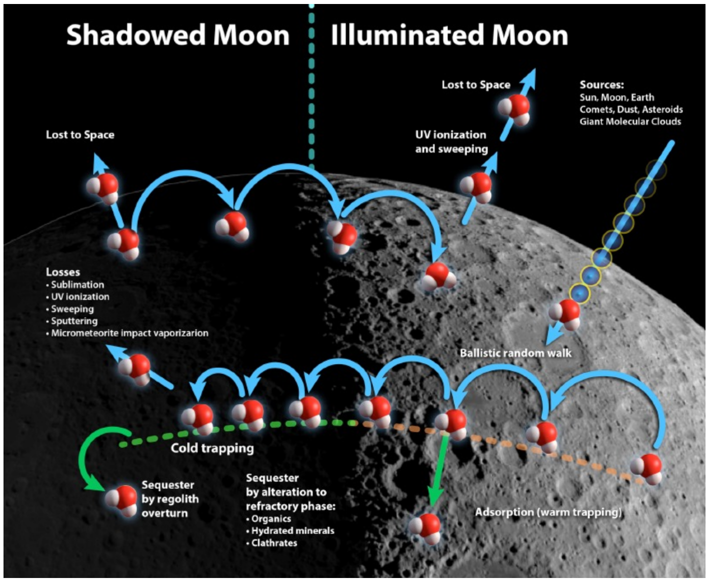


Figure 3.3.8: The lunar water cycle is complex with numerous sources and sinks. Temporal variations in illumination provide a critical fourth-dimension to understanding the spatial behavior of a variety of volatile species. Figure from Hayne et al. 2014.

- **Finding 3.3.8b**: The three-dimensional structure and temporal behavior of the exosphere should be characterized to understand how water is transported through the lunar environment and measure the effects of human exploration on the exosphere.
- **Finding 3.3.8c**: Exospheric measurements of the abundance and dynamics of volatile species that may result from space-regolith interaction should be carried out, especially CO_2 and ammonia.
- **Finding 3.3.8d**: The temporal behavior of hydration bands observed in the infrared should be characterized with definitive separation of reflected and thermal effects.
- **Finding 3.3.8e**: The abundance, distribution and dynamics of hydroxyl and water molecules should be unambiguously separated and characterized, including nightside abundances.
- **Finding 3.3.8f**: The volatile emissions from lunar exploration should be exploited as controlled experiments in volatile transport, deposition and modification.

3.3.9 Heliosphere and the Lunar Plasma Environment

For heliospheric science, the Moon represents an ideal laboratory for the study of plasma interactions with small scale structures and gradients. The Moon itself represents a meso-scale object, ~10-20 ion inertial lengths in radius. The solid surface of the Moon acts primarily as an absorber, creating a trailing plasma wake structure that can extend to 10s of lunar radii. This wake is permeated by beams of charged particles that refill the wake cavity both along (ions, electrons) and transverse (ions) to the magnetic field; these refilling beams drive a variety of plasma instabilities, primarily electrostatic in nature. Topics for heliospheric investigations at the Moon include solar wind reflection, small scale shocks and reconnection, and solar wind monitoring through the lunar orbit, which includes the pristine solar wind, the terrestrial foreshock, and the terrestrial magnetosheath and magnetotail. New scientific investigations should include key measurements beyond the ARTEMIS (Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun) mission, including a complete suite of energetic particle observations, high frequency electromagnetic wave measurements (up to and above the plasma frequency), and ion mass composition.

The modulation of the solar wind by lunar magnetic anomalies will soon be tested on the ground by the CLPS Lunar Vertex Payloads and Research Investigations on the Surface of the Moon (PRISM) mission that will probe the local magnetosphere at the Reiner Gamma magnetic anomaly. Space weathering is known from remote sensing to be highly anomalous at this and other lunar swirls.

Transformative Investigations

Determine the three-dimensional structure of magnetic fields associated with lunar magnetic anomalies, their relationship with surface features (e.g., lunar swirls) and the space environment

Despite their minute scale, the lunar magnetic fields can reflect/deflect a substantial fraction of the solar wind, with reflection fractions of up to 50% of the incoming ions observed above the strongest magnetic sources. The presence of "swirl" albedo markings (Fig. 3.3.9)in the more intensely magnetized regions of the lunar surface may further indicate that in some locations the reflection fraction approaches 100%. Recent orbital observations and modern simulations suggest that the observed ion reflection may result at least in part from Hall electric fields, with integrated potential changes of 100s of volts inferred from remote measurements; however, the structure of this potential remains unmeasured. In situ measurements also demonstrate that both ion and electron heating can occur, but we lack a complete accounting of how the energy of bulk plasma motion is converted to other forms in the magnetic field interaction regions. Furthermore, we do not yet have a full understanding of the temporal variability of the interaction and its response to changing solar wind conditions. The

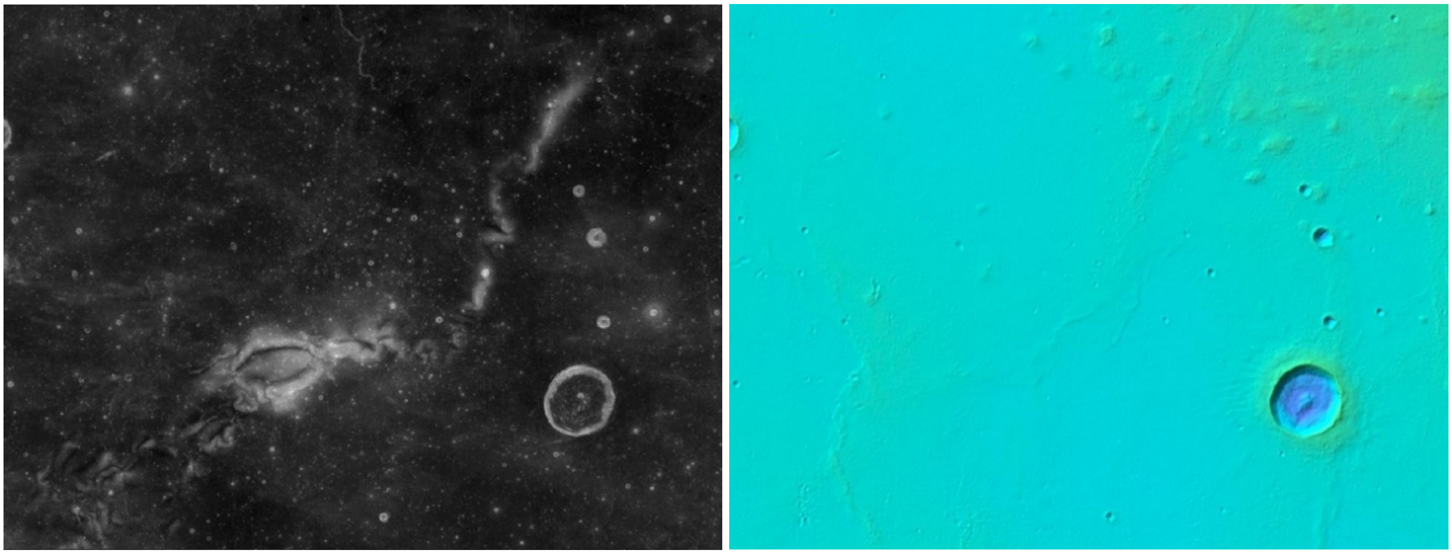


Figure 3.3.9: Lunar swirls are enigmatic albedo patterns associated with some magnetic anomalies. Reiner Gamma, a prominent magnetic anomaly in mare of Oceanus Procellarum on the lunar nearside, is associated with an unusual albedo region (left) but no significant topographic features (right). The large crater Reiner (30 km in diameter) is to the right of Reiner Gamma and small Marius Hills occur in the upper right part of the image.

upcoming Lunar Vertex investigation will attempt to test these hypotheses, however future multipoint measurements from the surface and concurrent with orbital measurements are needed to fully understand the solar wind's role in lunar swirl formation.

Example Measurements: electron and ion plasma analyzers for plasma composition (§5.2.1), electric and magnetic field (§5.2.2)

Implications for Exploration

The charge state on the lunar surface arises from the interaction with the local plasma environment and solar UV and X-ray induced photoemission of electrons. Lunar surface charging is dynamic, and can change rapidly when transitioning from the sun lit surface to shadow (and back), either from explorer traverses or the apparent motion of the sun in the lunar sky. The motion of lunar dust that is lofted by micrometeorite impacts or the activity of explorers can be charged and its motion affected by ambient fields created within the plasma. The local charging environment has implications for future explorers and orbital measurements can help untangle complex processes especially during solar energetic particle (SEP) events, the effects of which are poorly constrained for the lunar environment. SEP events pose a risk to humans and hardware and a deeper understanding of plasma processes around the Moon during these events are needed to fully understand this risk, and develop strategies for reduction and mitigation. For example, the magnetic fields arising from crustal magnetic anomalies alone are insufficient to shield from SEP events. However, when combined with diverting electric fields formed by the separation of solar wind electrons from ions, magnetic anomalies may provide protection from SEP particles during an event.

Findings

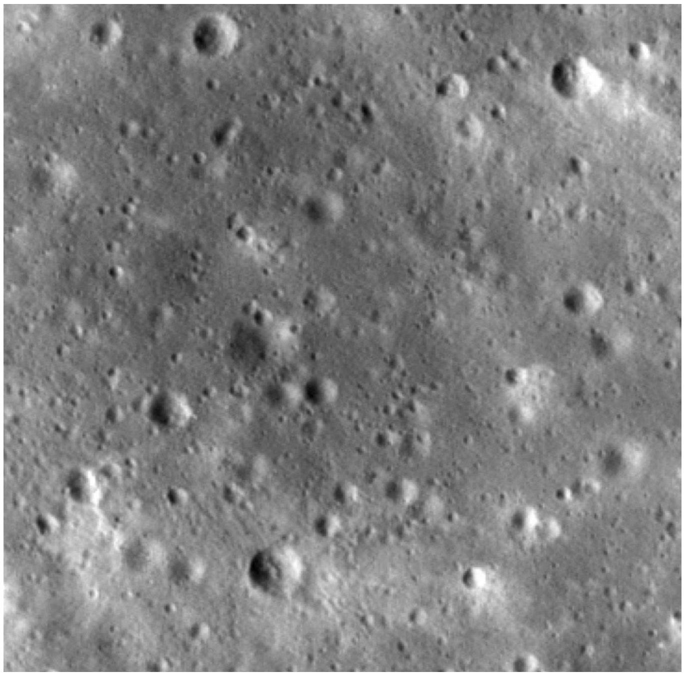
- **Finding 3.3.9a**: Characterizing the three-dimensional structure of magnetic fields associated with anomalies helps elucidate the relationship between surface anomalies and the heliospheric environment.

- **Finding 3.3.9b**: Additional orbital measurements are necessary for a deeper understanding of the temporal variability of the lunar plasma environment, the solar winds interaction with the Moon, and the response to changing solar wind conditions especially near the terminator, polar environment, and around magnetic anomalies.

Box 1

Lunar Reconnaissance Orbiter 2009 – present

The Lunar Reconnaissance Orbiter (LRO) was launched in June 2009. Carrying seven instruments onboard, LRO went into orbit around the Moon and has been operating and returning enormously valuable data about the surface for well over 13 years. It is the epitome of a successful and highly productive mission designed to obtain lunar data from orbit. LRO has demonstrated the critical value of long-term lunar orbital presence and long-baseline observations acquired over many years. While this mission duration was never envisioned, LRO has proven the value of the long-duration orbiter. The LRO mission began in support of exploration tasked with collecting data required for future human landing sites and continues for this purpose as well as for science, directly supporting the Artemis program, international missions, the robotic CLPS program and Moon 2 Mars Objectives. The global community of lunar scientists and engineers rely on this diverse accumulated data and have also come to expect results to be available for planned (and unplanned) ongoing events that continue to occur on the lunar surface. An example of the value of ongoing observations is a recent March 4, 2022 impact crater (~28 meter diameter) on the far-side of the Moon created by a large wayward artificial object (hypothesized to be a discarded booster of undetermined origin) whose presence was tracked by amateur astronomers.



LROC image before.....

and after March 2022

A healthy lunar science and exploration program cannot be maintained without long-lived integrated orbital capabilities. Given the typical lifetime of a satellite and the rate at which new and/or improved instrumentation becomes available, it is important to plan for updated replacements of LRO-like orbital capabilities on a regular timeline.

4. Implementation Approaches and Architectures

4.1 Introduction and Scope

The Moon is both the natural first deep space outpost for human exploration of the Solar System as well as an important destination for study of the Earth-Moon system. Establishing an outpost on the Moon is a necessary step on the way to human exploration of Mars and beyond. The outpost will enable holistic exploration of the Moon but requires substantial investment in orbital and surface assets. New orbital measurements are required for appropriate resource, topographic, and geochemical maps, to support site selection, and to enable scientific advances. Orbital platforms also provide communications relay and navigation capabilities, especially for farside locations.

Many core science goals can only be achieved by a continuous presence at the Moon. A few examples include:

- Change detection – the surface of the Moon evolves slowly but it does evolve. Through long-term observation of the Moon, it will be possible to observe changes (physical and compositional) that take place over years and decades.
- Impact processes – hypervelocity impacts at velocities much greater than the speed of sound (within the solid Moon) are highly non-linear events that are not currently replicated by laboratory experimentation. These impacts are not common enough that short missions can be anticipated to adequately observe them. But with continuous observations from orbit, it will be possible to observe an impact when it happens, or soon after, and details such as energy partitioning, can be discerned. Both high temporal resolution and spectrally resolved impact flash detection can be achieved from distant orbits that will reveal the impact process in unprecedented detail as well as aspects of the chemical composition of the surface at the location of the impact and the nature of impactors.
- New global datasets at high resolution (spectral and spatial) take years to acquire, especially those that are Sun-angle dependent. LRO was meant to be a two-year mission, but its decade-long extension proved the value of a continuous orbital presence even though its scientific payload was not selected with this possibility in mind. A follow-on LRO-class mission with an intentionally selected long-term scientific payload can be expected to yield groundbreaking results (as is often the case) beyond what the science teams envision.

Meeting these goals will require multiple approaches involving several orbits and/or orbiters, but there are a large number of stakeholders in our return to the Moon, including commercial and international partners, whose resources can be shared and leveraged to meet diverse goals while minimizing cost.

4.2 Orbits

Different lunar orbits serve a variety of science and exploration objectives. Along with scientific observational objectives, orbital assets will be needed to support robust high data rate relay from assets on the surface and in cis-lunar space to Earth.

While there are infinite potential orbits around the Moon, we broadly classify subsets useful for lunar exploration as polar, equatorial, and distant. Distant orbits include Lagrange Points and Near Rectilinear Halo Orbits (NRHOs).

4.2.1 Circular vs. Elliptical Orbits

Polar and equatorial orbits can be near circular or elliptical. Circular orbits enable coverage with high and uniform spatial resolution. Low circular orbits must be maintained with frequent station-keeping maneuvers, requiring large propellant budgets. Certain classes of elliptical orbits (sometimes termed

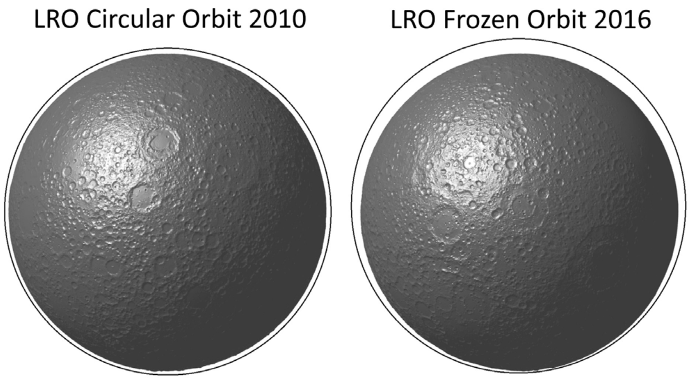


Figure 4.2.1: Illustration of the distinction between a low-altitude circular orbit and elliptical frozen orbit from LRO. In absolute terms the change in orbital eccentricity from the 2010 to the 2016 is small but is substantial with respect to orbit altitude.

frozen orbits) require significantly fewer station-keeping maneuvers and allow an orbiter to remain active with minimal fuel cost. An example from LRO illustrates the distinction in Figure 4.2.1.

Since frozen orbits are stable over decadal time frames, they will attract multiple missions over time. Therefore, consideration should be given to end-of-mission scenarios to prevent overcrowding. Potential options include deorbiting with a controlled impact or movement to a higher frozen orbit less likely to be occupied by future missions. A controlled and targeted impact also provides an opportunity for an impact experiment, such as performed by the LCROSS mission, monitoring the impact plume and temperature changes associated with the impact, and determining the crater morphology.

Highly elliptical orbits with low periapsis can enable high resolution measurements over a targeted area on the Moon. They require lower ΔV to achieve than circular orbits and thus are well-suited for resource-constrained spacecraft such as cubesats.

- **Finding 4.2.1a**: Low-altitude circular orbits are ideal for uniform high resolution measurements but require frequent station-keeping maneuvers and thus large fuel reserves.

- **Finding 4.2.1b**: Transition from circular to a low-cost elliptical frozen orbit should be planned carefully with enough remaining propellant to perform angular momentum adjustments and phasing maneuvers.

4.2.2 Polar vs. Equatorial Orbits

Polar orbits enable global or near-global surface coverage over time. Equatorial orbits enable high temporal coverage at the expense of global spatial coverage, specifically at high latitudes. In reality, orbits evolve over time and generally lie between precisely polar and equatorial due to inclination drift away from an initial state.

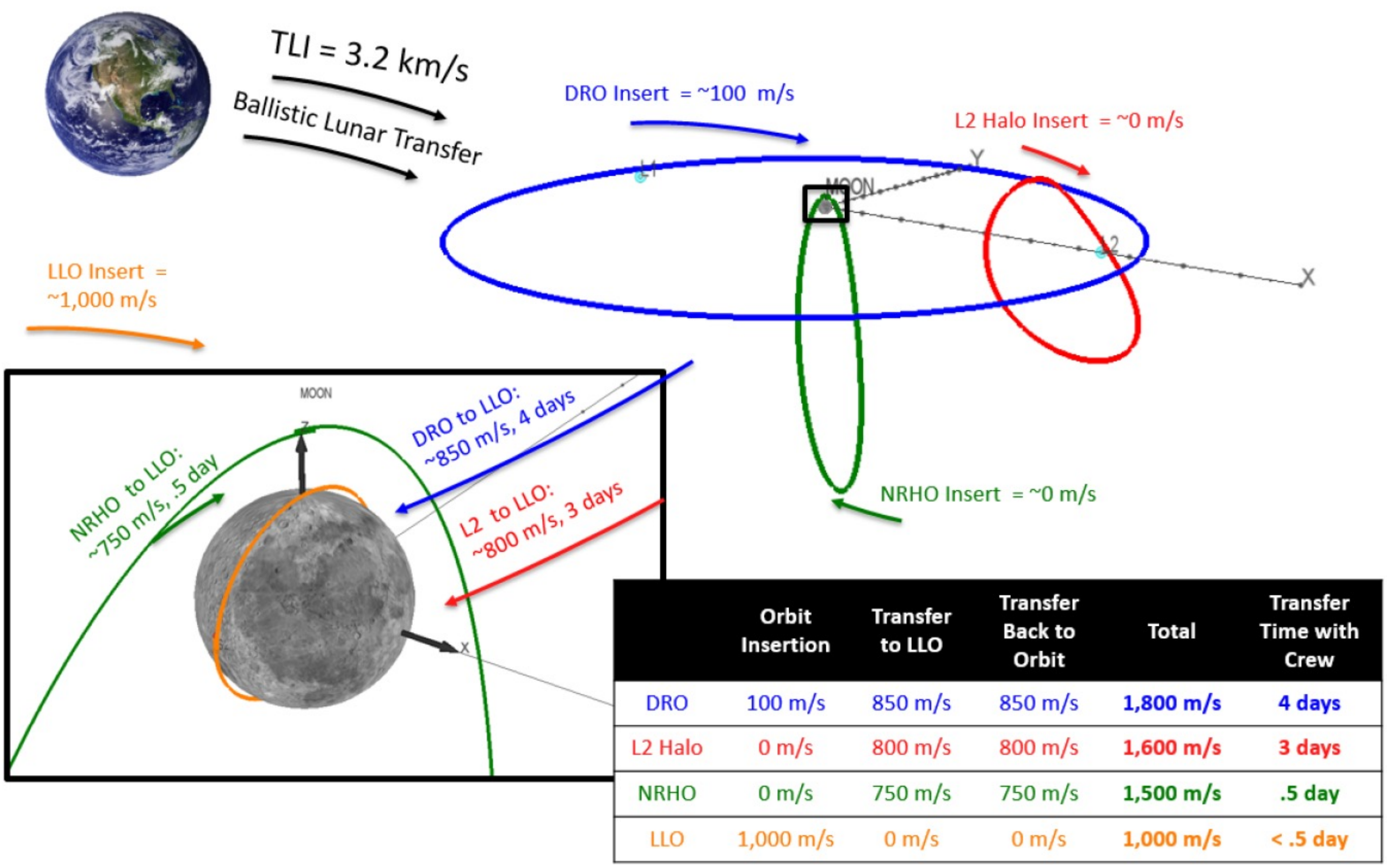
- **Finding 4.2.2a**: Polar orbits provide global coverage over time and are broadly applicable to a wide range of investigations.

- **Finding 4.2.2b**: The benefits of equatorial orbits are generally underutilized. Equatorial orbits can be adopted for rapid repeat (orbit to orbit) coverage over a selected low- to mid-latitude area (as the area rotates under the orbit path) and these orbits provide high local time resolution measurements.

4.2.3 Distant Orbits

Distant orbits include orbits around Lagrange Points (e.g. L1, L2) and NRHOs, as demonstrated by Capstone and envisioned for Gateway (Fig. 4.2.3). Orbits around Lagrange points provide near-hemispherical coverage of the Moon, ideal for communication stations (e.g. far side communication relay from L2) and to observe impact flashes, while the Gateway NRHO provides access to the lunar surface (at periapsis) and a low-cost destination from Earth (near apoapsis).

An example distant orbit science mission would measure the current lunar impact flux from long-duration platforms that maximize lunar surface coverage. Instruments required to monitor impact flashes (with or without spectroscopy) can be accommodated on smaller-sized spacecraft and still be expected to have long-duration missions due to the low fuel cost to maintain these orbits. A single



	Orbit Insertion	Transfer to LLO	Transfer Back to Orbit	Total	Transfer Time with Crew
DRO	100 m/s	850 m/s	850 m/s	**1,800 m/s**	**4 days**
L2 Halo	0 m/s	800 m/s	800 m/s	**1,600 m/s**	**3 days**
NRHO	0 m/s	750 m/s	750 m/s	**1,500 m/s**	**.5 day**
LLO	1,000 m/s	0 m/s	0 m/s	**1,000 m/s**	**< .5 day**

Figure 4.2.3: A variety of lunar distant orbits, including distant retrograde orbit (DRO), L2 halo orbit, and near rectilinear halo orbit (NRHO), with low lunar orbit (LLO) for comparison. Lunar gateway will use a NRHO characterized by a perilune radius of approximately 3,200 km over the northern hemisphere and apolune radius of approximately 70,000 km over the southern hemisphere. Figure from Whitley et al. 2017.

spacecraft in halo orbit of a Lagrange point provides continuous hemispherical surface coverage. Multi-spacecraft configurations around the L1+L2 or L2+L4+L5 provide complete or overlapping coverage respectively.

- **Finding 4.2.3a**: Distant orbits including orbits around Lagrange Points and Near-Rectilinear Halo Orbits (NRHOs) have characteristics well-suited to support communication infrastructure.

- **Finding 4.2.3b**: Although most orbital science objectives will require low altitude orbits, distant orbits typically have low fuel maintenance requirements and are uniquely enabling for long-duration communications, PNT, and science missions that monitor broad areas of the Moon or the cis-lunar environment.

Figure 4.3: NASA's currently active lunar orbiters include both larger, long-lived integrated orbiter LRO (left) and smaller, focused investigation orbiter CAPSTONE (right). Images from NASA: https://www.nasa.gov/mission_pages/LRO/multimedia/lrocraft2.html (left); https://www.nasa.gov/image-feature/capstone-slated-for-launch-into-lunar-orbit (right)

4.3 Platforms

Continuous orbital presence at the Moon necessarily relies on a variety of platforms (Fig. 4.3). No single platform or approach can meet all science and exploration needs.

4.3.1 Larger Long-lived Integrated Spacecraft

Throughout the history of planetary exploration, spacecraft capable of multiple extended missions with multi-instrument payloads have yielded scientific results far beyond the mission's original goals and objectives. Examples include the twin Voyager spacecraft, Pioneers 10 and 11, Mariner 10, Mars Reconnaissance Orbiter (MRO), and Cassini. Along with LRO, these missions exemplify the advantages of the larger spacecraft approach, where multidisciplinary science teams work collaboratively to take advantage of a stable, long-lived platform and develop new modes of operations for both the spacecraft and instruments, thus expanding science objectives that might otherwise require an entirely new mission. While the return on investment from long missions is considerable, instruments and spacecraft do eventually age. As spacecraft and instrument technology improves, a program that plans for the eventual replacement of long-lived orbiters should be adopted. Future larger lunar missions will include carefully selected instruments that provide complementary and comprehensive data relevant to one or more transformative science investigations outlined in Chapter 3 and will benefit from multi-year investigations for global, high-spatial resolution measurements, and change detection. For example, a mission focused on polar region special environments might include active infrared spectroscopy through multiband lidar, microwave and infrared radiometry, subsurface radar to search for ice signatures, and highly sensitive visible imagers.

- **Finding 4.3.1a:** An LRO-class orbiter with state-of-the-art instrumentation is needed for long term coverage of the Moon with coordinated new and improved measurements.

- **Finding 4.3.1b:** A systematic replacement program, perhaps modeled after the successful Landsat Earth observation satellite program, is important to take advantage of technical advances and to enable new discoveries to be addressed.

4.3.2 Intermediate-scale Spacecraft

Medium-sized missions with only a few instruments that are narrowly focused on high-priority objectives can quickly yield transformative science. Past lunar examples include Clementine, Lunar Prospector, GRAIL, LADEE, and LCROSS. The upcoming Lunar Trailblazer spacecraft will deploy advanced infrared sensors to characterize the spatial and temporal distribution of water and cold traps and is scheduled to launch in mid-2023. Given recent advances in launch vehicles, these types of spacecraft can often ride along with other launches or use smaller launch vehicles leading to lower overall costs. As with Lunar Trailblazer and GRAIL, instruments on medium spacecraft can be state-of-the-art, equivalent to any that might be flown on larger missions. A future mission example might include Ka-band polarimetric SAR for 15-cm scale radar imaging with all 4 Stokes parameters and with opportunities for high-resolution sounding SAR to search for areas of anomalous radar scattering including very high TiO_2 and even ices.

- **Finding 4.3.2a:** Intermediate-scale orbiters (e.g. LADEE, GRAIL, and Lunar Trailblazer) are well-suited for focused, often shorter-duration investigations that address compelling scientific objectives using the most advanced and capable instrumentation.

4.3.3 Smaller Spacecraft

Over the next few years NASA will deploy a number of small missions including, for example, the cubesats Lunar IceCube, LunaH-Map and Lunar Flashlight. Because these missions are low-cost, require minimal resources, and have shorter development times, they enable higher-risk approaches to test new ideas and return valuable science quickly. Furthermore, multi-spacecraft missions can be considered, such as tethered cubesats or swarms that return 3-dimensional distributed data sets of the lunar environment. Such platforms will enable targeted, brief duration missions such as very low altitude magnetometer measurements over lunar swirls or cm-scale images of targets of high interest such as the silicic domes, fresh impact craters, or lunar pits.

- **Finding 4.3.3a:** Cubesats and other small platforms are relatively low-cost with rapid development cycles, enabling higher risk tolerance, high payoff investigations, and novel architectures such as constellations, tethered pairs, and other configurations addressing unique science.

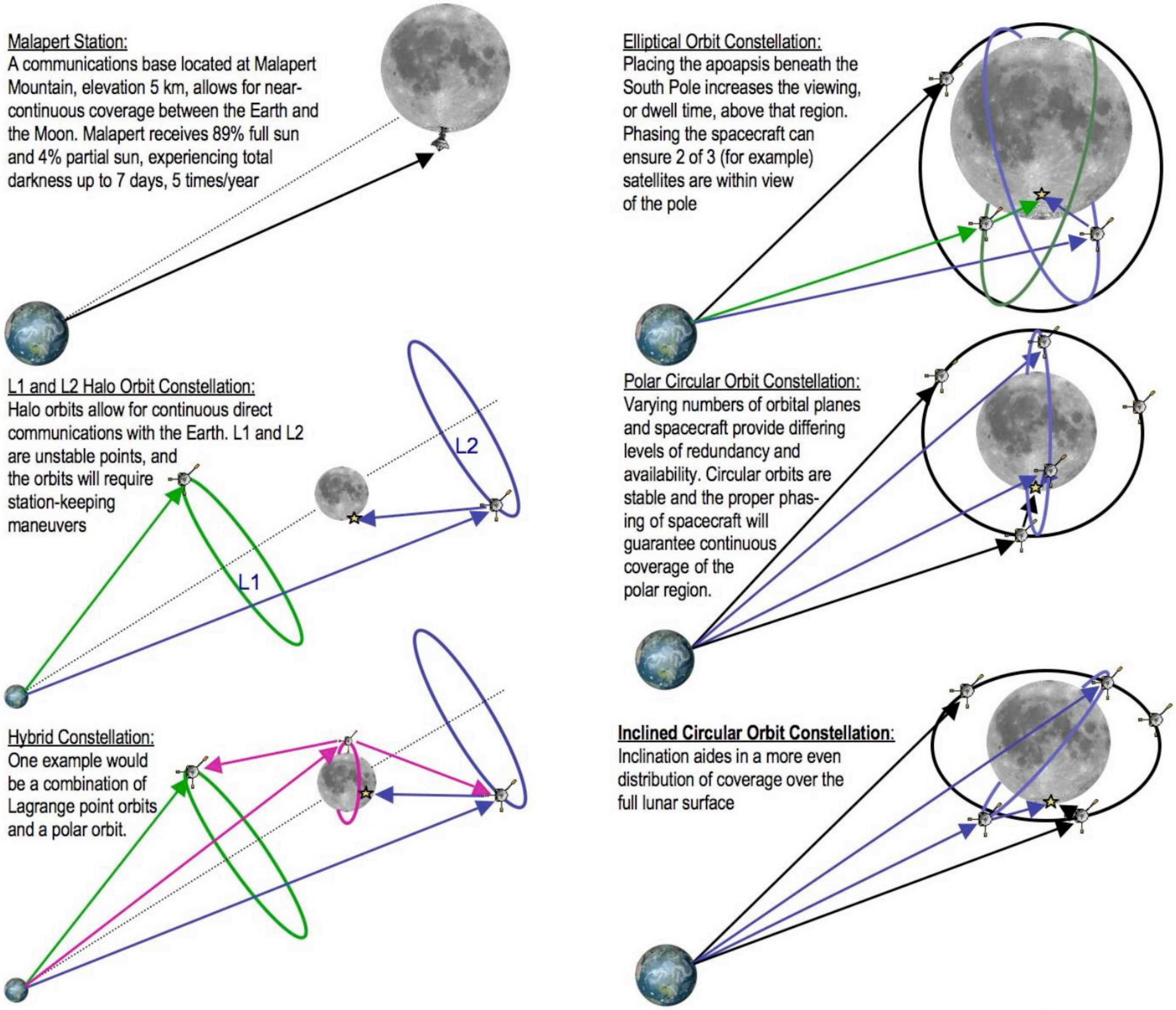
4.4 Communications and Navigation

Continuous orbital presence at the Moon will require Earth-based infrastructure including communication for commanding, tracking for Positioning, Navigation, and Timing (PNT) purposes, along with extensive data transfer for science and exploration (Figure 4.4).

4.4.1 Communications

A continuous lunar presence using state-of-the-art and high-resolution instrumentation will require commensurate advances in communication capabilities. For science alone, and for the kinds of measurements and resolutions described here, we estimate that daily data volumes could increase by a factor of 10 to 100 over the current demands of LRO. Also, 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. A broad capabilities approach may go beyond the needs of any one stakeholder but will ultimately lower costs through a communication infrastructure that provides global access to the Moon. The availability of communication relay satellites can lower mission costs by enabling high data rate instruments on smaller platforms that cannot support the large antennas and transmitters needed for fast, direct-to-earth communication.

The lunar farside is shielded from Earth-based radio



Malapert Station:
A communications base located at Malapert Mountain, elevation 5 km, allows for near-continuous coverage between the Earth and the Moon. Malapert receives 89% full sun and 4% partial sun, experiencing total darkness up to 7 days, 5 times/year

Elliptical Orbit Constellation:
Placing the apoapsis beneath the South Pole increases the viewing, or dwell time, above that region. Phasing the spacecraft can ensure 2 of 3 (for example) satellites are within view of the pole

L1 and L2 Halo Orbit Constellation:
Halo orbits allow for continuous direct communications with the Earth. L1 and L2 are unstable points, and the orbits will require station-keeping maneuvers

Polar Circular Orbit Constellation:
Varying numbers of orbital planes and spacecraft provide differing levels of redundancy and availability. Circular orbits are stable and the proper phasing of spacecraft will guarantee continuous coverage of the polar region.

Hybrid Constellation:
One example would be a combination of Lagrange point orbits and a polar orbit.

Inclined Circular Orbit Constellation:
Inclination aides in a more even distribution of coverage over the full lunar surface

Figure 4.4: A large number of potential architectures exist to support lunar surface communications. Here are examples of six different architectures studied by the Space Communication Architecture Working Group (SCAWG). Figure from Bhasin et al. 2006.

Box 2

The Science and Exploration Imperative for High Data Volumes from the Moon.

Transformative science and exploration is enabled by modern instruments that require high data throughput. Although the phrase, “a picture is worth a thousand words,” remains true, technical capabilities have progressed well beyond information found in a single image. Next generation data from lunar orbit will be obtained by modern sensors spanning multiple parts of the spectrum, each often with hundreds of spectral channels and high precision. Desired capabilities also extend over a wide range of both spatial and temporal resolutions. Data from such modern capabilities transmitted to Earth for integrated analysis will inevitably result in new discoveries and advancements for science and exploration. The multidimensional nature of modern lunar measurement capabilities is unprecedented, as is the resulting data volume for the Moon. Given the Moon’s proximity, it is reasonable to consider data rates and volumes comparable to Earth-observing missions.

In order to fully assess the transformative science identified in this report, it is important that a robust, high-data-rate communication infrastructure be implemented in order to acquire and downlink data from modern instruments designed to explore the Moon in detail during the decades ahead. This infrastructure could take many forms, ranging from dedicated global communications relay(s) to direct nearside lunar surface to Earth links, etc.

In addition to the desire for high data volumes from lunar orbit, **landed missions to the farside of the Moon require data relays**. At present, NASA does not have a communications relay capability for the farside of the Moon (although China does and provides support for their Chang’e-4 lander and Yutu-2 rover on the lunar farside). NASA’s first planned landed mission to the lunar farside will be a CLPS mission, CP12 (PRISM1B), and the CLPS provider will need to provide a communications relay to support this lander. Looking toward the future, there is a clear need for more substantive infrastructure, especially for the half of the Moon unseen from Earth. For example, the strongly recommended Endurance-A concept for a long-range rover to the South Pole–Aitken basin described in the Decadal Survey would require a communications relay for an extended period. Unfortunately, none currently exist but there are several communication relay possibilities under consideration for the future. These include Goonhilly/SSTL/ESA’s Lunar Pathfinder, NASA’s Gateway and a Lunar Communications Relay and Navigation Systems (LCRNS) project, Argotec’s Andromeda constellation (see Appendix I of the Endurance-A concept study report), and other potential partners in NASA’s Near Space Network during the years ahead.

transmission, which provides an opportunity for radio wave astronomy. This advantage can be lost if steps are not taken to preserve radio-quiet areas on the farside. Portions of the radio spectrum can be reserved for radio astronomy by an agreement between all stakeholders to avoid contamination (continuously or at particular times). It is important to get these agreements in place early before opportunities are lost.

- **Finding 4.4.1a**: Lunar surface and cis-lunar vicinity communications must be planned and supported to advance science and exploration objectives.
- **Finding 4.4.1b**: Development of advanced, high data rate communication (e.g. laser-based, internet in space) should be actively pursued.
- **Finding 4.4.1c**: Measurement and communication strategies should be implemented that are compatible with lunar farside radio astronomy opportunities.

4.4.2 Navigation

Navigating, or more broadly Positioning, Navigation and Timing (PNT), about the Moon is enabled by the high-resolution gravity field measured by the GRAIL mission. However, tracking and spacecraft attitude control improvements will enable more accurate and precise observation geolocation. Additionally, orbital navigation services will aid activities on the surface where precise geolocation is required. For example, local geophysical surveys with portable instruments require horizontal location precision at the ~10 cm scale, while larger geophysical surveys require m-scale precision. This could be addressed with a Global Navigation Satellite System (GNSS), such as will be tested by the CLPS mission Lunar GNSS Receiver Experiment (LuGRE).

- **Finding 4.4.2a**: No additional refinement of the lunar gravity field is currently necessary for navigation purposes (although science advancements through high spatial resolution gravity measurements are possible).
- **Finding 4.4.2b**: Improved geolocation technology can assist surface operations. In the long term, global positioning satellites will enable precise (m-scale) location information for any asset on the Moon.

Implications for exploration

The infrastructure for communication and navigation will be shared with, and may be driven by, the needs of exploration and the Artemis program. As lunar exploration evolves, so will requirements. For example, the initial Artemis landing sites will be near the south pole in areas capable of direct line-of-site communication with the Earth, however curiosity and the search for resources will compel farside exploration. The NRHO of Artemis Gateway is designed to enable global access to the Moon which, in turn, requires developing a global communications network. Thus the tools of navigation and communication can be shared by exploration and science as there are parallel objectives and these tools should be developed to meet the requirements of each.

4.5 Operations and Ground Segment

Over the next decade and beyond, NASA, other government agencies, international space agencies, and commercial interests will undertake considerable activity at the Moon, presenting a significant challenge for coordination and cooperation arising from a multi-agency, multi-mission space environment. However, these efforts will also offer an opportunity to achieve common goals with lower costs as redundant activities are eliminated.

4.5.1 Multi-Mission Operations

One possibility to be explored is the use of common multi-mission operation centers within NASA or industry to save on costs, improve communications across missions, and reduce the demands on personnel and training.

- **Finding 4.5.1a:** Multi-mission operation centers should be evaluated for potential cost savings and improved communications across missions.

4.5.2 International Agencies and Commercial Space

Cooperation and communication will be essential as activities at the Moon increase among diverse stakeholders. NASA should establish a single office tasked with coordinating across space agencies and within NASA to coordinate sharing resources, such as communications networks and orbital strategies. For example, a spacecraft's orbit altitude and orbit plane could be chosen partially based on the requirements of other orbiters.

- **Finding 4.5.2a**: Establishment of a single office or point person tasked with coordinating across space agencies and within NASA for sharing resources and optimizing science return from the Moon and cis-lunar environment should be considered.

4.6 Planetary Data System and Data Management Strategies

Advanced communication capabilities will enable unprecedented planetary data collection and downlink, fulfilling exploration and scientific needs. These advanced measurements will require orders of magnitude larger data volume, similar to that of NASA's Earth orbiting platforms. The Planetary Data System (PDS) should be scaled to accommodate the expected increases in data and these data should be treated under a consistent framework that enables different datasets to be compared and used together. This increase in data returned will require effective data management strategies, including adopting methods developed in Earth observing programs such as Landsat or commercial remote sensing satellite operations. Existing and new lunar datasets will need to be cartographically registered, i.e., photogrammetrically, radargrammetrically, or altimetrically controlled under a common reference frame (i.e., the current internationally accepted lunar reference frame is based on the JPL DE 421 ephemeris as rotated to the mean Earth/polar axis / ME system) so overlapping datasets can be compared and used together. For example, to enable "change detection" investigations, control of the images is needed to register images as closely as possible.

Given the increasingly complex sensors and spacecraft platforms being used to collect the datasets in question, processing of such data has become orders of magnitude more complex, time consuming, and demanding of human resources. Tasks include the development of: (a) new data processing algorithms; (b) new (and better standardized) sensor models; (c) data processing software that accounts for (and geodetically controls) the new types of datasets; (d) software that accounts for the increasingly massive datasets in question; (e) algorithms and software for doing quality control of products; and (f) pipeline-managed automatic generation of such products. Data must be usable; aside from making sure that datasets have been properly registered, it is also necessary to make them easily accessible, and interoperable to maximize their benefits to all.

Accurate high-resolution topographic models are required to co-register and photometrically correct almost all remote sensing observations. To take full advantage of new and existing orbital datasets, they are orthographically projected onto higher accuracy topographic models, both to correctly map them spatially, but also to apply appropriate photometric models. The ultimate accuracy of resource, volatile, thermal, and other types of mapping is highly dependent on accurate photometric corrections.

- **Finding 4.6a**: The Planetary Data System must be appropriately scaled over time to accommodate the expected increases in data returned from the lunar surface and orbit.

- **Finding 4.6b**: New and existing data sets should be registered to a common, improving framework based on the highest accuracy topographic maps available.

5. Measurement Approaches

5.1 Introduction and Scope

Since 2007, numerous orbital missions led by the U.S., India, China, Japan, and South Korea have flown to the Moon, carrying a variety of scientific instruments designed to make key observations and measurements tied to specific exploration and science objectives. As described in Section 3.2, those objectives are defined by U.S. and international priority documents, including the Decadal Surveys, the SCEM report, the ASM-SAT report, the LER, and the Global Exploration Roadmap (GER). In order to meet the consensus science objectives of the U.S. and international lunar and planetary science communities, and to facilitate surface robotic and human exploration of the Moon, additional improved or new measurements are needed from lunar orbit. These measurements, driven by the lunar science community's science objectives and human and robotic exploration requirements, may enhance previously acquired orbital data sets or enable new ways to address lunar science and exploration objectives. New measurements from lunar orbital platforms, including the many examples provided in this chapter, can potentially enable or improve the success of future lunar science and exploration, including Artemis and CLPS landings. The types of measurements highlighted in this report are not intended to be an all-inclusive list, but can serve as a starting point for identifying the types of measurements that might be considered when seeking to address specific needs.

This chapter is driven by the high priority scientific and exploration objectives described in Chapter 3, Science and Exploration Objectives and Needs. This chapter outlines some examples of measurements that could be made from lunar orbit to address these objectives; these example measurements also link to Chapter 4, Implementation Approaches and Architectures. Throughout this chapter, we strive to describe types of measurements that are needed to achieve high-priority science and exploration objectives while remaining agnostic on specific instruments or implementations that might be used to make those measurements. For each type of measurement described in this chapter, we consider: how it is an improvement on prior measurements; the type of observation needed; the time period over which it needs to be acquired; which objectives it enables or enhances; whether it would support or enable upcoming or future missions; whether it is relevant to Planetary Science Division (PSD), human exploration, and/or Space Technology Mission Directorate (STMD); and whether it would impose any mission-level requirements (e.g., communications, data rates, or orbits). We include techniques in a variety of development stages from theoretical to proven technologies. We did not evaluate whether a technique would be feasible for a particular mission; we leave it to future instrument teams to demonstrate a measurement's readiness state for flight with a specific implementation. The information used for this chapter is drawn primarily from previously concluded LEAG reports, the Decadel Survey white papers submitted to CLOC-SAT, and feedback received from the community on draft versions of this report.

We recognize that measurement approaches are continuously evolving and advancing, and we stress that those presented here are examples of measurements with the potential to enable advancement of community science and exploration objectives. However, there are other possible measurements and approaches that we do not include, and additional technology developments and scientific discoveries are likely to influence the types of measurements needed or desired in the future. As additional measurements are acquired and analyzed, new discoveries will drive new requirements for future measurements, approaches, or types of data desired from the Moon; thus, anticipated measurement needs are likely to evolve with time. Thus this list should not be considered complete or indicating a preference for a listed measurement approach; viable or better alternatives might be identified in the future.

Measurements are grouped into several broad categories in this section: Fields and Particles, Spectroscopic Approaches for Surface Characterization, Surface Geology and Geomorphology, Surface Temperatures, and Approaches for the Subsurface. Each category has a summary table for quick reference.

5.2 Fields and Particles

5.2.1 Radiation and Plasma Detectors

Continuous orbital measurements are required to monitor solar activity and the radiation and electromagnetic environment at the lunar surface and in cis-lunar space (Section 3.3.9; Fig. 5.2). Observations that would enable “space weather forecasting” capabilities relevant to the safety of human explorers in cis-lunar space and on the surface are highly desirable. Enhanced knowledge of solar activity and the cis-lunar radiation environment will also inform modeling efforts and the development of shielding technology for spacecraft and scientific instruments. Long-duration monitoring would allow the characterization of the galactic cosmic ray (GCR) and solar particle flux over different solar cycles. Short- and long-term monitoring of incident flux can also be used as inputs for ion weathering rates of the surface and can capture rare extreme events. Orbital measurements include measurements within the Earth’s magnetotail, and because of this, there is an opportunity to use platforms at multiple orbital positions to study the 3-dimensional interaction of solar wind with our Earth-Moon system and to characterize the radiation and plasma environment on the lunar surface. Observations acquired over the long-term are highly desired, expanding on ARTEMIS measurements and providing a fourth dimension to these studies. Because space plasmas

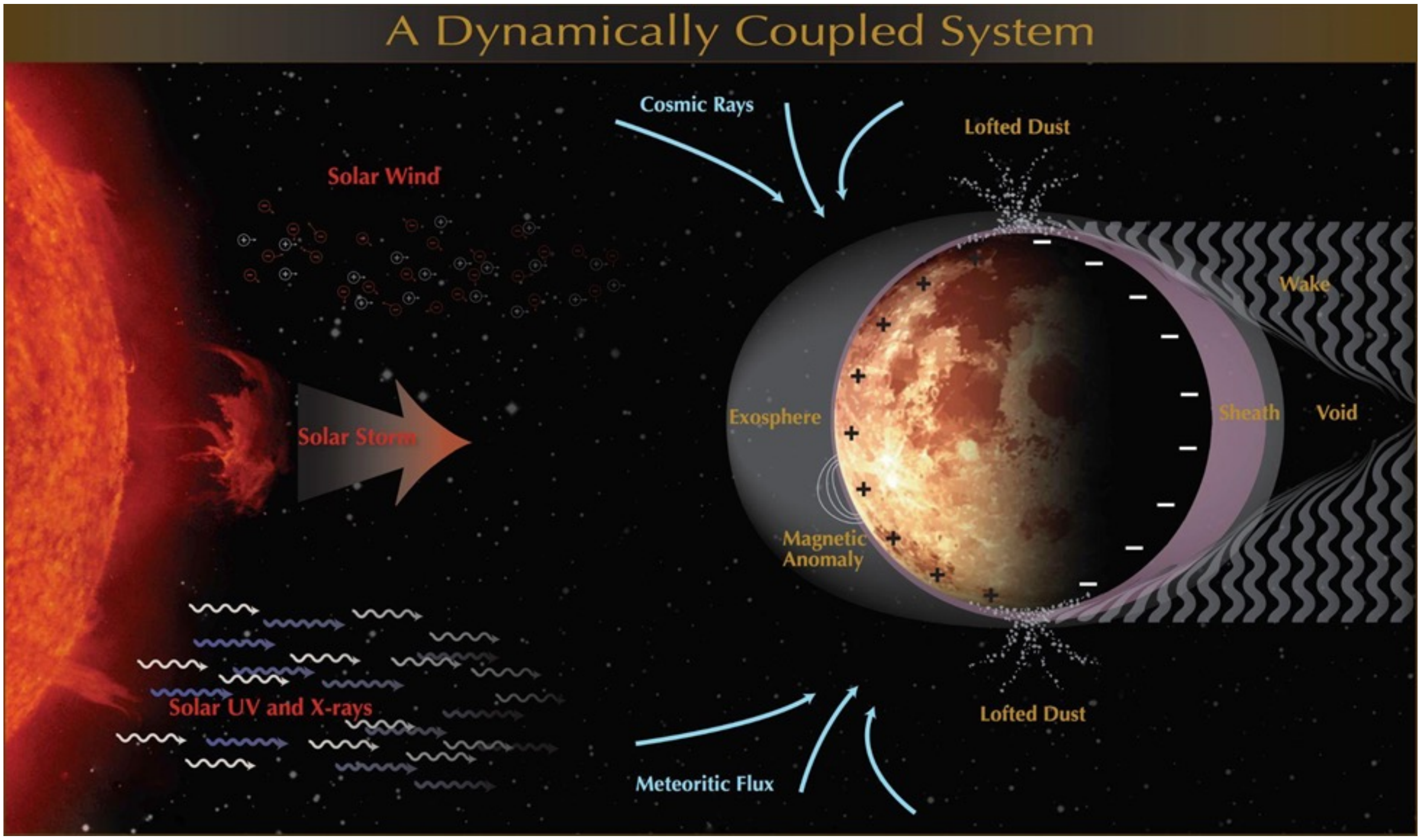


Figure 5.2: The Moon resides in a complex plasma environment that contributes to space weathering and with implications for exploration. Ideally simultaneous multipoint measurements from orbit and the surface will address fundamental questions for the Moon and other solar system bodies with surface bounded exospheres. Credit NASA/GSFC/W.M. Farrell/T.J. Stubbs

are dynamic with highly coupled components (fields and particles), their study is ideally accomplished with a comprehensive plasma package (although there is clear value to individual measurements, such as magnetic fields as well). Such a package would include fields and particle instruments, e.g. fast ion and electron analyzers, ion composition, electric and magnetic fields, radio wave, and electron density and temperature measurements. A subset of instruments can be tailored and optimized for specific objectives when a full complement is not practical.

The Cosmic Ray Telescope for the Effects of Radiation (CRaTER) instrument has been monitoring the energetic particle environment about the Moon from the deep minimum of solar cycle 23 through to the peak and now descending phase of solar cycle 24. Orbital measurements of linear energy transfer (LET) spectra and total dosage should continue through future solar cycles and a variety of solar conditions. This will enable concurrent observations with surface assets and provide vital measurements during large solar energetic particle events. The CRaTER instrument included tissue equivalent plastic to explore biological impacts of radiation in the lunar environment and future orbiters could further advance this work with additional experiments.

The ARTEMIS mission's two spacecraft continue to provide vital information on the Moon's plasma environment and the solar wind's interaction with the Moon, complementing prior missions such as Lunar Prospector and SELENE, which included plasma characterization instrumentation. Future long-term orbiter measurements should include a full complement of advanced plasma characterization instrumentation, fields and particles with high time resolution and composition measurements of sputtered ions and photoionized neutrals that have been picked up by the solar wind. Limited measurement packages suitable for smallsat missions could also be employed, for example, continuous close proximity two point field measurements from tethered cubesats.

5.2.2 Magnetic Fields

Future orbital platforms can also enable the measurement of magnetic fields at multiple altitudes and enable characterization of electromagnetic field and solar wind interactions upstream from the surface. For example, magnetic field measurements at low altitudes (<<100 km) would be collected to gain a better understanding of the sources and depths of lunar magnetic anomalies associated with lunar swirls. One critical question for future explorers is the degree to which, if any, the magnetic fields co-located with lunar swirls provide protection from space weather and radiation at the surface (Section 3.3.9). Measurements focused on determining space weathering, magnetic fields, and radiation levels at lunar swirls could directly address this question. An orbital platform for such measurements could provide information for multiple swirl locations or magnetic anomalies, which are found in both highlands and mare regions around the Moon. The connection between lunar magnetic anomalies, lunar swirls, and the solar wind should be investigated multidimensionally with surface measurements taking place concurrently with orbital measurements. Future orbital measurements should seek to significantly improve on the measurements of Lunar Prospector Magnetometer data and SELENE Lunar Magnetometer; improved models for the weak magnetic fields on the surface could be derived from new data and could provide further insights into impact magnetization or demagnetization, thermoremnant magnetization in ejecta, lava tubes, and/or dikes, and dynamo evolution through paleopole wander.

Surface and orbital magnetometers both require masts or other methods of separating spacecraft magnetic fields from ambient ones, as well as complementary plasma packages that include fields and particle measurements to understand how conditions on the surface respond to the dynamic solar wind and interact with magnetic field anomalies. The orbital package should also include an energetic neutral atom detector that can monitor the solar wind reflected and neutralized upon impact with the surface.

5.2.3 Neutral and Ion Mass Spectrometry

Observations of the lunar exosphere by prior spacecraft including LADEE (NMS) and SELENE (ion analyzers) have provided key insights into its density, distribution, and composition. Additional measurements of the lunar exosphere should provide new high spatial and temporal resolution constraints on the lunar volatiles cycle (Section 3.3.8). New measurements are required to monitor the movement of volatiles, to understand their sources and governing processes, and reveal the history of polar volatiles. For example, direct measurements of exospheric water (and other volatiles) at all latitudes, various times of day, and seasons would advance our understanding of the volatile cycle (Section 3.3.7). Long-term orbital measurements could also detect the exosphere's response to transient exogenous events including periods of micrometeoroid impacts and anthropogenic or robotic activities, and could monitor possible release of gasses that might be triggered by tectonic events. Additionally, sputtered ions from the surface can be detected and measured from orbit, reflecting surface compositions.

TABLE 5.2: Measurements for Fields and Particles

Measurement	Objectives	Future Mission Support	Directorate Relevance	New or Advancement	Type of Observation	Mission Level Requirements
Radiation and plasma detectors	Hazard mitigation; Flux variations over solar cycles (3.3.9)	All missions to cis-lunar space (including Artemis, Gateway)	Helio, PSD, Human	Improves on ARTEMIS; New on-demand and real-time knowledge	Continuous; long-term and ongoing; global	Multiple positions in cis-lunar space
Magnetic fields	Space-surface interactions; Surface magnetic field strengths; Sources of magnetic fields; Hazard mitigation (3.3.9)	Relevant to missions encountering or studying magnetic fields	PSD, Human	Improves on Lunar Prospector and other magnetic field meas.; New global low-altitude measurements	Multiple; widespread	Low-altitude passes
Neutral and ion mass spectrometry	Flux of species; Volatiles cycle (3.3.8); Potential resources (3.3.7)	All surface missions sensitive to exosphere composition	PSD, Human	Improves on LADEE and Kaguya/ SELENE; Improved detection limits to expand study to additional components	Long-term, global	Polar orbit for volatiles

5.3 Spectroscopic Approaches for Surface Composition

5.3.1 UV-VIS-NIR Spectroscopy and Multispectral Imaging

UV-VIS-NIR multispectral images and imaging spectroscopy is a cornerstone of remote sensing science investigations of the lunar surface (Sections 3.3.2, 3.3.5, 3.3.6, 3.3.7, 3.3.8). Clementine, Chandrayaan-1, LRO, and SELENE have provided some of the best UV-VIS-NIR maps and images of the lunar surface to date at ~20 to 400 m scales. Clementine, LRO, and SELENE all included multiband imagers as a payload. An imaging spectrometer such as Chandrayaan-1 Moon Mineralogy Mapper (M3) provides contiguous narrow bandpasses that can resolve broad highly diagnostic spectral features of specific minerals. A comprehensive global inventory of mineralogy and composition is critical to understanding the Moon's evolution as well as for the identification of potential resources such as pyroclastics, metals, trace elements, and volatiles.

In the visible and near-infrared (VNIR), which spans 0.4 to 4.0 μm, spectral features are used to investigate iron-bearing minerals with diagnostic absorptions around 1 and 2 μm, as well as OH/H_2O absorptions near 3 μm (Table 5-3-1). The UV-VIS spectral region (0.3 to 1 μm) has been used to study and map glass, titanium, ilmenite, hematite, and space weathering components on the Moon's surface. Advances in detectors, optics, and controllers influence the spectral and spatial resolution available for multispectral imaging and imaging spectrometers. Additional high spatial resolution (e.g., 10 to 50 m scales) UV-VIS and VIS-NIR imaging, either multispectral imaging or imaging spectroscopy, would enable lithologic mapping of Fe-bearing minerals, OH/H_2O, and surface optical maturity (a proxy for degree of space weathering) at roughly an order of magnitude better spatial resolution than M3.

Imaging spectrometers have the benefit of providing information at different wavelengths that can be used to better characterize spectral features in a spatial context. Point spectrometers provide measurements for locations along a path made each orbit. With time, accumulated data gradually provides spatial coverage of the surface. In contrast, imaging spectrometers and multispectral imagers use 2D-detectors paired with spacecraft motion to build up an image along the spacecraft's track. Images are generally better suited for mapping purposes. New high resolution maps would substantially improve upcoming missions like Lunar Trailblazer (which has a nominal spatial resolution of 70 m and spectral range of 0.6 to 3.6 μm), and the Chandrayaan-2 Imaging IR spectrometer (80 m sampling with range of 0.8 to 5 μm).

Additionally, values of single scattering albedo derived from images taken by the LROC NAC (a panchromatic camera and not a spectroscopic instrument) have demonstrated the importance of compositional imaging at the few m-scale or better. While the single broadband UV-VIS sensitivity of the NAC limits the types of materials that can be definitively distinguished from single scattering albedo, the results pave the way for multiband instruments in the future. Multiband imaging at the m-scale would enable mapping of rock and soil types suitable for sampling strategy planning. Such images could be obtained with passive imagers, or with active illumination, such as multiband lasers (Section 5.3.7).

5.3.2 TIR Spectroscopy

Beyond about 5 μm, light from the lunar surface is dominated by thermal infrared (TIR) emission. The current best TIR compositional maps to date are provided by LRO Diviner, with spatial sampling of ~250 to 500 m and three bands used for compositional analysis centered near 8 μm. Higher spatial and spectral resolution and greater spectral range than Diviner covering specific wavelengths of mineral spectral features would be beneficial to studies of volcanism, differentiation, lunar magma ocean, magmatism, and global mineralogy and composition (Sections 3.3.2, 3.3.6). For example, the Lunar Trailblazer Lunar Thermal Mapper (LTM) marks a significant advance in spatial resolution and number of bands over Diviner, with 11 channels between 7 and 9 μm, although data will be extremely limited in coverage to targeted locations owing to data volume limitations on the spacecraft. However, an LTM-like instrument would be an ideal global compositional survey instrument. A high resolution (e.g., 10 m scales) TIR imaging spectrometer (focused on 5 to 14 μm) would provide lithologic mapping complementary to UV-VIS-VNIR measurements, especially of Fe-poor lithologies (Sections 3.3.2, 3.3.6). Corresponding surface temperature measurements (Section 5.4.6) are useful to determine lunar surface thermophysical properties of the materials. A TIR imaging spectrometer has not yet been flown to the Moon, and future measurements should include both global mapping with LTM-like properties and targeted thermal infrared imaging spectroscopy.

5.3.3 IMIR Spectroscopy

Between the traditional NIR and TIR wavelength ranges, lies the "cross-over NIR-MIR region" or intermediate infrared (IMIR) (4 to 8 μm), which has recently been shown to provide a strong indicator of olivine and pyroxene solid solution composition. This wavelength region could also be used to readily identify features due to quartz and other silica polymorphs and would provide new insights into global mineralogy and composition (Sections 3.3.2, 3.3.6). The IMIR wavelength region also includes molecular H_2O absorptions near 6 μm and can uniquely identify H_2O to characterize hydration and disambiguate H_2O from OH across the lunar surface (Sections 3.3.7, 3.3.8). Furthermore, this wavelength region appears to be relatively insensitive to space weathering, which can complicate interpretations of VIS-NIR and TIR data. This is a new spectral region for planetary studies for which data have not yet been acquired using spacecraft (Fig. 5.3.3).

A broad range of spectral measurements spanning UV to TIR and including new IMIR measurements at spatial scales better than 50 m (i.e., aiming to improve on current spatial and/or spectral resolution) would enable a new global inventory of surface compositions (Section 3.3.6). As with the other spectral measurements above (Sections 5.3.1, 5.3.2), measurements at scales better than 10 m are needed to assess large boulder compositions and mineralogy

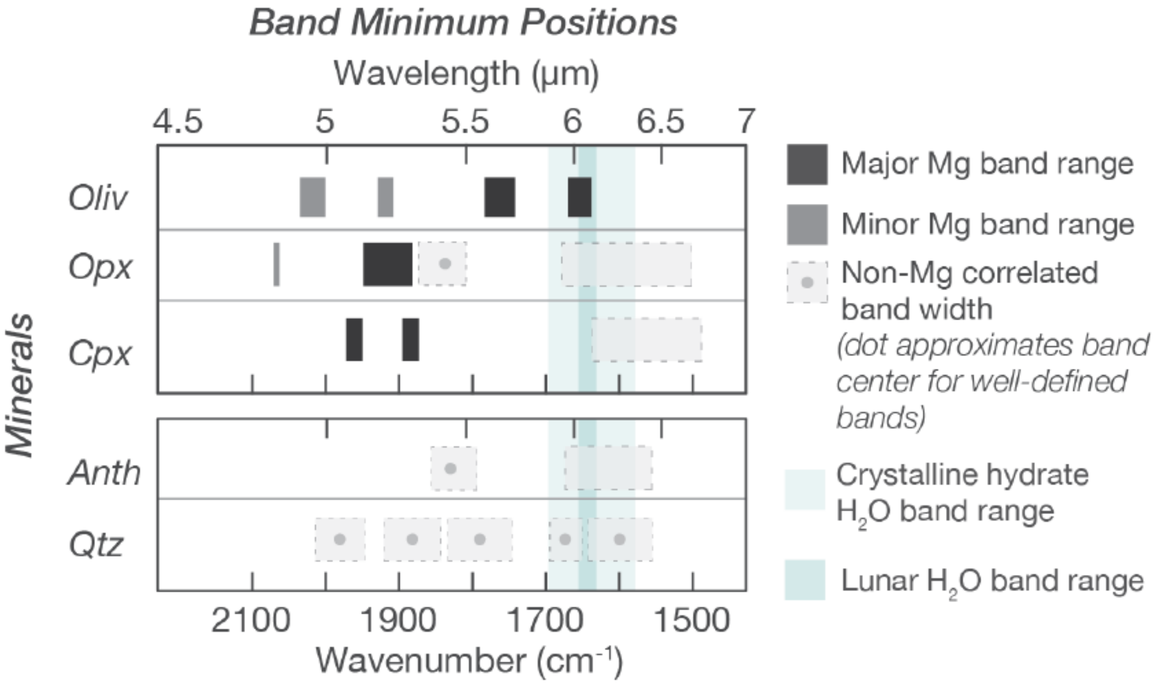


Figure 5.3.3: The IMIR spectral region, which has sensitivities to Mg-Fe variations of major and minor mineralogy and also to volatiles, is well-suited for high spectral resolution measurements from lunar orbit. Credit: Kremer et al. CLOC-SAT White Paper

in the IMIR. Meter-scale measurements from orbit are also highly desirable in spectral ranges spanning the UV to TIR for robotic and human-scale planning and operations on the lunar surface, and for investigating microenvironments. Boulder and human-scale composition and mineralogic information derived from a range of spectral regions, while highly beneficial in planning future missions, also provide key mineralogic and compositional context for localized surface activities and investigations.

5.3.4 Far UV Spectroscopy

Lunar surface volatiles, especially water frost (a potentially accessible science target and resource for use or sample return by humans), would further be quantitatively characterized through ultraviolet (UV) imaging spectroscopy of the lunar surface (Sections 3.3.7, 3.3.8). The Far-UV (FUV) is typically considered the wavelength range from 120 to 300 nm (0.12 to 0.3 μm) and contains the Lyman-alpha feature. An advanced FUV imaging spectrometer would provide higher spatial resolution, increased sensitivity, and more spectral feature resolution than the current LRO LAMP instrument. LAMP data have been used to characterize water frost at the poles, as well as global variations in space weathering and water abundance. New measurement approaches that can retrieve H_2O abundances at the 1 wt% level and in surface thicknesses of 1 μm would be beneficial. Extending coverage to 308 nm would enable a search for OH in the exosphere, plus Mg, Fe, and Si. Far-UV lunar imaging is also complementary to geochemical measurements such as X-ray spectroscopy (XRS) that constrain elemental abundances and composition of the surface (Section 3.3.6).

5.3.5 X-Ray Spectroscopy

Lunar surface chemistry can be characterized through X-ray spectroscopy (XRS). X-ray fluorescence spectrometers have flown on Apollo, Lunar Prospector, SELENE, and Chang'e-2. XRS techniques require sufficient counting statistics to make high signal-to-noise measurements as well as concurrent monitoring of solar X-rays. XRS also requires strong solar activity, and the timing of future XRS instrument deployments should be optimized with the Sun's solar cycle in mind. Very low orbits coupled with technical advances could potentially achieve spatial resolutions of 10 to 30 km scales for major geochemical elements from which major lithologies and mineralogies can be determined (Section 3.3.6).

5.3.6 Gamma Ray and Neutron Spectroscopy

Neutron spectroscopy (NS) provides an independent quantification of hydrogen (H)-abundance, which is

Table 5.3a: Wavelength Ranges and Sensitivities of Spectroscopic Measurements

Short Label	Generic Description*	Wavelength range (approx.)	Sensitivity
UV	Ultraviolet	115 – 340 nm	Water frost; maturity
VIS	Visible	300 – 800 nm	Oxides, sulfur, soil types; maturity
NIR	Near-Infrared	0.7 – 4.0 μm	Mineralogy; maturity, OH
IMIR	Intermediate Infrared	4 – 8 μm	Mineral composition; H_2O
TIR	Thermal Infrared	5 – 100 μm	Mineralogy; H_2O; temperature

*General descriptions of typical wavelength ranges are provided, but in actual use these labels are community-dependent, and often used with deviations from the general description. For example, "UVVIS" often refers to the overlap area between the UV and VIS regions around 300 to 450 nm, but sometimes UVVIS also extends to 1000 nm because of the detector used. Similarly, 'VNIR' is often used to describe a combined VIS and NIR to 2500 nm.

highly complementary to UV-VIS, VIS-NIR, IMIR, as well as other techniques aimed at characterization of OH and H_2O and their mineralogical environments. NS techniques require sufficient counting statistics to make high signal-to-noise measurements. H-abundance maps might be improved to 5 or 10 km scales, by orbiting at lower altitudes than was done for Lunar Prospector (the lowest orbiting NS to date), which would elucidate bulk hydrogen, temperatures, surficial water/OH deposits, and resource potential of many PSRs (Section 3.3.7). Hydrogen abundances could be tied to surface temperature measurements to further investigate the relationships between polar hydrogen and thermal stability. NS measurements of bulk H also provide a depth-dimensionality that can be tied to surficial measurements characterizing OH and H_2O. LunaH-Map (an upcoming cubesat mission) may acquire GRS-NS data at low altitudes, although additional polar coverage and higher statistics are likely beneficial. Thus, additional NS measurements are complementary and desirable, particularly if additional measurements of fast neutrons can provide information about layering and variations in H-abundances with depth.

Gamma ray spectroscopy (GRS) has previously been used to define global lunar terranes and map major elements as well as thorium (Th) and potassium (K) at relatively low spatial resolution up to 0.5 pixel per degree, enabling the detection of geochemical anomalies on the lunar surface (Section 3.3.6). GRS techniques, like NS, also require sufficient counting statistics to make high signal-to-noise measurements. Future GRS measurements could make use of high purity germanium (HPGe) detectors to substantially improve upon the energy resolution and sensitivity of previous measurements, enabling high precision measurements of Mg, Ca, Ti, Si, and Al. In addition, an HPGe sensor would enable measurements of some lower abundance elements including Na, P, Cr, and possibly Mn. For orbital gamma-ray measurements, spatial resolution is directly tied to the spacecraft altitude. The prime Lunar Prospector GRS measurements (H, Th, and Fe) were taken with an average spacecraft altitude of 30 km, resulting in a spatial resolution of ~45 km. All other lunar GRS measurements were taken from an average altitude of 100 km, with a corresponding spatial resolution of ~150 km. Therefore, an HPGe GRS sensor would provide the highest science return from a circular polar orbit of 30 km or lower. A minimum of ~6 months of data accumulation would be required, although longer mission timelines would be desirable.

Additional regional-scale knowledge of compositions, geochemical anomalies, and potential resource deposits coming from GRS and NS data could provide valuable inputs into landing site selections, particularly if planning long-term human activities and resource utilization models. Additional understanding of the abundance and distribution of H_2O in the subsurface and within PSRs is also beneficial to landing site selections, particularly future polar missions.

5.3.7 Active Reflectance Spectroscopy

Orbital laser-based techniques can be used to characterize lunar volatiles and aid in resource characterization using H_2O absorptions, as well as the spectral signatures created by other volatile species (Section 3.3.7). For example, multispectral laser measurements tuned to the 3 μm H_2O/OH-bands could be used to search for surface-exposed H_2O in permanently shadowed regions (PSRs) and transiently shadowed regions (TSRs) and complement VIS-NIR and IMIR spectroscopic data. The single-wavelength LRO LOLA instrument demonstrated the use of active lidar (at 1064 nm) to detect surface reflectance variations in PSRs and TSRs, some of which might be attributed to surface water-ice or frost. Lunar Flashlight was designed to use four laser wavelengths to search for water-ice absorption features at 1.5 and 2 μm. Active laser reflectance at wavelengths tuned to certain mineralogical spectral features with higher spatial scales (e.g., ~1 m) would also aid in the characterization of global composition and lithologies (Section 3.3.6).

Repeat observations using active laser spectroscopy would have the benefit of being independent of solar

TABLE 5.3b: Spectroscopic Compositional Measurements

Measurement	**Objectives**	**Future Mission Support**	**Directorate Relevance**	**Heritage or New**	**Type of Observation**	**Mission-Level Requirements**
FUV spectroscopy	Geochemistry, volatiles, exosphere (Sect. 3.3.6, 3.3.7, 3.3.8)	All, especially context for missions investigating volatiles	PSD, Human	Improve on LAMP measurements	Global or regional	High resolution imaging usually tracks with low altitude and high data rates
UVVIS-VNIR imaging spectroscopy	Mineralogy, volcanism, magmatism, OH, space weathering, resources, mission planning (Sect. 3.3.2, 3.3.5, 3.3.6, 3.3.7, 3.3.8)	All, especially context for surface exploration missions	PSD, Human	Improve spatial or spectral resolution over current data sets; provide temporal variations of OH/ H2O data	Global coverage	Higher resolution imaging usually tracks with lower altitude and higher data rates
IMIR imaging spectroscopy	Mineral composition, volcanism, magmatism, H2O, resources, mission planning (Sect. 3.3.2, 3.3.6, 3.3.7, 3.3.8)	All, especially context for surface missions	PSD, Human	New type of measurement at the Moon	Global or regional	High resolution imaging usually tracks with low altitude and high data rates
TIR imaging spectroscopy	Mineralogy, volcanism, magmatism, mission planning (Sect. 3.3.2, 3.3.6)	All, especially context for surface missions	PSD, Human	Improve spatial and spectral resolution over Diviner	Global or regional	High resolution imaging usually tracks with low altitude and high data rates
Active reflectance spectroscopy (lasers)	Mineralogy, volatiles, resources (Sect. 3.3.6, 3.3.7, 3.3.8)	All, especially context for missions investigating volatiles under low illumination	PSD, Human	Multiple wavelengths is a new capability; Improve LOLA 1064 nm data in spatial resolution	Global requires many orbits	Altitude constraints
Active fluorescence spectroscopy	Organics (Sect. 3.3.7)	Context for missions exploring or retrieving organics	PSD, Human	New type of measurement for the Moon	Polar/PSR	Polar orbit, <100 km altitude
XRS	Geochemistry (Sect. 3.3.6)	All	PSD	Improve on current measurements	Local; Global requires many orbits	Altitude constraints, high solar activity for XRS
GRS, NS	Geochemistry, volatiles, resources, mission planning (Sect. 3.3.6, 3.3.7, 3.3.8)	All	PSD, Human	Improve current data available; provide higher spatial resolution	Local; Global requires ≥ 6 mo. of orbits	Altitudes 30 km or lower

illumination and could be used to detect changes over time, including those generated by diurnal volatile behaviors and seasonal changes (Section 3.3.8), as well as robotic or human surface activities. Lasers in these instruments could also make use of retroreflectors on the lunar surface to achieve better than 10 cm ranging precision (Section 5.4.5).

5.3.8 Active Fluorescence Spectroscopy

Decades of airborne measurements of surface and oceanographic organic fluorescence stimulated by visible or UV-wavelength lasers have shown the utility of this method for detection and characterization of organics. This is a potential new method for high sensitivity detection and mapping of organics in regions of permanent shadow or other polar regions (Section 3.3.7). Organics are of interest to future human explorers, including as potential resources for use, or as potentially hazardous components in the local regolith. Organic-bearing deposits are also of high scientific interest and are a high-priority material for eventual sample return.

5.4 Approaches for Surface Geology, Geomorphology and Thermophysics

5.4.1 Imaging of the Surface

Orbital imaging provides one of the best opportunities for surface geology characterization while also providing key local, regional, and global context for other missions as well as returned samples. Global mosaics of LROC WAC images are one of the current foundational datasets for the Moon (along with global topography) and are used to reference other data and features. Examples of imaging systems include cameras (monochrome, color, and multiband), spectroscopic instruments, and radar. Imaging is also a foundational data type for geologic mapping and investigations of geomorphologic features such as faults and fractures, impact craters, and volcanic materials (Sections 3.3.2, 3.3.3, 3.3.4). Reflectance and albedo from optical cameras have also provided key insights into soil maturity and space weathering and surface composition (Sections 3.3.5, 3.3.6). Very sensitive detectors and long exposure times can also allow imaging using secondary illumination in dark polar areas, including TSRs and most PSRs (Section 3.3.7).

Additional imaging of the lunar surface at sub-meter scales (e.g., 30 cm) is highly desirable to facilitate identification of roughly m-scale hazards that are often relevant to finding safe landing sites (Fig. 5.4.1). As an example, the Chandrayaan-2 Orbiter High Resolution Camera (OHRC) has a nominal pixel scale of 30 cm from a 62 km altitude orbit. Autonomous capabilities to land safely and accurately might require real-time onboard high resolution imaging or laser altimetry (lidar) processing (Section 5.4.5) and/or preloaded, preflight orbital data. Orbital sub-meter scale images could also be used to test hazard-tolerant landing systems and avoidance technologies.

Pairs of images with different viewing angles can also be used to generate high resolution topography from images at scales that depend on the input images, a technique that complements topography from laser altimetry. LROC NAC images currently provide some of the most abundant high resolution topography of

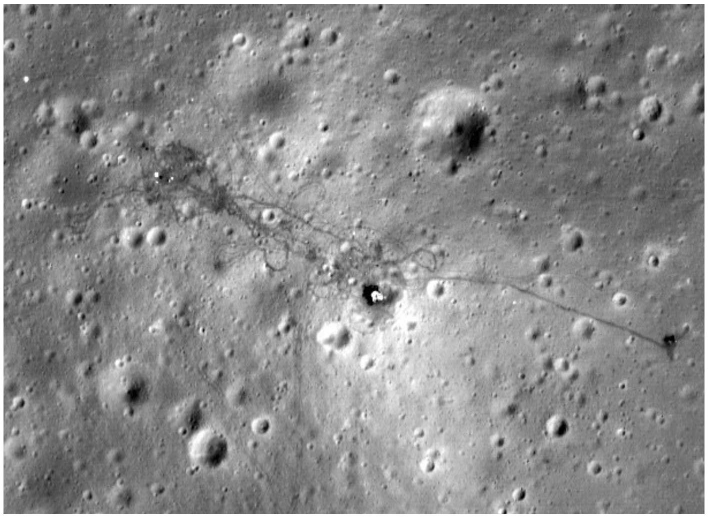


Figure 5.4.1: LROC NAC sub-meter imaging of the Apollo 15 landing site. This image, which was taken at 41 cm per pixel illustrates the utility of sub-meter surface imagery. Routine images at ~10 cm per pixel would significantly enhance the detailed planning of surface operations. [LROC NAC M175252641LR]

the Moon at 2 to 5 m scales using photogrammetric methods (from 0.5 to 1.2 m scale input image pairs). Photogrammetrically derived LROC WAC topography (sampled to 100 m per pixel) complements laser altimetry-derived topography from LOLA (Section 5.4.5), which has been interpolated between sampling points and tracks.

High resolution images (from framing or line scanning cameras) and derived topography are also very useful in planning surface operations for human and robotic activities, identification of science targets for in situ study and sample returns, and for operational plans and assessments of terrain including trafficability, hazards, and operational limitations. Very high resolution images (e.g., 10 cm pixel scales) could also be used for human and robotic surface activities (e.g., location reference, planning, and mapping). To achieve fine-scale precision of topographic models prepared from line-scanning cameras, spacecraft jitter needs to be characterized or mitigated.

5.4.2 Radar Imaging

Radar images provide information about geomorphology (Sections 3.3.2, 3.3.3), composition (Section 3.3.6), presence of ice (Section 3.3.7), and surface roughness and regolith (Section 3.3.5). For example, LRO Mini-RF provides S-band (12.6 cm) and X-band (4.2 cm) synthetic aperture radar (SAR) views of many locations on the Moon in monostatic and bistatic configurations. Pixel scales range from 30 m to ~150 m, nominally. Global radar and polarimetric parameter maps of Mini-RF S-band data (i.e., mosaics of early mission monostatic observations) are available at 128 pixels per degree. Chandrayaan-2 Dual Frequency Synthetic Aperture Radar (DFSAR) also seeks to image in L- and S-bands at pixel scales spanning 2 to 75 m (L-band ~24 cm).

Higher frequency (short wavelength) polarimetric SAR observations in multiple wavelengths, including P- (70 cm), L- (24 cm), and S- (12.5 cm) bands, can be used together in combined studies to investigate different depths within the subsurface. Measurements focused on shallow depths of 5 to 10 cm can be applied to characterize to diurnal skin depths, ilmenite (titanium) content, and near-surface ice contents. Ilmenite, water (particularly when found in glassy pyroclastic deposits), and water-ice are all potential resources of interest to future exploration. These depths are complementary to TIR measurements of the upper surface and other remote sensing instruments. Additional measurements that seek to improve on current radar coverage, its spatial resolution, or range of wavelengths and depths sensed are desirable. Orbital radar measurements in different bands complement other measurement approaches, as well as provide context and subsurface information that can feed into exploration site planning. Additional bistatic observations (with viewing geometry between the Moon and Earth, for example) might be useful to further constrain phase angle variations of different deposits and search for ice.

5.4.3 Repeat Images for Surface Changes

Repeated high spatial resolution visible/optical imaging and interferometric synthetic aperture (InSAR) are techniques that can be used to measure small-scale geophysical, albedo, or chemical surface changes over time in the present day.

Because the Moon is tectonically active, orbital measurements of surface features associated with tectonic processes enable characterization of those processes and provide new information about the lunar interior (Section 3.3.3). Additionally, quantifying the current tectonic activity, including identifying zones of high activity, are important to understanding and defining potential tectonic hazards to surface missions.

InSAR may be a powerful tool for measuring surface changes on the Moon. InSAR has revolutionized terrestrial geosciences, enabling a variety of scientific advances–from measuring active slip on faults, inflation/deflation of subsurface melt chambers, damage due to earthquakes, and more. InSAR works by taking two radar images from almost the exact same position in orbit at two different times, and then interfering the two images to quantify displacements in the line-of-sight direction. Since InSAR relies on interference, it provides displacements at the scale of the radar wavelength, which is generally smaller than visible/optical methods, which can provide displacements on the scale of the image pixel. On Earth, InSAR can measure displacements to sub-centimeter precision. At the Moon, InSAR could conceivably be used to look for displacement on faults that have been inferred to be active due to boulder falls, and characterize changes due to small impacts. However, while InSAR is powerful, it has substantial challenges, particularly requiring high data rates and precise orbit knowledge and control.

High-resolution visible/optical imaging at scales of 10s of cm to a few m provides another method to measure and characterize the surface geomorphic expression of tectonic activity on the Moon. Repeat imaging, obtained at nearly the same illumination conditions, of small areas of the surface can be used to detect and measure surface changes over time between the images, at scales comparable to the imaging pixel.

Repeat imaging at regular time intervals can also be used to look for surface changes resulting from impact cratering (Section 3.3.4), informing sizes, velocities, and frequencies of impactors. Topography derived from images of the resulting craters and debris can be used to investigate the impact process itself at new scales. Repeated TIR imaging (Section 5.3.2) can reveal craters with anomalous thermal behaviors indicating they might be recent impacts, and can be used to investigate the structure of newly or recently formed crater ejecta. Repeated imaging after a new change is detected can follow the evolution of that feature over time, including any space weathering or degradation, including landslides (Sections 3.3.3 and 3.3.5). Some landslides might be triggered by endogenic tectonic activity, rather than by impacts. Repeated imaging (or lidar, Section 5.4.5) could also be used to search for visible surface changes in the polar regions, including the formation and loss of surface water frost in PSRs (Section 3.3.8).

Repeat imaging to detect seismic activity, impacts, changes in polar surface deposits, as well as surface changes caused by robotic or human activities are highly relevant to the Artemis program and other future lunar surface exploration activities. In addition, the LGN mission is one of several New Frontiers concept missions recommended by the Decadal Survey. Orbital measurements can support LGN, improve chances of mission success, and enable new science to be done with LGN nodes. By its nature, LGN requires long-term surface operations. These operations would be enhanced with concurrent long-term orbital monitoring for seismically-induced surface changes and/or fault activities (e.g., landslides, boulder tracks, surface displacement) and impact-flash monitoring for impact sources of seismic energy detected by surface instruments.

5.4.4 Real-time and On-Demand Monitoring

LROC NAC images have been used to locate or document most of the historic human activity on the Moon. The high resolution (sub-meter pixel scale) images reveal astronaut footpaths, rover tracks, scientific instruments, and spacecraft debris left on the surface, in most cases more than 50 years ago. This new location context has finally resolved a long-standing discrepancy in composition and maturity measurements tying remote sensing to returned sample analyses from Luna 24 and Mare Crisium. On-demand images of spacecraft debris can also help determine the fate of unresponsive hardware. On-demand imaging is critical to locate rovers or other surface assets, as is acquiring repeat imaging to monitor those sites of activity over time.

Real-time monitoring for meteors and micro-impacts or other debris could inform current impact rates (Section 3.3.4) and could be used for hazard assessments. Real time detection of impact flashes can be used as a warning system to mitigate the secondary cratering hazard. On-demand imaging following astronomical observations of impact flashes at the Moon can help locate the new impact crater.

Coordinated communications between surface systems and other assets (e.g., in cis-lunar space or on Earth) would be used for on-demand support or monitoring of system health and safety, political or regulation purposes, or for communicating activities with the population of Earth. High temporal resolution to enable rapid, frequent, or timely acquisition of images could capture EVA or robotic activities as they occur (or shortly after). Near-to-real-time capability will enable monitoring of human and robotic surface activities so as to record and determine locations visited, paths taken, sequencing of events, and to precisely establish context for any acquired datasets and samples.

5.4.5 Laser Altimetry and Ranging

High-precision laser altimetry (lidar) mapping is another technique that can be used to measure small-scale geophysical surface changes over time in the present day (Fig. 5.4.5). Advances in laser altimetry with very high measurement rates (e.g., swath mapping lidar) could potentially increase spatial sampling to 0.5-m spacing. Precise pointing and geometric knowledge is important for correlating repeat measurements and measuring small changes. Lasers targeting surface retroreflectors can achieve better than 10 cm ranging precision. High spatial sampling and accurate elevation data also enable topographic and geometric corrections of other data including photometric and spectroscopic measurements.

Laser altimetry can be used to develop topographic models of the surface as well as to derive roughness at different length scales greater than the spatial scale of sampling. The current LOLA and LOLA-SELENE global combined models, sampled to 512 pixels per degree (or 60 m at the equator, with vertical accuracy of 3 or 4 m) are the most complete and best controlled. The LOLA-SELENE model combines laser ranging (lidar) with photogrammetrically processed camera images to produce a topographic model. These models are foundational datasets and are currently used to geometrically tie many other datasets together and also are used to correct for topographic effects in many other types of measurements, including spectral, radar, and optical images. They can also be used as initial inputs into shape-from-shading tools that can generate high spatial resolution topography from similar resolution images.

As other datasets improve in spatial resolution, there is a related need for improved spatial resolution of

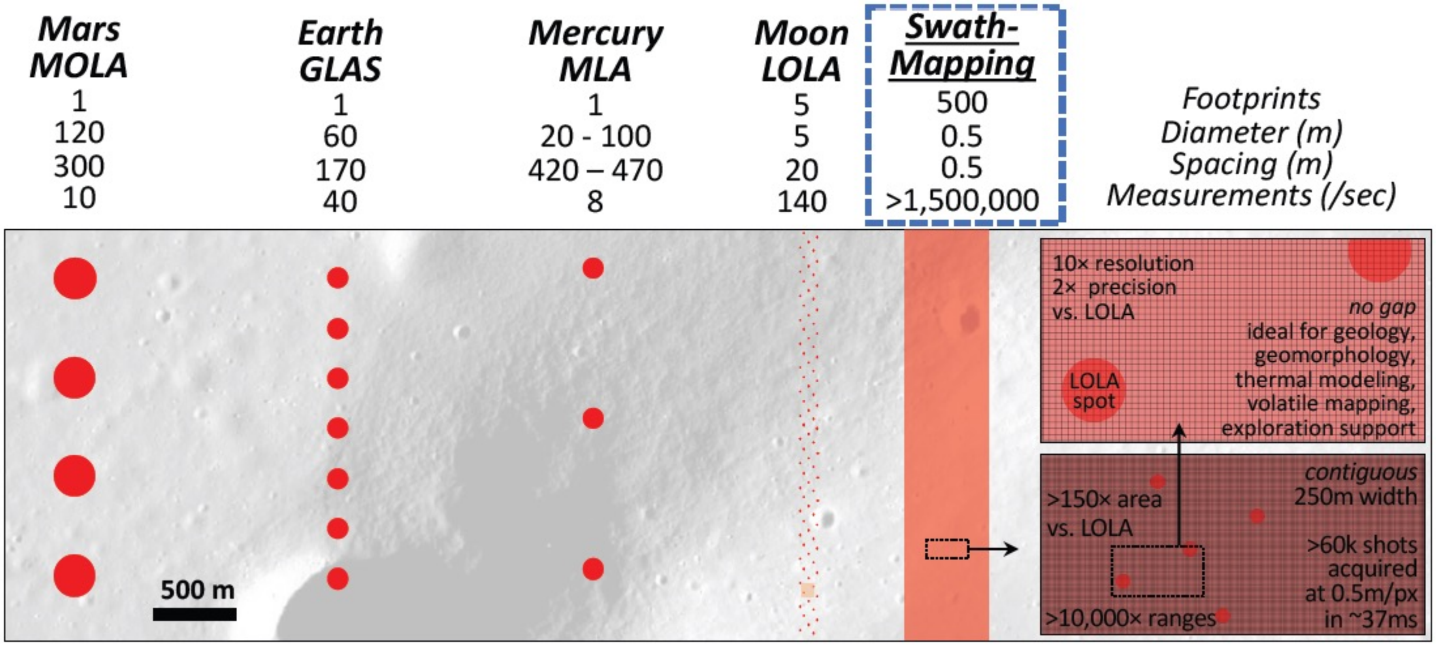


Figure 5.4.5: Comparison of lidar techniques used across the inner solar system. Swath-mapping is a new approach that enables more complete sampling of the surface compared to previous approaches. Credit: Mazarico et al. CLOC-SAT White Paper.

the corresponding topographic information as well. Higher resolution global topography at 5 m to 15 m pixel scales would fill a gap in intermediate resolution, and would be a new foundational data set if carefully controlled. It could fulfill a variety of science objectives either directly or indirectly (by being used to carefully remove topographic effects on data), including many of those highlighted in Section 3, and it could also provide critical intermediate scale topography for landing and descent path planning for future surface missions. Automated landing capabilities might also employ a laser ranging (lidar) system to identify hazards. Orbital data sets could be used to test such systems or could be pre-loaded as onboard data for navigation and descent.

Additional laser ranging opportunities could be used to improve the lunar geodetic grid and surface position knowledge. These are measurements that would increase the accuracy and precision of lunar reference (foundational) data sets, and any data tied to them. The current reference frame (JLP DE 421 in the ME system) is accurate to about 1 to 2 m. Greater levels of accuracy, such as might be desired for future exploration planning (both robotic and human), including accurate and safe landings, updates to the reference frame as well as corresponding updates to any measurements or observations controlled to that frame (e.g., images, radar, and spectral maps) are needed. It can be very effort-intensive to control large quantities of high resolution observations and derived cartographic maps at the fine-scale. Improvements in control also depend on whether absolute or relative accuracy is required at the sub-meter scale.

Laser ranging systems can also provide views into PSRs that are not dependent on solar illumination, and can be used to search for surface ice deposits (Section 5.3.7). Repeated laser altimetry (lidar) measurements can be used to search for visible changes, such as the formation and loss of surface water frost in PSRs, that could indicate volatile activity on daily, seasonal, or yearly timescales (Section 3.3.8).

Additional high-resolution topography to complement or improve on the regional 5-m LOLA polar topographic models of parts of the south polar region are highly desired for both science and exploration objectives. Models with the least interpolation between samples provide the most confidence in knowledge of the terrain. Topographic models are used as inputs into polar illumination models and time-dependent forecasts of illumination that are crucial to planning surface polar missions. Planning surface activities requires evaluations of power generation methods at a site and whether solar technologies are sufficient. Planning for power capabilities (e.g., generation and storage) are needed for lunar nighttime stays and mobile systems as well.

5.4.6 Surface Temperature and Infrared Radiometry

Infrared radiometry is the primary technique used to measure surface and near-surface temperatures and thermophysical properties. By quantifying emitted TIR radiation (typically 5 to 500 μm) from the epiregolith (top mms to cms of regolith), infrared radiometry provides a passive measurement of surface brightness temperature. Because infrared radiometry is an optical technique, spatial resolutions scale with telescope size and can be comparable to UV-VIS-NIR instruments. Importantly, temperatures within these depths are strongly affected by diurnal variations, and observed differences in the warming and cooling properties can be used to infer the subsurface thermophysical properties, including near surface rock abundance and regolith porosity to depths of 10s cms (Section 3.3.5).

Volatile stability is driven by the local thermal environment, with persistent cold temperatures allowing for diffusion timescales greater than 1 Gyr, and additional surface temperature measurements will aid in determining where surface and near-surface volatiles are likely to be found at local scales (e.g., <100 m; Section 3.3.7). In addition to these permanent “cold traps,” transient cold traps may exist that collect natural and anthropogenic volatiles on shorter time-scales, for which additional thermal measurements are needed to temporally resolve

(Sections 3.3.7, 3.3.8). Furthermore, the presence of ice in the subsurface may lead to significant increases in subsurface thermal inertia that could be observed “short-circuits'' in thermal properties across sharp temperature boundaries (e.g. PSR and illuminated terrain) when compared to numerical thermal models.

Along with temperature, infrared radiometry measurements at discrete spectral bandpasses within the TIR allows the inference of useful thermophysical properties such as emissivity, surface rock fraction, and regolith thermal inertia. Infrared radiometry has the potential for high spatial resolution and future developments in this area should focus on exceeding the data spatial, temperature, and temporal resolution of LRO Diviner, which has measured the lunar surface at all local times with spatial resolutions of ~250 to 500 m and minimum detectable temperatures below 25 K. These improvements would enable an expanded understanding of surface environments with particular relevance to determining processes that create regolith thermophysical variations around young impact craters (Section 3.3.4) and identifying potential volatile resources. Time-dependent models of surface temperatures that will be encountered are crucial for planning future surface missions, especially in polar regions.

Improvements over LRO Diviner’s spatial resolution to 10s m while maintaining or improving the radiometric accuracy and minimum detectable temperatures would allow significantly higher impact to understanding the subsurface properties at scales relevant to future surface missions.

TABLE 5.4 Geomorphology, Geology, and Thermophysical Measurements

Measurement	**Objectives**	**Future Mission Support**	**Directorate Relevance**	**New or Advancement**	**Type of Observation**	**Mission-Level Requirements**
Images (cameras)	Context imaging and foundational data, mission planning, hazards, volcanism, tectonics, impacts, space weathering, composition, polar terrains (Sect. 3.3.2, 3.3.3, 3.3.4, 3.3.5, 3.3.6, 3.3.7)	All	PSD, Human	Improve on LROC and OHRC	Global for mosaics; Localized for ultra-high resolution	Precise position and localization needed; jitter needs to be controlled; high-res and lower altitudes
Radar Imaging	Volcanism, tectonics, impacts, regolith, buried ice, resources, mission planning (Sect. 3.3.2, 3.3.3, 3.3.4, 3.3.5, 3.3.7)	Context for landed missions, Artemis	PSD, Human	Some new wavelengths for the Moon; improve spatial coverage and resolution	Multiple complementary wavelengths; Global and polar/PSRs	Bistatic configuration requires Earth view and coordination
Repeat Observations (cameras, radar, lidar, TIR)	Geophysical, chemical, and albedo surface changes (Sect. 3.3.3, 3.3.4, 3.3.5, 3.3.8)	All surface missions, particularly long-duration missions; LGN support	PSD, Human	Build on LROC temporal imaging	Long-term; Temporal considerations	Precise control needed; high-res and lower altitudes
Real-time or On-Demand Imaging	Location information, impacts, landslides, spacecraft debris (Sect. 3.3.4)	All surface missions	PSD, Human	Build on LROC data set; new images of future surface missions	Targeted	Precise timing and coordination; rapid response to emerging opportunities; real-time req's high data rate
Laser Ranging and Altimetry; Topography	Foundational data set, volcanism and magmatism, impacts, tectonics, volatiles, resources, mission planning, hazards, polar terrains, illumination modeling (Sect. 3.3.2, 3.3.3, 3.3.4, 3.3.7, 3.3.8)	All	PSD, Human	Build on LOLA, SELENE Terrain Camera, and LROC WAC	Global and regional	Altitude constraints; retroreflector observation; coordinated Earth-to-Moon ranging if desired
Surface Temperature and Infrared Radiometry	Volatiles, PSRs, regolith, impacts (Sect. 3.3.4, 3.3.7, 3.3.8)	All surface missions; any future data/models that have temperature dependent values	PSD, Human	Improve on Diviner in spatial, temperature, or temporal resolution	Global, regional, polar/PSR; At several local times and over a diurnal cycle	Altitude constraints; precessing polar orbit for global

5.5 Approaches to Investigate the Subsurface

5.5.1 Radio-Frequency Sounding

Active radar observations at frequencies between 20 and 400 MHz (~75 cm - 15 m) could provide information about depths of ~5 to 100 m that are complementary to existing SAR studies between 400 MHz and 8 GHz (3.75 - 75 cm). These observations could reveal insights into regolith and structure of maria, pyroclastics, impacts, faults and subsurface deformation, subsurface pits and voids, and water ice (Sections 3.3.2, 3.3.3, 3.3.4, 3.3.5, 3.3.7). Lower frequency, deeper investigations that complement or improve on SELENE's Lunar Radar Sounder (at 5 MHz), which revealed structures at up to ~2 km depths, and the Apollo 17 Lunar Sounder Experiment could reveal structures found within parts of the megaregolith. Frequencies between 20 and 40 MHz are ideal for upper regolith characterizations. Orbital radar measurements complement any radar sounding (e.g., ground penetrating radar) made from the lunar surface.

Radio frequency sounding can also use passive wide band receivers that take advantage of natural subsurface R/F pulses induced by extremely high energy cosmic rays. These events occur Moon-wide annually at tens of thousands of random locations. While contiguous maps are not possible, statistical characterization of the upper 10 to 30 m of the regolith, including at the poles, could be carried out.

5.5.2 Microwave Radiometry

Microwave radiometry, a passive technique, with improved spatial resolution over current data sets (i.e., better than 10 km spatial resolution and sensitivity similar to Apollo Heat Flow Experiment measurements) can be used to measure subsurface heat flow from orbit (Section 3.3.1; Fig. 5.5.2). In many ice-free areas, passive microwave radiometry could be used to measure the geothermal gradient of the Moon's regolith at intermediate frequencies (600 MHz to 3 GHz) to reach below diurnal variations. Microwave radiometric measurements at these frequencies can also be used to reconstruct regolith thicknesses and depth to any buried density contrasts, such as rocks or ground ice, within the upper 15 m or so (Sections 3.3.5, 3.3.7). Sampling at several frequencies provides the most information, and owing to the sensitivity of microwaves to ilmenite and buried rocks, these

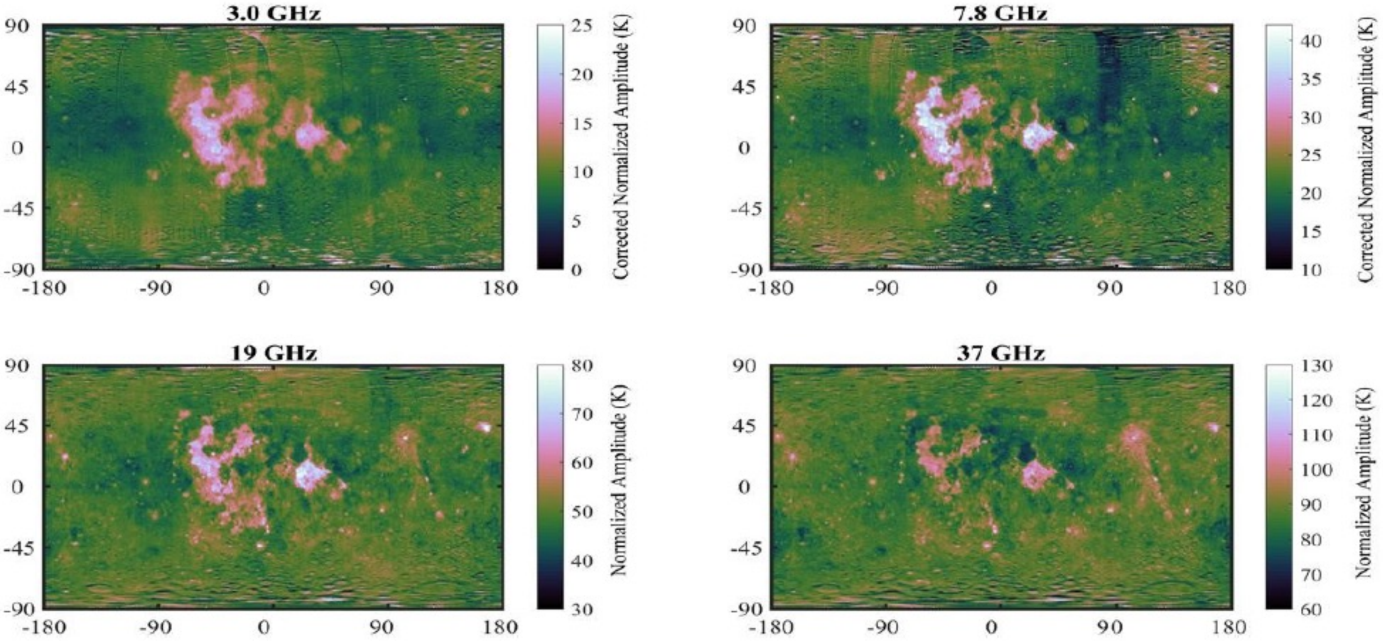


Figure 5.5.2: Comparison subsurface temperature amplitudes (max – min) for different frequencies. Passive microwave radiometry at longer wavelengths could reveal subsurface properties to depths of ~15 m. Credit: Siegler et al. CLOC-SAT White Paper.

measurements can reveal physical properties as well as composition of near-surface materials. In addition, local measurements of crustal heat flow by the proposed LGN nodes would provide pin-point ground truthing for global spatially resolved heat flow measurements acquired from orbit.

5.5.3 Infrared Radiometry for the Subsurface

Infrared radiometry (Section 5.4.6) is another passive technique that can be used to measure shallow subsurface properties. Infrared radiometry measures emitted TIR radiation from the Moon (typically 5 to 500 µm) at depths of < 1 mm to a few cms. For areas that receive negligible direct or reflected illumination over long periods of time (i.e. doubly- or triply- shadowed PSRs) the observed surface temperature is primarily constrained by heat flow from the interior. This measurement is particularly useful since the polar regions are far from the PKT, which has a significant additional crustal heat source from radiogenic isotopes.

In addition, because microwave radiometry does not capture the surface temperature and thus has incomplete information of solar temperature-forcing as a function of time, coordinated infrared data and models are also a critical input into interpreting these deeper temperature depth profiles (Section 3.3.1).

5.5.4 Gravimetry

Gravity measurements from orbital data are utilized to determine subsurface structure and interpret geologic context for impact basins, subsurface mass concentration, bulk crustal density, and models constraining the radius and shape of the lunar core-mantle boundary (Section 3.3.1).They also provide context for landed gravimeter measurements made at specific locations.

GRAIL provided an advanced global lunar gravity model from co-orbiting spacecraft at an altitude of 10s of km, which is currently state-of-the-art. Improvement of the global gravity model is possible with additional measurements from a higher spatial resolution gravity gradiometer flown at low-altitude lunar orbit. The peculiarities of GRAIL's polar orbit means that there is better resolution in the north-south direction than the east-west direction (as the orbits were spaced out in longitude). Non-polar orbits could conceivably "fill in the gaps" with GRAIL's already impressive dataset. Additionally, measuring time-dependent gravity may be a novel technique for probing the Moon's deepest interior (Section 3.3.1). Such measurements would benefit from longer duration missions, plausibly in higher, more stable orbits.

5.6 Findings Related to Measurement Approaches

5.6.1 New and Improved Measurements

We expect that as technology advances, new measurement approaches as well as improvements over existing data sets are possible:

- **Finding 5.6.1a**: There is ample breadth of new orbital measurements that could be made to address a variety of transformative science questions and would be highly beneficial for upcoming human and robotic explorers on the surface.

- **Finding 5.6.1b**: There are valuable new measurement types that have been under development since LRO launched and are poised to make significant advances in our understanding of the Moon from orbit.

- **Finding 5.6.1c**: Appropriate and stable funding for maturation and flight-readiness of orbital instruments and measurements (e.g., DALI and MATISSE programs) are essential to address the breadth of measurements needed for future activities at/on the Moon.

- **Finding 5.6.1d**: Mature instrument designs required to make specific desired measurements will need to develop in-step with orbiter capabilities in power, volume, mass, data, communication, orbital configuration, and any operational or mission-level constraints.

TABLE 5.5: Subsurface Measurements

Measurement	Objectives	Future Mission Support	Directorate Relevance	New or Advancement	Type of Observations	Mission-Level Requirements
Radio-frequency sounding	Volcanism, tectonics, impacts, regolith, buried ice, resources, mission planning (Sect. 3.3.2, 3.3.3, 3.3.4, 3.3.5, 3.3.7)	Context for landed missions, Artemis	PSD, Human	Some new wavelengths for the Moon; improve spatial coverage and resolution	Multiple complementary wavelengths; Global and polar/ PSRs	Altitude
Microwave radiometry	Heat flow, regolith, PSRs and ice (Sect. 3.3.1, 3.3.5, 3.3.7)	LGN, context for landed missions, Artemis	PSD, Human	Improve on Apollo, Diviner, and Chang'E measurements	Global and within PSRs	At several local times and over a diurnal cycle
IR radiometry	Heat flow (3.3.1), Regolith Structure (3.3.5), PSRs and Ice (3.3.7)	LGN, context for landed missions, Artemis	PSD, Human	Improve on Diviner measurements	Global and within PSRs	At several local times and over a diurnal cycle
Gravimetry	Lunar interior (Sect. 3.3.1)	Context for landed gravimeter measurements	PSD	Improve on GRAIL	Global	Mission architecture constraints

- **Finding 5.6.1e**: Next-generation orbital measurements will have significant data return, including high spatial/spectral resolution data, targeted, as well as global coverage, and long-term monitoring, which require effective data management strategies.

5.6.2 Time-Dependent and Time-Variable Measurements

Some measurement approaches would be best served through implementation of long-term ongoing or continuous lunar orbital presence, including measurements that seek to describe time-dependent or time-variable processes and activities:

- **Finding 5.6.2a**: Temporal coverage and repeated observations are highly beneficial to address many new transformative science objectives related to diurnal, seasonal, or yearly variations, and are also desired to monitor and assist surface activities over time.

5.6.3 Improvements in Localization and Spatial Scales

The following findings are related to improvements in localization and spatial scales of measurements:

- **Finding 5.6.3a**: New measurements should improve on existing global, local, and regional datasets, with many of these measurements seeking to improve spatial resolution of data using low-altitude orbits.

- **Finding 5.6.3b**: Many of the highly beneficial improvements sought in spatial resolution also require a corresponding improvement in topographic information to permit corrections for topographic effects at scales similar to or better than the measurements. Global spatial improvements in topography and images, if well controlled, can be new foundational data products for the Moon.

- **Finding 5.6.3c**: Measurements that enable linkages between current and new orbital measurements and groundtruthed properties are highly desired.

- **Finding 5.6.3d**: To achieve fine-scale relative or absolute location accuracy at the human, rover, and rock scales, corresponding improvements in the lunar reference frame are required; however, controlling many large datasets and derived cartographic maps at high accuracy can be an effort-intense process.

6. Summary

Throughout this Report, topical findings have been presented in context for specific aspects of capabilities. Here we take a broader view and provide overarching findings that span investigations, implementation approaches, and measurements. The overarching findings are aggregated into four themes: (1) Lunar Orbital Needs; (2) Science <=> Exploration; (3) Preparing for the Future; and (4) The Next Step.

6.1 Key Overarching Findings

6.1.1 Lunar Orbital Needs:

Continuity of Capabilities

- **Overarching Finding 1:** Continuous lunar orbital capabilities are essential for the U. S. to maintain a leadership role at the Moon during the coming decades of international science and exploration. Plans must be made now to ensure continuity.

As we move forward towards a sustained human presence on the Moon, we enter a period in which continuous science and exploration capabilities are required in lunar orbit. Much in the same way that Earth-observing satellites have defined life-cycles and planned replacements, part of the lunar orbital capability strategy must consider how series of spacecraft are required to provide critical capabilities over time.

Critical Need for Long-lived Integrated Orbiter Capabilities

- **Overarching Finding 2:** The demonstrated value of an LRO-class satellite with diverse instruments operating collaboratively at the Moon is a cornerstone of any science and exploration program that cannot be overstated. Plans for a next generation long-lived integrated orbiter with modern instruments that can replace the highly productive LRO (launched in 2009) are long overdue.

Some measurements and investigations are inefficient to execute on anything other than a larger-scale, highly capable orbital platform designed to last for an extended period of time in an advantageous low-altitude circular orbit. Furthermore, the collaborative environment that can be produced by complementary instruments working together is not easily reproduced with disaggregated approaches. The role that the LRO science team has had in fostering the next generation into the current lunar community has been continuously recognized at every senior review.

Diversity of Implementation Capabilities

- **Overarching Finding 3**: To meet lunar science and exploration orbital needs through the next decades, diverse orbits and implementation approaches ranging from small exploratory satellites to long-lived LRO-class satellites will be required. A single LRO-class satellite is unlikely to meet all science and exploration orbital needs alone.

A single LRO-class satellite is not enough to meet science and exploration needs. NASA should continue using a variety of implementation methods. These plausibly range from larger orbiters that address many different needs to smaller missions with narrowly focused science or exploration investigations. These missions could be implemented through a mix of competitive proposals (e.g., SMD's SIMPLEx and Discovery programs) and directed missions within an integrated lunar science and exploration strategy. A diversity of implementation approaches within the strategic framework is critical to provide programmatic efficiencies required to execute an integrated lunar strategy.

6.1.2 Science <=> Exploration:

Landing-Site-Scale Capabilities

- **Overarching Finding 4:** A variety of very high spatial resolution observations (~1 m-scale) are essential for characterizing landing sites and surroundings and monitoring temporal variations as exploration activities expand. To best support active crewed and robotic surface operations, these observations should also have capabilities for high temporal resolution.

Additional orbital measurements with spatial resolutions optimized for landing site scales would provide highly beneficial information addressing critical observation gaps between orbital-, lander-, rover-, human-, and individual rock-scales. At a few-meters scale or better, these data can address fundamental science questions tying regional to local and rock scale interpretations and facilitate or lower risk for future missions. In addition, very high spatial resolution (~10 cm/pixel) visible images and topographic datasets (not just those derived from imagery but also from LiDAR or radar) are needed for planning surface operations, including identification of science targets, traverse planning, and hazard / traversibility assessment. Furthermore, if high-resolution observations can be acquired with a rapid repeat cadence, near-real-time monitoring of surface operations (robotic and human) would be enabled. For example, it would be possible to track where surface assets or crew went during an EVA in time to make appropriate adjustments to future EVAs, to give context to field data/samples soon after they are collected, or to enable higher precision/accuracy of positioning/navigation and other cartographic needs in an actionable timeframe.

Global Context Capabilities

- **Overarching Finding 5:** High-quality global-scale data provide valuable context for addressing science questions and long-term mission planning. As modern orbital instruments are flown and global data for exploration and science investigations returned, new insight into, and understanding of, planetary-scale issues will result from orbital studies of the whole Moon.

Additional orbital measurements that are uniquely suited to providing the comprehensive global context are critical to making further evaluations of science questions related to surface geology, geomorphology, and composition of both regolith and volatiles. Critically, global and regional context is also enabling for mission planning and when choosing destinations for focused surface science and exploration or sample return.

Long Temporal-Baseline Capabilities

- **Overarching Finding 6:** Long temporal-baseline measurements enable critical monitoring of the surface and exosphere, including the effects of both natural and anthropogenic activities.

Understanding the dynamic Moon requires long temporal baseline measurements. Continued long-term monitoring (e.g., decadal-scale) measurements and imaging of the lunar surface would enable transformative new investigations 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, surface temperature, regolith chemistry, exosphere behavior, radiation, and space weather. Temporal measurement capabilities may include on demand observations, repeated observations (with similar and different surface viewing conditions), and measurements that target specific surface local times.

6.1.3 Preparing for the Future:

Next Generation of Orbital Capabilities

- **Overarching Finding 7:** A new generation of technologies in spacecraft, instruments, and communications is emerging that can provide breakthrough capabilities to advance our knowledge of the lunar surface and exosphere and to enable robust communication and navigation support for assets on the surface and cis-lunar space. Technology development programs are essential to continue the development of advanced orbital instruments and spacecraft capabilities.

Since LRO was launched in 2009, progress in spacecraft and instrument technologies has enabled advanced capabilities for a new orbiter within the same mission class. There are many compelling, new measurement types, including laser reflectance spectroscopy, ultraviolet through thermal infrared spectroscopy, microwave radiometry, and radar sounding, that have the potential to address multiple transformative investigations across different scientific themes. Observing the Moon across these unexplored wavelengths has the potential to address a variety of transformative science questions, from probing the Moon's heat flow to the three-dimensional structure of the uppermost crust, composition of the surface, and spatial distribution of volatiles. While some of these capabilities will be featured on upcoming missions, a comprehensive combination of modern spacecraft and instrument capabilities addressing the needs identified in this report is not planned. These next-generation lunar orbiters will address high priority science and exploration needs for the decades ahead.

New technologies in spacecraft, instruments, and communications with breakthrough capabilities related to (or in support of) science and exploration require pathways to maturation, demonstration and flight. NASA should continue to support development of instruments for next-generation lunar orbiters. Leveraging a large number of opportunities to reach cis-lunar space and a higher risk tolerance could allow the technologies to advance at the rapid rates.

Data Downlink and Access Capabilities

- **Overarching Finding 8:** Lunar surface and orbital data acquisition and relay are not severely constrained by transmission distance, therefore robust data throughput (data rate) must become standard at the Moon in order to realize the potential of next-generation instrumentation. A holistic strategy for processing and archiving these large data sets is also needed.

Reliable high-rate downlink is an enabling capability for both science and exploration. Reliable communications relay from the lunar surface or cis-lunar space are a foundational capability required to support a sustainable lunar presence and the pathfinding missions already under development. Furthermore, modern instruments provide multiple channels with high precision and high resolution, resulting in orders of magnitude larger data volumes than those currently and previously acquired at the Moon.

Given the expectation for vast new volumes of data from the Moon, it is critical that plans for archiving and sharing these data be established and reviewed by the community of data producers and data users at regular intervals.

6.1.4 The Next Step:

Orbital Capabilities as Part of an Integrated Lunar Strategy

- **Overarching Finding 9:** An integrated lunar strategy should include a robust orbital remote sensing component to ensure maximum return from surface exploration and scientific activities. Appropriate and necessary orbital capabilities should be brought to bear on timelines that maximize their value to science and exploration.

Orbital lunar assets provide critical capabilities in support of surface science and exploration activities. A comprehensive lunar strategy should be developed, including plans for how multiple landers and orbiters can build on each other synergistically, to support addressing priority science, while also providing the necessary infrastructure for surface operations.

Orbital capabilities are a critical component of an integrated lunar strategy. Next-generation lunar orbiters could substantially enhance prioritized science and exploration surface missions, including VIPER, CLPS missions, and crewed Artemis missions. Additionally, planning for future surface missions (e.g. Endurance-A, Lunar Geophysical Network, and future CLPS missions) will require new orbital observations;

unique new measurements could have a substantial impact on site selection and traverse planning. Furthermore, many missions require operations on the lunar farside, and next-generation lunar orbiters may be enabling assets for infrastructure, including communications relay capabilities, and monitoring of surface activities.

6.2 Path Forward

This document establishes community input for lunar orbital capabilities and provides details required to evaluate a broad range of science and exploration needs and applications. The next steps are for stakeholders to consider the content of this report and plan to move forward. It is our intent that program strategists use these findings to connect lunar orbital capabilities to specific near- and long-term goals and activities within an integrated lunar strategy. Investigation teams should use these inputs to hone their investigations within a broad new context. Private industry should use these inputs to identify the recurring themes and potential new opportunities providing not just infrastructure but also data acquisition services to government agencies and the interwoven science community. All involved should recognize the importance of Earth-Moon communications links for every type and scale of effort. Indeed, this is an exciting and continuous process of science and exploration of Earth's nearest neighbor.

Appendices

- *Appendix 1: Acknowledgements*
- *Appendix 2: List of All Findings*
- *Appendix 3: List of Acronyms*
- *Appendix 4: Glossary*
- *Appendix 5: References*
- *Appendix 6: Alphabetical List of White Papers*
- *Appendix 7: CLOC-SAT TOR*

Appendix 1: Acknowledgements

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Community Kickoff Presentations

- Maria Banks
- Bradley Jolliff
- Clive Neal
- Angela Stickle

Feedback on Preliminary Findings

- Bill Bottke
- Kieran Carroll
- Caleb Fassett
- Cesare Grava
- Samuel Lawrence
- Alfred McEwen
- Andrew Poppe
- Parvathy Prem
- Jacob Richardson
- Tom Watters

Feedback on Draft Report

- Brent Archinal
- Kieran Carroll
- James Garvin
- Jasper Halekas
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- David Folta
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Appendix 2: List of All Findings

Overarching Findings

The 9 overarching findings below are not in a prioritized order:

Lunar Orbital Needs Overarching Findings

- Continuity of Capabilities

  Overarching Finding 1: Continuous lunar orbital capabilities are essential for the U. S. to maintain a leadership role at the Moon during the coming decades of international science and exploration. Plans must be made now to ensure continuity.

- Critical Need for Long-lived Integrated Orbiter Capabilities

  Overarching Finding 2: The demonstrated value of an LRO-class satellite with diverse instruments operating collaboratively at the Moon is a cornerstone of any science and exploration program that cannot be overstated. Plans for a next generation long-lived integrated orbiter with modern instruments that can replace the highly productive LRO (launched in 2009) are long overdue.

- Diversity of Implementation Capabilities

  Overarching Finding 3: To meet lunar science and exploration orbital needs through the next decades, diverse orbits and implementation approaches ranging from small exploratory satellites to long-lived LRO-class satellites will be required. A single LRO-class satellite is unlikely to meet all science and exploration orbital needs alone.

Science <=> Exploration Overarching Findings

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  Overarching Finding 4: A variety of very high spatial resolution observations (~1 m-scale) are essential for characterizing landing sites and surroundings and monitoring temporal variations as exploration activities expand. To best support active crewed and robotic surface operations, these observations should also have capabilities for high temporal resolution.

- Global Context Capabilities

  Overarching Finding 5: High-quality global-scale data provide valuable context for addressing science questions and long-term mission planning. As modern orbital instruments are flown and global data for exploration and science investigations returned, new insight into and understanding of planetary-scale issues will result from orbital studies of the whole Moon.

- Long Temporal-Baseline Capabilities

  Overarching Finding 6: Long temporal-baseline measurements enable critical monitoring of the surface and exosphere, including the effects of both natural and anthropogenic activities.

Preparing for the Future Overarching Findings

- Next Generation of Orbital Capabilities

  Overarching Finding 7: A new generation of technologies in spacecraft, instruments, and communications is emerging that can provide breakthrough capabilities to advance our knowledge of the lunar surface and exosphere and to enable robust communication and navigation support for assets on the surface and cis-lunar space. Technology development programs are essential to continue the development of advanced orbital instruments and spacecraft capabilities.

- Data Downlink and Access Capabilities

  Overarching Finding 8: Lunar surface and orbital data acquisition and relay is not severely constrained by transmission distance, and robust data throughput (data rate) must become standard at the Moon in order to realize the potential of next-generation instrumentation. A holistic strategy for processing and archiving these large data sets is also needed.

The Next Step Overarching Finding

- Orbital Capabilities as Part of an Integrated Lunar Strategy

  Overarching Finding 9: An integrated lunar strategy should include a robust orbital remote sensing component to ensure maximum return from surface exploration and scientific activities. Appropriate and necessary orbital capabilities should be brought to bear on timelines that maximize their value to science and exploration.

Topical Findings

The 69 topical findings below are presented in the order of the report and are not prioritized:

Chapter 3 - Science and Exploration Objectives and Needs

3.3.1 The state and evolution of the interior of the Moon

- **Finding 3.3.1a**: Global, high-resolution (~10 km) measurements of heat flow are required to understand the geophysical evolution, structure, and composition of the Moon, and to place ground truth measurements into global context.
- **Finding 3.3.1b**: Regional heat flow measurements at the poles are required to support interpretation of Artemis III and other surface polar data, and to better understand the distribution of buried ice.
- **Finding 3.3.1c**: Time-dependent gravity measurements may provide a unique method for probing the Moon's core, complementary to landed geophysical measurements.

3.3.2 Lunar Volcanism and Magmatism

- **Finding 3.3.2a**: Determining the nature of irregular mare patches would better constrain the thermal evolution of the Moon.
- **Finding 3.3.2b**: Additional measurements should be undertaken to complete detection and mapping of mare pits and lava tube distribution to better understand the utility of these features to future exploration activities and astronaut habitation.
- **Finding 3.3.2c**: Increased spectral and imaging resolution is required to characterize localized pyroclastic deposits, map new deposits along known fractures and determine their hydration states.
- **Finding 3.3.2d**: Thermal-infrared imaging spectroscopy and high spatial resolution GRS measurements are required to fully characterize the compositions and distribution of silicic features on the Moon.

3.3.3 Lunar Tectonics

- **Finding 3.3.3a**: Measurements of accumulating stress should be carried out to understand the contemporary tectonic environment and better characterize the seismic hazard.
- **Finding 3.3.3b**: Detection of mass wasting events as a result of ongoing lunar seismicity should be continued.

3.3.4 Understanding the Impact Process

- **Finding 3.3.4a**: Direct detection of new impacts as they occur can enable characterization of the impact process as it develops, and constrain the composition of the impactors through flash spectroscopy.
- **Finding 3.3.4b**: Continuous monitoring at the >1 m-scale is required to refine the measurements of the primary and secondary flux and detect new impacts at the <<1 m-scale.
- **Finding 3.3.4c**: Real time detection of impacts can provide a direct measurement of the secondary impact hazard for surface operations.
- **Finding 3.3.4d**: Determination of the secondary impact rate at << 10-m scale is required to understand the relationship between secondaries and primaries, and to define impact hazards.
- **Finding 3.3.4e**: Additional measurements are required to constrain the unknown formation process of cold spot formation, a fundamental product of lunar impact cratering that fades on the scale of 1 Ma.

3.3.5 The Lunar Regolith and Space Weathering

- **Finding 3.3.5a**: Mapping the structure and composition of the regolith and the upper megaregolith can improve our understanding of how the Moon has responded to the cratering flux.
- **Finding 3.3.5b**: Characterizing the products of chemistry in the lunar surface with generalized mineralogic sensors extends the understanding of the range of potential reactions that may occur, and provides constraints on what reactions are possible.
- **Finding 3.3.5c**: Newly discovered compounds may provide resources for ISRU, such as carbon at the poles, and recoverable water in hydrated iron oxides.
- **Finding 3.3.5d**: Remote characterization of surface physical properties can improve landing site selection, resource evaluation, and siting of exploration infrastructure.

3.3.6 The composition of the Moon through the lens of its surface deposits

- **Finding 3.3.6a**: Significantly improving the resolution of geochemical sensing (e.g. Th, K/Th, Mg/Fe ratios) to <30 km globally, and locally to 10 km resolution will result in significant advancements.
- **Finding 3.3.6b**: Completing the compositional inventory of the Moon with high quality contiguous global compositional measurements at <50 m resolution is essential to ensure the mineralogic diversity of the Moon is captured and documented.
- **Finding 3.3.6c**: Direct measurements of the compositional nature of the lunar mantle through detection and characterization of ultramafic lithologies at ~10 m scale would place strong constraints on models of the evolution of the lunar interior and provide high value candidates for in situ investigation or sample return.
- **Finding 3.3.6d**: Compositional imaging of the Moon at ~1-10 m or resolution is a priority to support surface operations.

3.3.7 Special Polar Region Environments

- **Finding 3.3.7a**: Key measurements enabling a more complete global assessment and monitoring of hydrogen-species, other volatiles, and organics on and below the lunar surface are vital for understanding the lunar volatile system as well as the sources of volatiles.
- **Finding 3.3.7b**: High priority science and exploration objectives remain regarding the distribution of surface and near-surface volatiles. Water-ice, carbon dioxide and potentially hazardous volatiles like HCN should be mapped within all PSR surfaces and surroundings at rover-accessible scales (<100 m) with context of surface temperature and temperature history.
- **Finding 3.3.7c**: Additional integrated measurements of volatiles and organics are also highly beneficial as context for and inputs into resource identification, planning for systems that make use of the Moon's resources, as well as inputs into architectures for surface activities.
- **Finding 3.3.7d**: Neutron measurements of hydrogen with sufficient resolution to resolve larger PSRs would provide key validating measurements for other methodologies, and provide a bridge between the near-surface and more deeply buried volatiles.
- **Finding 3.3.7e**: Measuring the isotopic composition of ejecta lofted into lunar orbit from contemporary natural impacts could provide the isotopic composition of sequestered volatiles.
- **Finding 3.3.7f**: The dynamics of water-ice at diurnal, seasonal and precessional timescales should be characterized with measurements sensitive to abundances well below 1%, ice layer thicknesses much less than 1 μm, and include measurements at the coldest locations.
- **Finding 3.3.7g**: Searches for buried water ice should be conducted to depths of 10 m or greater to test emplacement hypotheses and to address the viability and sustainability of the water-ice resource.
- **Finding 3.3.7h**: Evidence should be sought in the exosphere for volatiles activated by loss mechanisms.
- **Finding 3.3.7i**: The presence and distribution of methane and more complex organics should be evaluated (prior to significant human activity) to define their scientific and resource potential.

3.3.8 The Lunar Volatile System

- **Finding 3.3.8a**: The critical constraint of abundance of water in the exosphere makes confirming and extending beyond the LADEE NMS dataset essential. This should be carried out as soon as is practical before the exosphere is further altered by extensive spacecraft traffic.

- **Finding 3.3.8b**: The three-dimensional structure and temporal behavior of the exosphere should be characterized to understand how water is transported through the lunar environment and measure the effects of human exploration on the exosphere.

- **Finding 3.3.8c**: Exospheric measurements of the abundance and dynamics of volatile species that may result from space-regolith interaction should be carried out, especially CO_2 and ammonia.

- **Finding 3.3.8d**: The temporal behavior of hydration bands observed in the infrared should be characterized with definitive separation of reflected and thermal effects.

- **Finding 3.3.8e**: The abundance, distribution and dynamics of hydroxyl and water molecules should be unambiguously separated and characterized, including nightside abundances.

- **Finding 3.3.8f**: The volatile emissions from lunar exploration should be exploited as controlled experiments in volatile transport, deposition and modification.

3.3.9 Heliosphere and the Lunar Plasma Environment

- **Finding 3.3.9a**: Characterizing the three-dimensional structure of magnetic fields associated with anomalies helps elucidate the relationship between surface anomalies and the heliospheric environment.

- **Finding 3.3.9b**: Additional orbital measurements are necessary for a deeper understanding of the temporal variability of the lunar plasma environment, the solar winds interaction with the Moon, and the response to changing solar wind conditions especially near the terminator, polar environment, and around magnetic anomalies.

Chapter 4 - Implementation Approaches and Architectures

4.2.1 Circular vs. Elliptical Orbits

- **Finding 4.2.1a**: Low-altitude circular orbits are ideal for uniform high resolution measurements but require frequent station-keeping maneuvers and thus large fuel reserves.

- **Finding 4.2.1b**: Transition from circular to a low-cost elliptical frozen orbit should be planned carefully with enough remaining propellant to perform angular momentum adjustments and phasing maneuvers.

4.2.2 Polar vs. Equatorial Orbits

- **Finding 4.2.2a**: Polar orbits provide global coverage over time and are broadly applicable to a wide range of investigations.

- **Finding 4.2.2b**: The benefits of equatorial orbits are generally underutilized. Equatorial orbits can be adopted for rapid repeat (orbit to orbit) coverage over a selected low- to mid-latitude area (as the area rotates under the orbit path) and these orbits provide high local time resolution measurements.

4.2.3 Distant Orbits

- **Finding 4.2.3a**: Distant orbits including orbits around Lagrange Points and Near-Rectilinear Halo Orbits (NRHOs) such as Gateway have characteristics well-suited to support communication infrastructure.

- **Finding 4.2.3b**: Although most orbital science objectives will require low altitude orbits, distant orbits typically have low fuel maintenance requirements and are uniquely enabling for long-duration missions that monitor broad areas of the Moon or the cis-lunar environment.

4.3.1 Larger Spacecraft

- **Finding 4.3.1a**: An LRO-class orbiter with state-of-the-art instrumentation is needed for long term coverage of the Moon with coordinated new and improved measurements.

- **Finding 4.3.1b**: A systematic replacement program is important to take advantage of technical advances and to enable new discoveries to be addressed.

4.3.2 Medium Spacecraft

- **Finding 4.3.2a**: Intermediate-scale orbiters (e.g. LADEE, GRAIL, and Lunar Trailblazer) are well-suited for focused, often shorter-duration investigations that address compelling scientific objectives using the most advanced and capable instrumentation.

4.3.3 Smaller Spacecraft

- **Finding 4.3.3a**: Cubesats (e.g. LunaH-Map and Lunar Flashlight) and other small platforms are relatively low-cost with rapid development cycles, enabling higher risk tolerance, high payoff investigations, and novel architectures such as constellations, tethered pairs, and other configurations addressing unique science.

4.4.1 Communications

- **Finding 4.4.1a**: Lunar surface and cis-lunar vicinity communications must be planned and supported to advance science and exploration objectives.

- **Finding 4.4.1b**: Development of advanced, high data rate communication (e.g. laser-based, internet in space) should be actively pursued.

- **Finding 4.4.1c**: Measurement and communication strategies should be implemented that are compatible with lunar farside radio astronomy opportunities.

4.4.2 Navigation

- **Finding 4.4.2a**: No additional refinement of the lunar gravity field is currently necessary for navigation purposes (although science advancements through high spatial resolution gravity measurements are possible).

- **Finding 4.4.2b**: Improved geolocation technology can assist surface operations. In the long term, global positioning satellites will enable precise (m-scale) location information for any asset on the Moon.

4.5.1 Multi-Mission Operations

- **Finding 4.5.1a**: Multi-mission operation centers should be evaluated for potential cost savings and improved communications across missions.

4.5.2 Agencies and Entities

- **Finding 4.5.2a**: Establishment of a single office or point person tasked with coordinating across space agencies and within NASA for sharing resources and optimizing science return from the Moon and cis-lunar environment should be considered.

4.6 Planetary Data System (PDS) and Data Management Strategies

- **Finding 4.6a**: The Planetary Data System must be appropriately scaled over time to accommodate the expected increases in data returned from the lunar surface and orbit.

- F**inding 4.6b**: New and existing data sets should be registered to a common, improving framework based on the highest accuracy topographic maps available.

Chapter 5 - Measurement Approaches

5.6.1 New and Improved Measurements

- **Finding 5.6.1a**: There is ample breadth of new orbital measurements that could be made to address a variety of transformative science questions and would be highly beneficial for upcoming human and robotic explorers on the surface.

- **Finding 5.6.1b**: There are valuable new measurement types that have been under development since LRO launched and are poised to make significant advances in our understanding of the Moon from orbit.

- **Finding 5.6.1c**: Appropriate and stable funding for maturation and flight-readiness of orbital instruments and measurements (e.g., DALI and MATISSE programs) are essential to address the breadth of measurements needed for future activities at/on the Moon.
- **Finding 5.6.1d**: Mature instrument designs required to make specific desired measurements will need to develop in-step with orbiter capabilities in power, volume, mass, data, communication, orbital configuration, and any operational or mission-level constraints.
- **Finding 5.6.1e**: Next-generation orbital measurements will have significant data return, including high spatial/spectral resolution data, targeted, as well as global coverage, and long-term monitoring, which require effective data management strategies.

5.6.2 Time-Dependent and Time-Variable Measurements

- **Finding 5.6.2a**: Temporal coverage and repeated observations are highly beneficial to address many new transformative science objectives related to diurnal, seasonal, or yearly variations, and are also desired to monitor and assist surface activities over time.

5.6.3 Improvements in Localization and Spatial Scales

- **Finding 5.6.3a**: New measurements should improve on existing global, local, and regional datasets, with many of these measurements seeking to improve spatial resolution of data using low-altitude orbits.
- **Finding 5.6.3b**: Many of the highly beneficial improvements sought in spatial resolution also require a corresponding improvement in topographic information to permit corrections for topographic effects at scales similar to or better than the measurements. Global spatial improvements in topography and images, if well controlled, can be new foundational data products for the Moon.
- **Finding 5.6.3c**: Measurements that enable linkages between current and new orbital measurements and groundtruthed properties are highly desired.
- **Finding 5.6.3d**: To achieve fine-scale relative or absolute location accuracy at the human, rover, and rock scales, corresponding improvements in the lunar reference frame are required; however, controlling many large datasets and derived cartographic maps at high accuracy can be an effort-intense process.

Appendix 3: Acronyms and Abbreviations Used in this Report

A III SDT	2020 Artemis III Science Definition Team
Artemis	NASA'S Artemis Program
ARTEMIS	Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun (an operating flight mission, not to be confused with Artemis)
ASM-SAT	2018 LEAG Advancing Science of the Moon Specific Action Team
CAPSTONE	Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment
CF	Christiansen feature
CLOC-SAT	Continuous Lunar Orbital Capabilities Specific Action Team
CLPS	Commercial Lunar Payload Services
CRaTER	Cosmic Ray Telescope for the Effects of Radiation
Decadal Survey	2022 NASEM Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032
Diviner	Diviner Lunar Radiometer Experiment
DRO	Distant Retrograde Orbit
EVA	Extravehicular activity
FUV	Far ultraviolet
GCR	Galactic cosmic ray
GER	Global Exploration Roadmap
GNSS	Global Navigation Satellite System
GPR	Ground penetrating radar
GRAIL	Gravity Recovery and Interior Laboratory
GRNS	Gamma ray and neutron spectroscopy
GRS	Gamma ray spectroscopy
HCN	Hydrogen cyanide
IMIR	Intermediate infrared
IMP	Irregular Mare Patches
InSAR	Interferometric Synthetic Aperture Radar
ISRU	In Situ Resource Utilization
ITT	Investigation Traceability Tensor (see Table 2.2)
JAXA	Japan Aerospace Exploration Agency
KREEP	potassium, rare-earth elements, and phosphorus
LADEE	Lunar Atmosphere Dust and Environment Explorer
LAMP	Lyman Alpha Mapping Project
LCROSS	Lunar Crater Observation and Sensing Satellite
LEAG	Lunar Exploration Analysis Group
LEND	Lunar Exploration Neutron Detector
LER	2016 LEAG Lunar Exploration Roadmap
LET	Linear Energy Transfer
LGN	Lunar Geophysical Network
LiDAR	Light Detection and Ranging
LLO	Low Lunar Orbit
LOLA	Lunar Orbiting Laser Altimeter
LRO	Lunar Reconnaissance Orbiter
LROC	Lunar Reconnaissance Orbiter Camera
LROC NAC	Lunar Reconnaissance Orbiter Camera Narrow Angle Camera
LROC WAC	Lunar Reconnaissance Orbiter Camera Wide Angle Camera

LTM	Lunar Thermal Mapper
LuGRE	Lunar GNSS Receiver Experiment
MRO	Mars Reconnaissance Orbiter
MTT	Measurement Traceability Tensor (see Table 2.3)
NAC	Narrow Angle Camera
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Sciences, Engineering, and Medicine
NIR	Near infrared
NMS	Neutral Mass Spectrometer
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NRHO	Near Rectilinear Halo Orbit
NS	Neutron spectroscopy
OHRC	Orbiter High Resolution Camera
PDS	Planetary Data System
PKT	Procellarum KREEP Terrane
PNT	Positioning, Navigation, and Timing
PRISM	Payloads and Research Investigations on the Surface of the Moon
PSD	NASA Planetary Science Division
PSR	Permanently Shadowed Region
SAR	Synthetic Aperture Radar
SCAWG	Space Communication Architecture Working Group
SCEM	2007 NRC The Scientific Context for Exploration of the Moon
SELENE	SELenological and ENgineering Explorer “KAGUYA”
SEP	Solar energetic particle
STM	Science Traceability Matrix
STMD	NASA Space Technology Mission Directorate
TEM	Transmission electron microscopy
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TIR	Thermal infrared
TOR	Terms of Reference
TSR	Transiently shadowed regions
UV	Ultraviolet
UVVIS	Ultraviolet and visible
VIPER	Volatiles Investigating Polar Exploration Rover
VIS	Visible
VNIR	Visible and near-infrared
WAC	Wide Angle Camera
XRS	X-ray spectroscopy

Appendix 4: Glossary of Measurement Techniques

Cosmic ray spectroscopy – utilizes natural subsurface wide band radio emission from extremely energetic cosmic rays to probe the upper few tens of m using passive wide-band receivers in orbit to detect subsurface reflectors such as ice or regolith layers.

Energetic neutral atom **(ENA)** analyzer – measures reflected solar wind and sputtered neutral atoms and molecules from 10 eV to 30 keV

Gamma ray and neutron spectroscopy **(NRNS)** – measures neutron and gamma ray emission arising from nuclear fission and cosmic ray spallation collisions

X-ray spectroscopy **(XRS)** – measures x-ray fluorescence from inner electron shell excitation of surface elements

Far UV **(FUV)** – radiation over wavelengths from ~50 nm to 300 nm, commonly measured as reflected radiation. Sensitive to lunar soil types and H_2O.

Ultraviolet **(UV)** – radiation over wavelengths from ~300 nm to 400 nm, commonly measured as reflected radiation.

Visible **(VIS)** - radiation over wavelengths from ~400 nm to 700 nm, measured as reflected radiation.

Ultraviolet/Visible **(UVVIS)** - extended spectral region (0.3 to 1 μm) measured as reflected radiation and widely used for multi-spectral imaging. Sensitive to lunar soil types and maturity.

Visible near-infrared **(VNIR)** - radiation over wavelengths from ~400 nm to 2500 nm, measured largely as reflected radiation.

Active reflectance spectroscopy – a technique to determine surface reflectance by measuring the returned power (relative to transmitted) of a VNIR laser. By including multiple laser wavelengths, a reflectance spectrum can be acquired that is useful for mapping surface volatiles or mineralogy. Particularly well-suited for low solar lighting conditions such as at the lunar poles.

Near-infrared **(NIR)** - radiation over wavelengths from ~700 nm to 4000 nm (0.7 - 4 μm). Measurements can include reflected radiation and thermal emission, depending on temperature of the surface. Continuous spectra (100s channels) contain diagnostic electronic transition absorptions of several minerals and molecular absorptions of OH/H_2O.

Intermediate infrared **(IMIR)** spectroscopy - continuous spectra (100s channels) covering wavelengths from 4 to 7 μm measured largely as thermal emission. Contains features diagnostic of mineral composition and H_2O.

Thermal IR spectroscopy **(TIR)** – radiation over wavelengths from ~5 to 100 μm measured as thermal emission. Spectra are sensitive to molecular and lattice vibrations of most geologic materials and ices.

Infrared radiometry – surface to few cm deep measurements of brightness temperature and variations related to composition and thermophysical properties (thermal inertia, density, porosity).

Microwave radiometry – subsurface (cm to many m) measurements of brightness temperature and variations related to composition (through dielectric properties) and density. Can be used to infer heat flow.

Radar Sounding - active radar measurements between 20 to 400 MHz for 3-dimensional structure and stratigraphy of surface/subsurface.

Polarimetric Synthetic Aperture Radar - radar measurements to characterize the scattering response of the surface using multiple radar polarizations.

Multi-spectral imaging - Two dimensions of spatial information (an image) obtained of the surface at several wavelengths and each wavelength image is accurately co-registered to other images. Typically <10 co-registered spectral channels are acquired to map specific spectral variations across the surface.

Hyperspectral imaging - see imaging spectroscopy.

Imaging spectroscopy - Two dimensions (2D) of spatial information (an image) of a surface obtained with simultaneous spectra (typically with >100 co-registered contiguous spectral channels) for each individual surface element (pixel) within the 2D image. Data products are ‘image cubes’ with one dimension of spectroscopic data for compositional analysis set within a 2D image context. The spectra are designed to allow individual diagnostic mineral absorption features to be identified and characterized.

Appendix 5: References

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Appendix 6: Alphabetical List of White Papers

Advanced UV Water Frost and Adsorption Signature Orbital Mapping Instrument Concepts (**Retherford, K., et al.**)

The Case for Orbital Lidar Swath-Mapping at the Moon (**Mazarico, E., et al.**)

A Case for Passive Microwave Wavelength Measurements from Lunar Orbit (**Siegler, M., et al.**)

Characterization of Lunar Surface Thermal Environment and Physical Properties using Advanced Thermal Imagers (**Greenhagen, B., et al.**)

The Contribution of Active Spectroscopy to Orbital Remote Sensing of Lunar Volatiles (**Cremons, D., et al.**)

Cross-Over Infrared Spectroscopy: A New Tool for Remote Mineral Detection and Compositional Determination in the 4-8 μm Wavelength Range (**Kremer, C., et al.**)

Hydrogen Prospecting at the Lunar Poles: Orbital Mission Concept with Neutron Spectroscopy Measurements (**Lawrence, D., et al.**)

Lunar Volatiles and Solar System Science (**Prem, P., et al.**)

Lunar Volatiles Orbiters (**Lucey, P., et al**.)

The Need for Better Characterization of the Primary Anorthositic Crust with New Orbital Observations (**Martinot, M., et al.**)

The Next Lunar Orbiter: Some Observations and Programmatic Perspectives (**Smith, D., et al.**)

Orbital Capabilities to Support Upcoming CLPS Lunar Surface Exploration (**Banks, M., et al.**)

Why Radar Sounding is Crucial for Future Orbital Observatories (**Morgan, G., et al.**)

Why Orbital Magnetometer Instruments are Crucial for Future Improved Lunar Magnetic Observations (**Waller, D., et al**.)

Appendix 7:

Continuous Lunar Orbital Capabilities Specific Action Team (CLOC-SAT) Terms of Reference

A LEAG-sponsored Activity

RATIONALE:

The Lunar Reconnaissance Orbiter (LRO) has delivered >1.3 PB of data to the NASA Planetary Data System since it began operation in 2009, and now is in the process of preparing for the 5th extended mission. With only a few years of fuel left, depending on orbital choices, it is essential to make plans for its successor. In addition, the Lunar Critical Data Products Specific Action Team (LCDP-SAT) recently released the final report of their findings. This SAT was held jointly between the Lunar Exploration Analysis Group (LEAG) and the Mapping and Planetary Spatial Infrastructure Team at the request of NASA's Science Mission (SMD) and Human Exploration and Operations (HEO[1]) Mission Directorates. The LCDP-SAT report, among other things, addressed recommendations laid out in the Artemis III Science Definition Team report[2] and presents findings about data products as well as where gaps in data exist. However, it does not define a path forward to filling those gaps. Key orbital measurements that are needed are also noted in the 2007 NRC Scientific Context of the Moon[3] report and the 2017 LEAG Advancing Science of the Moon[4] report. A successor to LRO, and/or several smaller successors, is needed to address those science and exploration gaps as well as to advance the state of knowledge for the lunar surface such as for defining landing sites for the Commercial Lunar Payload Services (CLPS). Continuous lunar orbital capabilities are also essential in the decades ahead for expanding our general understanding of the lunar environment and resources and for improving PNT (point, navigation, and timing) and GNC (guidance, navigation, and control) for the lunar surface.

Furthermore, findings from the last two annual LEAG meetings have also addressed the need to develop a long-term orbital strategy, particularly with regards to a post-LRO era.

- Finding 2.8 from the 2020 LEAG annual meeting[5]: LEAG supports the definition of a long-term strategy to meet orbital remote sensing and other needs beyond the life of the 2009 Lunar Reconnaissance Orbiter. Specifically, LEAG encourages NASA to engage the community in this activity, provide details on trade studies to date, and evaluate a broad range of science and exploration use cases.
- Finding 2.2 from the 2021 LEAG annual meeting[6]: NASA should work with the community towards identifying and addressing all necessary remote sensing capabilities employed around the Moon (currently and in the future) to accomplish high-priority science and exploration objectives.

Because of all these, LEAG finds that now is the ideal time to actively engage the community and investigate the needs for the next lunar orbiter(s), which will be achieved by the Continuous Lunar Orbital Capabilities Specific Action Team (CLOC-SAT) as sponsored by LEAG.

DELIVERABLES:

The CLOC-SAT will deliver responses to the tasks below in a report whose draft will be presented at a Town Hall at or around the time of Solar System Research Virtual Institute **(SSERVI) Exploration Science Forum (July 2022)** with the final version completed and delivered to NASA by the end of August 2022, and corresponding with the 2022

LEAG annual meeting:

- Develop integrated findings that address questions associated with lunar orbital capabilities in the years ahead, in particular Why? What? and How? These interwoven issues essentially refer to the rationale, specific needs/goals, and realistic opportunities/capabilities for assets in orbit needed to carry lunar science and exploration forward during the next decade(s).
- Identify, and prioritize if possible, the top investigations and/or measurements to be completed by future orbital mission(s). Descriptions of these investigations will include: rationale; categorization with regard to science, technology, and/or exploration goals; orbit(s) and duration required to achieve measurement objectives.
- Identify orbital measurements and capabilities that may involve or benefit different NASA directorates.
- Identify measurements that may benefit from flying together on one large orbiter and those that may fly on separate, smaller orbiters (e.g., group by needs for specific orbits, altitudes, single vs repeat measurements, and/or data volume).
- Identify valuable new measurements that were not obtained by LRO; measurements currently being made by LRO but need next-generation technology; measurements or capabilities that will enhance the success of the Artemis and CLPS landings; and other orbital data that will enable or improve success of future lunar science and exploration goals.
- Develop a potential strategy for long duration orbital assets complimented by short duration measurements/missions (by NASA or commercial entities). Such a strategy could include prioritization of sequential measurements as well as a plan for continuous successor missions modelled, for example, on the LANDSAT series of Earth observation satellites.

POTENTIAL TIMELINE FOR CLOC-SAT AND REPORT

- February 15: Kickoff Virtual Event
- March 4: Submission deadline for nominations (including self-nominations) to join the SAT
- March 25: Full CLOC-SAT team established
- March 31: Target submission deadline for white papers (3-page max w/o references)
- April-July: CLOC-SAT develops integrated strategy and recommendations using community input; SAT members meet several times a month (virtually) with the frequency to be determined by the co-chairs to discuss and write the report; draft report prepared by mid-July.
- July 20-23: Present draft at SSERVI Exploration Science Forum and solicit community feedback
- July-August 2022: Revise report based on community feedback
- End of August: Report delivered to NASA; present final report findings at annual LEAG meeting.

SOME RECOMMENDED DOCUMENTS FOR REFERENCE

- Artemis III Science Definition Team Report
- Scientific Context for Exploration of the Moon
- Science Associated with the Lunar Exploration Architecture (Tempe Report)
- Advancing Science of the Moon (ASM-SAT) report
- Lunar Critical Data Products Specific Action Team (LCDP-SAT) report
- Lunar related white papers submitted to the Decadal Survey
- Decadal Survey Report (to be released mid-April 2022)

MEMBERSHIP

The CLOC-SAT is established as a LEAG activity and will utilize the expertise of a broad range of subject matter experts from the community. A CLOC-SAT team will be comprised of two co-chairs and additional members for addressing Why, What, and How issues that need to be accomplished with continuous lunar orbital capabilities. An open call will be made to the lunar community to solicit additional members of the SAT team. Membership shall be comprised of members with appropriate expertise across areas relevant to lunar orbital measurements.