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

Lunar Exploration Analysis Group (LEAG)

August 2022

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Executive Summary

[Executive Summary text forthcoming following the completion of the final report. In its place, the draft report presents a list of eight overarching findings below]

Overarching Findings

The findings below are numbered for convenience and are not prioritized:

1. **Continuous lunar orbital capabilities are essential** to moving forward during the coming decades of international science and exploration. The next generation of orbital capabilities is required to enable more robust knowledge of the Moon and to provide communication and navigation support for both the lunar surface and cis-lunar vicinity.
2. **Maintaining a path forward for emerging new instruments and capabilities** enables new and unexpected discoveries.
3. Lunar science and exploration orbital needs through the next decades will **benefit from diverse orbits and implementation approaches** ranging from small exploratory satellites to modern instruments on long-lived LRO-class satellites.
4. The **needs for lunar orbiter data storage, access, and retrieval** must be regularly reviewed and upgraded so that data collections are readily available for new and ongoing analyses.
5. A variety of very high spatial resolution observations (< 1 meter) are essential for **characterizing landing sites and surroundings** and monitoring temporal variations as exploration activities expand.
6. Long temporal-baseline platforms enable critical **monitoring of the surface and exosphere**, including the effects of both natural and anthropogenic activities.
7. High-quality **global-scale data provide valuable context** for addressing current questions and long-term planning. As diverse orbital tools and information for exploration and science activities evolve, insight into and understanding of planetary-scale issues will result from orbital studies of the whole Moon.
8. The demonstrated value of an **LRO-class satellite with diverse instruments operating collaboratively at the Moon** cannot be overstated. Plans for a next generation lunar satellite with modern instruments that can replace the highly productive LRO (launched in 2009) are long overdue.

1. Introduction

[Introduction text forthcoming following the completion of the final report. This chapter will focus on motivation, task assignment, community input, and process]

Rationale and Need

[text forthcoming]

Task Guidelines

[text forthcoming]

Community Inputs

[text forthcoming]

CLOC-SAT Discussions and Report Preparation

[text forthcoming]

2. How to Use This Document

2.1 CLOC-SAT Report Structure

This 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 the question 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. This chapter (Chapter 2) provides links between the contents of Chapters 3, 4, and 5 to efficiently provide information. Finally, Chapter 6 Example Mission Scenarios and Summary demonstrates how different measurement and implementation capabilities can be used to address one or more science and/or exploration objective.

[Additional text forthcoming on report structure]

2.2 Investigation-Driven Traceability

A primary expected use case is to show traceability from investigations to measurement approaches and implementation approaches. Table 1 provides the Investigation Traceability Tensor (ITT). This approach has similarities to a conventional science traceability matrix (STM); however, rather focusing on increasing specific measurement techniques and prescribed mission architectures, the ITT shows how investigations can be addressed with an increasingly broad range of measurement and implementation approaches. The ITT serves as a roadmap to the content presented in Chapter 4. Science and Exploration Objectives and Needs.

[A snapshot of the draft Table 1 Investigation Traceability Tensor is inserted below. The design and format of this table will be optimized for the Final Report. The content of the table will be updated to reflect the final text in the report.]

2.3 Measurement-Driven Traceability

Another expected use case is to show traceability from measurement approaches to investigations and implementation approaches. Table 2 provides the Measurement Traceability Tensor (MTT). In this approach, the same rows as ITT are rearranged to emphasize the measurements 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.

[A snapshot of the draft Table 2 Measurement Traceability Tensor is inserted below. The design and format of this table will be optimized for the Final Report. The content of the table will be updated to reflect the final text in the report.]

WHY➡ WHAT➡ HOW (the traditional STM format)

WHY:				WHAT:		HOW:						
THEME:	KEY / CRITICAL / TRANSFORMATIVE INVESTIGATION:			EXAMPLE MEASUREMENT TYPE:	IS THIS A NEW MEASUREMENT TYPE AT THE MOON?	OBSERVATION ALTITUDE:		SPATIAL COVERAGE:			TEMPORAL COVERAGE:	
						LOW-ALTITUDE (<100 km)	HIGH-ALTITUDE (>100 km) OR DISTANT ORBIT (e.g., L1, L2, Halo)	GLOBAL COVERAGE	POLAR COVERAGE (poleward of 80°N/S)	NON-POLAR LOCAL OR REGIONAL COVERAGE	"ONE LOOK"	LONG-TERM MONITORING (months to years)
1 INTERIOR	1.1	HEAT FLOW	Determine the magnitude and spatial distribution of the Moon's heat flow	Microwave radiometry	Yes	X		X			X	
				Infrared radiometry	No	X		X			X	
	1.2	MANTLE EXPOSURES	Identify and map mantle materials exposed on the lunar surface to constrain models of interior evolution	Visible spectroscopy	No	X		X			X	
				Infrared spectroscopy	No	X		X			X	
				High-resolution visible multispectral imagery	No	X		X			X	
	1.3	LUNAR CORE	Determine the state of the Moon's solid inner core	Gravity science	No	X		X				X
2 TECTONICS	2.1	MASS WASTING	Determine the magnitude, extent, and distribution of present-day mass wasting on the Moon, and its relationship to lunar tectonism and seismicity	High-resolution visible imagery	No	X		X		X		X
				High-resolution topography	No	X		X		X		X
	2.2	ACTIVE TECTONICS	Determine the present-day tectonic activity and seismic hazards through direct measurements of surface strain	Laser ranging	No	X		X		X		X
				High-resolution visible imagery	No	X		X		X		X
				High-resolution topography	No	X		X				X
				Interferometric synthetic aperture radar (InSAR)	Yes	X		X		X		X
3 IMPACTS	3.1	NEW IMPACTS	Determine the present-day impact rate through direct observation of new impacts, and the detection and characterization of surface changes >1-m in scale	Impact flash monitoring	Yes (although it's been done from Earth)		X	X				X
				Impact flash monitoring with spectroscopy	Yes		X	X				X
				High-resolution visible imagery	No	X		X				X
				High-resolution topography	No	X		X				X
	3.2	SECONDARY IMPACTS	Determine the present-day secondary crater impact rate at <<10-m scale to understand the relationship between secondary and primary impacts, and to characterize impact hazards	High-resolution visible imagery	No	X		X				X
				High-resolution topography	No	X						X
	3.3	COLDSPOTS	Determine the process that creates observable differences in regolith thermophysical and photometric propoerties around young impact craters	Infrared radiometry	No	X		X		X	X	
				High-resolution visible imagery	No	X		X		X	X	
4 REGOLITH AND SPACE WEATHERING	4.1	REGOLITH	Determine the three-dimensional structure of the regolith and megaregolith	Radar sounding	No	X		X			X	
				Microwave radiometry	Yes	X		X			X	
	4.2	MAGNETIC ANOMALIES	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	Magnetic field measurements	No	X				X	X	
				Neutral and ion mass spectroscopy	No	X				X	X	X
5 COMPOSITION OF THE MOON	5.1	GLOBAL COMPOSITIONAL MAPPING	Determine the compositional inventory of the Moon with high-quality, contiguous, global compositional measurements at <50-m resolution	Ultraviolet spectroscopy	No	X		X			X	
				Visible spectroscopy	No	X		X			X	
				Infrared spectroscopy	No	X		X			X	
	5.2	BOULDER MINERALOGY	Determine the major mineralogy of tageted large boulders, and the deposits in/around small craters at <10-m resolution	Ultraviolet spectroscopy	No	X		X		X	X	
				Vi[illegible] spectroscopy		X		X		X	X	
				[illegible]red spectroscopy	No	X		X		X	X	
				[illegible]erspectral imaging	No	X		X			X	
	5.3	LANDER-SCALE MINERALOGY	Determine the major mineralogy and chemistry of ta[illegible]ed regions at <1-m scale, as necessary to support [illegible] enhance human and robotic operations	High-[illegible]ution visible multispe[illegible] imagery	No	X		X	X	X	X	
6 POLAR ENVIRONMENTS	6.1	SPATIAL DISTRIBUTION OF POLAR VOLATILES	Determine the spatia[illegible]tion and compositio[illegible]urface and near-surface vola[illegible]s (w[illegible] hydrogen, car[illegible] dioxide, etc.) for the ent[illegible] polar regi[illegible] astronaut [illegible]nd rover scales, <100-mete[illegible]	Active IR spec[illegible]py	Yes	X			X		X	
				Passive IR spectroscopy	No	X			X		X	
				Ultraviolet spectroscopy	No	X			X		X	
				Active fluorescence spectroscopy	Yes	X			X		X	
				Neutron spectroscopy	No	X			X		X	
				~~Radar sounding~~	Yes	X			X		X	
				~~Cosmic ray spectroscopy~~	Yes	X			X		X	
				~~Microwave radiometry~~	Yes	X			X		X	
				Neutral and ion mass spectroscopy	No	X			X		X	
		DEEP VOLATILES	T[illegible]atiles at depth)	Radar sounding, microwave radiometry, cosmic ray								
	6.2	[illegible]MPORAL E[illegible]UTION OF POL[illegible]OLATIL[illegible]	C[illegible]acterize the temporal variability of lunar water and other [illegible]atiles across diurnal, seasonal, prescessional, and geologic timescales	Active IR spectroscopy	Yes	X			X			X
				Passive IR spectroscopy	No	X			X			X
				Ultraviolet spectroscopy	No	X			X			X
				Active fluorescence spectroscopy	Yes	X			X			X
				Neutral and ion mass spectroscopy	No	X			X			X
	6.3	ISOTOPIC COMPOSITION OF POLAR VOLATILES	Determine the isotopic composition of volatiles	Neutral and ion mass spectroscopy	No	X			X		X	
				Dust analyzer	No	X			X		X	
				Exospheric spectroscopy	Yes	X			X		X	
	6.4	ORGANICS AND HEMATITE	Determine the abundance and distribution of organics and hematite (and related minerals) in polar regions to define their scientific and resource potential	Active fluorescence spectroscopy	Yes	X			X		X	
				Neutral and ion mass spectroscopy	No	X			X		X	
7 VOLATILE SYSTEM	7.1	EXOSPHERE AND REGOLITH INTERACTIONS	Determine the spatial and temporal behavior of water transport through the lunar exosphere, and how it is affected by human and robotic exploration	Neutral and ion mass spectroscopy	No	X		X				X
				Ultraviolet spectroscopy	No	X		X				X
	7.2	SURFACE HYDRATION	Characterize the abundance, distribution, and temporal variability of hydration, including hydroxyl and molecular water, across the lunar surface	Infrared spectroscopy	No	X		X			X	X
				Laser reflectance spectroscopy	Yes	X		X			X	X
				Infrared spectroscopy	No	X		X			X	X
				Laser reflectance spectroscopy	Yes	X		X			X	X

WHAT ➡ WHY ➡ HOW

WHAT:		WHY:					HOW:						
EXAMPLE MEASUREMENT TYPE:	LUNAR HERITAGE (yes, partial, new)	THEME:		TRANSFORMATIVE INVESTIGATION:			OBSERVATION ALTITUDE:		SPATIAL COVERAGE:			TEMPORAL COVERAGE:	
							LOW-ALTITUDE (<100 km)	HIGH-ALTITUDE (>100 km) OR DISTANT ORBIT (e.g., L1, L2, Halo)	GLOBAL COVERAGE	POLAR COVERAGE (poleward of 80°N/S)	NON-POLAR LOCAL OR REGIONAL COVERAGE	"ONE LOOK"	LONG-TERM MONITORING (months to years)
Active fluorescence spectroscopy	New	6	POLAR ENVIRONMENTS	6.1	SPATIAL DISTRIBUTION OF POLAR VOLATILES	Determine the three-dimensional spatial distribution and composition of surface and near-surface volatiles (water ice, hydrogen, carbon dioxide, etc.) for the entire polar region at the astronaut and rover scales, <100-meters	X			X		X	
Active fluorescence spectroscopy	New	6	POLAR ENVIRONMENTS	6.2	TEMPORAL EVOLUTION OF POLAR VOLATILES	Characterize the temporal variability of lunar water and other volatiles across diurnal, seasonal, prescessional, and geologic timescales	X			X			X
Active fluorescence spectroscopy	New	6	POLAR ENVIRONMENTS	6.4	ORGANICS AND HEMATITE	Determine the abundance and distribution of organics and hematite (and related minerals) in polar regions to define their scientific and resource potential	X			X		X	
Active IR spectroscopy	New	6	POLAR ENVIRONMENTS	6.1	SPATIAL DISTRIBUTION OF POLAR VOLATILES	Determine the three-dimensional spatial distribution and composition of surface and near-surface volatiles (water ice, hydrogen, carbon dioxide, etc.) for the entire polar region at the astronaut and rover scales, <100-meters	X			X		X	
Active IR spectroscopy	New	6	POLAR ENVIRONMENTS	6.2	TEMPORAL EVOLUTION OF POLAR VOLATILES	Characterize the temporal variability of lunar water and other volatiles across diurnal, seasonal, prescessional, and geologic timescales	X			X			X
Cosmic ray spectroscopy	New	6	POLAR ENVIRONMENTS	6.1	SPATIAL DISTRIBUTION OF POLAR VOLATILES	Determine the three-dimensional spatial distribution and composition of surface and near-surface volatiles (water ice, hydrogen, carbon dioxide, etc.) for the entire polar region at the astronaut and rover scales, <100-meters	X			X		X	
Dust analyzer	Partial	6	POLAR ENVIRONMENTS	6.3	ISOTOPIC COMPOSITION OF POLAR VOLATILES	Determine the isotopic composition of volatiles	X			X		X	
Exospheric spectroscopy		6	POLAR ENVIRONMENTS	6.3	ISOTOPIC COMPOSITION OF POLAR VOLATILES	Determine the isotopic composition of volatiles	X			X		X	
Gravity science	Yes	1	INTERIOR	1.3	LUNAR CORE	Determine the state of the Moon's solid inner core	X		X				X
High-resolution topography	Partial	2	TECTONICS	2.1	MASS WASTING	Determine the magnitude, extent, and distribution of present-day mass wasting on the Moon, and its relationship to lunar tectonism and seismicity	X		X		X		X
High-resolution topography	Partial	2	TECTONICS	2.2	ACTIVE TECTONICS	Determine the present-day tectonic activity and seismic hazards through direct measurements of surface strain	X		X		X		X
High-resolution topography	Partial	3	IMPACTS	3.1	NEW IMPACTS	Determine the present-day impact rate through direct observation of new impacts, and the detection and characterization of surface changes >1-m in scale	X		X				X
High-resolution topography	Partial	3	IMPACTS	3.2	SECONDARY IMPACTS	Determine the present-day secondary crater impact rate at <<10-m scale to understand the relationship between secondary and primary impacts, and to characterize impact hazards	X		X				X
High-resolution visible imagery	Yes	2	TECTONICS	2.1	MASS WASTING	Determine the magnitude, extent, and distribution of present-day mass wasting on the Moon, and its relationship to lunar tectonism and seismicity	X		X		X		X
High-resolution visible imagery	Yes	2	TECTONICS	2.2	ACTIVE TECTONICS	Determine the present-day tectonic activity and seismic hazards through direct measurements of surface strain	X		X		X		X
High-resolution visible imagery	Yes	3	IMPACTS	3.1	NEW IMPACTS	Determine the present-day impact rate through direct observation of new impacts, and the detection and characterization of surface changes >1-m in scale	X		X				X
High-resolution visible imagery	Yes	3	IMPACTS	3.2	SECONDARY IMPACTS	Determine the present-day secondary crater impact rate at <<10-m scale to understand the relationship between secondary and primary impacts, and to characterize impact hazards	X		X				X
High-resolution visible imagery	Yes	3	IMPACTS	3.3	COLDSPOTS	Determine the process that creates observable differences in regolith thermophysical and photometric propoerties around young impact craters	X		X		X	X	
High-resolution visible multispectral imagery		1	INTERIOR	1.2	MANTLE EXPOSURES	Identify and map mantle materials exposed on the lunar surface to constrain models of interior evolution	X		X			X	
High-resolution visible multispectral imagery		5	COMPOSITION OF THE MOON	5.3	LANDER-SCALE MINERALOGY	Determine the major mineralogy and chemistry of targeted regions at <1-m scale, as necessary to support and enhance human and robotic operations	X		X	X	X	X	
Hyperspectral imaging		5	COMPOSITION OF THE MOON	5.2	BOULDER MINERALOGY	Determine the major mineralogy of tageted large boulders, and the deposits in/around small craters at <10-m resolution	X		X			X	
Impact flash monitoring	New	3	IMPACTS	3.1	NEW IMPACTS	Determine the present-day impact rate through direct observation of new impacts, and the detection and characterization of surface changes >1-m in scale		X	X				X
Impact flash monitoring with spectroscopy	New	3	IMPACTS	3.1	NEW IMPACTS	Determine the present-day impact rate through direct observation of new impacts, and the detection and characterization of surface changes >1-m in scale		X	X				X
Infrared radiometery	Partial	1	INTERIOR	1.1	HEAT FLOW	Determine the magnitude and spatial distribution of the Moon's heat flow	X		X			X	
Infrared radiometry	Partial	3	IMPACTS	3.3	COLDSPOTS	Determine the process that creates observable differences in regolith thermophysical and photometric propoerties around young impact craters	X		X		X	X	
Infrared spectroscopy	Partial	1	INTERIOR	1.2	MANTLE EXPOSURES	Identify and map mantle materials exposed on the lunar surface to constrain models of interior evolution	X		X			X	
Infrared spectroscopy	Partial	5	COMPOSITION OF THE MOON	5.1	GLOBAL COMPOSITIONAL MAPPING	Determine the compositional inventory of the Moon with high-quality, contiguous, global compositional measurements at <50-m resolution	X		X			X	
Infrared spectroscopy	Partial	5	COMPOSITION OF THE MOON	5.2	BOULDER MINERALOGY	Determine the major mineralogy of tageted large boulders, and the deposits in/around small craters at <10-m resolution	X		X		X	X	
Infrared spectroscopy	Partial	7	VOLATILE SYSTEM	7.2	SURFACE HYDRATION	Characterize the abundance, distribution, and temporal variability of hydration, including hydroxyl and molecular water, across the lunar surface	X		X			X	X
Infrared spectroscopy	Partial	7	VOLATILE SYSTEM	7.2	SURFACE HYDRATION	Characterize the abundance, distribution, and temporal variability of hydration, including hydroxyl and molecular water, across the lunar surface	X		X			X	X
Interferometric synthetic aperture radar (InSAR)	New	2	TECTONICS	2.2	ACTIVE TECTONICS	Determine the present-day tectonic activity and seismic hazards through direct measurements of surface strain	X		X		X		X
Laser ranging	Yes	2	TECTONICS	2.2	ACTIVE TECTONICS	Determine the present-day tectonic activity and seismic hazards through direct measurements of surface strain	X		X		X		X
Laser reflectance spectroscopy		7	VOLATILE SYSTEM	7.2	SURFACE HYDRATION	Characterize the abundance, distribution, and temporal variability of hydration, including hydroxyl and molecular water, across the lunar surface	X		X			X	X
Laser reflectance spectroscopy		7	VOLATILE SYSTEM	7.2	SURFACE HYDRATION	Characterize the abundance, distribution, and temporal variability of hydration, including hydroxyl and molecular water, across the lunar surface	X		X			X	X
Magnetic field measurements	Yes	4	REGOLITH AND SPACE WEATHERING	4.2	MAGNETIC ANOMALIES	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	X				X	X	
Microwave radiometry	Yes	1	INTERIOR	1.1	HEAT FLOW	Determine the magnitude and spatial distribution of the Moon's heat flow	X		X			X	
Microwave radiometry	Yes	4	REGOLITH AND SPACE WEATHERING	4.1	REGOLITH	Determine the three-dimensional structure of the regolith and megaregolith	X		X			X	
Microwave radiometry	Yes	6	POLAR ENVIRONMENTS	6.1	SPATIAL DISTRIBUTION OF POLAR VOLATILES	Determine the three-dimensional spatial distribution and composition of surface and near-surface volatiles (water ice, hydrogen, carbon dioxide, etc.) for the entire polar region at the astronaut and rover scales, <100-meters	X			X		X	
Neutral and ion mass spectroscopy	Partial	4	REGOLITH AND SPACE WEATHERING	4.2	MAGNETIC ANOMALIES	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	X				X	X	X
Neutral and ion mass spectroscopy	Partial	6	POLAR ENVIRONMENTS	6.1	SPATIAL DISTRIBUTION OF POLAR VOLATILES	Determine the three-dimensional spatial distribution and composition of surface and near-surface volatiles (water ice, hydrogen, carbon dioxide, etc.) for the entire polar region at the astronaut and rover scales, <100-meters	X			X		X	
Neutral and ion mass spectroscopy	Partial	6	POLAR ENVIRONMENTS	6.2	TEMPORAL EVOLUTION OF POLAR VOLATILES	Characterize the temporal variability of lunar water and other volatiles across diurnal, seasonal, prescessional, and geologic timescales	X			X			X
Neutral and ion mass spectroscopy	Partial	6	POLAR ENVIRONMENTS	6.3	ISOTOPIC COMPOSITION OF POLAR VOLATILES	Determine the isotopic composition of volatiles	X			X		X	
Neutral and ion mass spectroscopy	Partial	6	POLAR ENVIRONMENTS	6.4	ORGANICS AND HEMATITE	Determine the abundance and distribution of organics and hematite (and related minerals) in polar regions to define their scientific and resource potential	X			X		X	
Neutral and ion mass spectroscopy	Partial	7	VOLATILE SYSTEM	7.1	EXOSPHERE AND REGOLITH INTERACTIONS	Determine the spatial and temporal behavior of water transport through the lunar exosphere, and how it is affected by human and robotic exploration	X		X				X
Neutron spectroscopy	Yes	6	POLAR ENVIRONMENTS	6.1	SPATIAL DISTRIBUTION OF POLAR VOLATILES	Determine the three-dimensional spatial distribution and composition of surface and near-surface volatiles (water ice, hydrogen, carbon dioxide, etc.) for the entire polar region at the astronaut and rover scales, <100-meters	X			X		X	
Passive IR spectroscopy		6	POLAR ENVIRONMENTS	6.1	SPATIAL DISTRIBUTION OF POLAR VOLATILES	Determine the three-dimensional spatial distribution and composition of surface and near-surface volatiles (water ice, hydrogen, carbon dioxide, etc.) for the entire polar region at the astronaut and rover scales, <100-meters	X			X		X	
Passive IR spectroscopy		6	POLAR ENVIRONMENTS	6.2	TEMPORAL EVOLUTION OF POLAR VOLATILES	Characterize the temporal variability of lunar water and other volatiles across diurnal, seasonal, prescessional, and geologic timescales	X			X			X
Radar sounding		4	REGOLITH AND SPACE WEATHERING	4.1	REGOLITH	Determine the three-dimensional structure of the regolith and megaregolith	X		X			X	
Radar sounding		6	POLAR ENVIRONMENTS	6.1	SPATIAL DISTRIBUTION OF POLAR VOLATILES	Determine the three-dimensional spatial distribution and composition of surface and near-surface volatiles (water ice, hydrogen, carbon dioxide, etc.) for the entire polar region at the astronaut and rover scales, <100-meters	X			X		X	
Ultraviolet spectroscopy		5	COMPOSITION OF THE MOON	5.1	GLOBAL COMPOSITIONAL MAPPING	Determine the compositional inventory of the Moon with high-quality, contiguous, global compositional measurements at <50-m resolution	X		X			X	
Ultraviolet spectroscopy		5	COMPOSITION OF THE MOON	5.2	BOULDER MINERALOGY	Determine the major mineralogy of tageted large boulders, and the deposits in/around small craters at <10-m resolution	X		X		X	X	
Ultraviolet spectroscopy		6	POLAR ENVIRONMENTS	6.1	SPATIAL DISTRIBUTION OF POLAR VOLATILES	Determine the three-dimensional spatial distribution and composition of surface and near-surface volatiles (water ice, hydrogen, carbon dioxide, etc.) for the entire polar region at the astronaut and rover scales, <100-meters	X			X		X	
Ultraviolet spectroscopy		6	POLAR ENVIRONMENTS	6.2	TEMPORAL EVOLUTION OF POLAR VOLATILES	Characterize the temporal variability of lunar water and other volatiles across diurnal, seasonal, prescessional, and geologic timescales	X			X			X
Ultraviolet spectroscopy		7	VOLATILE SYSTEM	7.1	EXOSPHERE AND REGOLITH INTERACTIONS	Determine the spatial and temporal behavior of water transport through the lunar exosphere, and how it is affected by human and robotic exploration	X		X				X
Visible spectroscopy		1	INTERIOR	1.2	MANTLE EXPOSURES	Identify and map mantle materials exposed on the lunar surface to constrain models of interior evolution	X		X			X	
Visible spectroscopy		5	COMPOSITION OF THE MOON	5.1	GLOBAL COMPOSITIONAL MAPPING	Determine the compositional inventory of the Moon with high-quality, contiguous, global compositional measurements at <50-m resolution	X		X			X	
Visible spectroscopy		5	COMPOSITION OF THE MOON	5.2	BOULDER MINERALOGY	Determine the major mineralogy of tageted large boulders, and the deposits in/around small craters at <10-m resolution	X		X		X	X	

2.4 Implementation-Driven Traceability (Or the Lack Thereof)

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 combinations of platform orbits and orbiter capabilities for sample use cases in Chapter 6. Example Mission Scenarios and Summary. These mission concepts are illustrative only and intended to demonstrate how capabilities described herein can be used to build simple mission concepts. They are not intended to be endorsed by the CLOC-SAT as priority mission scenarios.

2.5 Additional Resources

The CLOC-SAT Report contains a number of resources in Appendices that may be useful as additional resources.

- **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 4: Glossary**
    - In addition to the complete List of Acronyms presented in Appendix 3, a subset of terms and techniques included in the text [will be] summarized in the Glossary (Appendix 2).
- **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 product. Rather, the references [to be] included in Appendix 5 focus on additional resources relevant to the specific 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 [will be] available on the LEAG CLOC-SAT Report [include link].

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 new missions, including the first sample return and rover missions since the 1970's. The near future will feature additional landed missions through the CLPS and international programs culminating in Artemis exploration that will provide unprecedented new data aimed at key science questions largely 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 the entire 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 important contributions to the unique needs of exploration science. We note that this report includes guidance from prior reports, including especially the most recent Decadal Survey, and also community responses to the aims of this SAT.

3.2 Traceability to Strategic Documents

[text and tables forthcoming linking objectives described in this Chapter to strategic and community documents]

- Linkage to decadal survey
- Follow on to SCEM, ASM-Sat
- Artemis 3SDT and Lunar Exploration Roadmap
- Additional insights from community white papers and community feedback

3.3 Science and Exploration Objectives

In this section we present brief backgrounds and areas of strategic research that could yield transformative sciences advances principally through measurements that are qualitative improvements over the datasets currently available, but are technically feasible and in many cases offer multiple approaches. Example technologies are presented in Section 5, whereas measurement goals and objectives are presented and defended here.

3.3.1 The state and evolution of the interior of the Moon

GRAIL and LRO produced the most precise gravity and topography measurements for any planetary object, giving rise to significant advances in understanding the lunar interior. Heat flow is another fundamental geophysical parameter for any object as it uniquely probes the interior through the presence of internal heat sources. Apollo measurements of heat flow have been used to estimate the bulk composition of the Moon through the influence of heat producing elements. In addition, recent demonstrations using data from the microwave sounder on Chang'E-1 and -2 showed that heat flow could also be derived remotely from passive microwave measurements. The Chang'E work added this critical geophysical parameter to global maps of gravity and topography, though existing microwave data are at too high a frequency to most effectively make this measurement. These measurements showed that the Procellarum KREEP Terrane (PKT) that shows anomalous concentrations of radioactive elements at the surface, is accompanied by enhanced heat flow showing the surface expression of heat producing elements characteristic of the PKT is not superficial. LRO Diviner observations also demonstrated an ability to remotely estimate heat flow by measuring temperatures in a few PSR regions that are doubly or triply shadowed from direct sunlight where surface temperatures are as low as 20K where flux is dominated by heat flow from the interior. These polar observations provide a heat flow estimate far from the Apollo heat flow measurements in the PKT. Concepts for the Lunar Geophysical Network (LGN) also include heat flow as a critical, distributed surface measurement for understanding the interior of the Moon and its evolution.

Transformative investigations

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

Remote mapping of heat flow at better than 10 km spatial resolution with sensitivity similar to Apollo heat flow measurements would reveal buried heat sources and allow modeling of igneous bodies at depth, as well as 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 CLPS missions at Schrodinger and Crisium basins and 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 buried rift system around the PKT discovered by GRAIL have a residual heat flow signature that might reveal its origin?

Example measurements: microwave radiometry; infrared radiometry

Determine heat flow at locations far from the Apollo zone

The Apollo heat flow measurements were obtained within the recognized thermal anomaly of the PKT. Thus, using these measurements to estimate bulk composition and other fundamental geophysical quantities is compromised. Measurements at great distances from the PKT will place the Apollo measurements in a global context and improve our understanding of the bulk composition of the Moon. Improvements in spatial resolution of infrared and microwave radiometry while preserving radiometric accuracy are likely to result in a larger number of small regions where this measurement can be performed.

Example measurements: infrared radiometry, microwave radiometry

Determine the state of the Moon's solid inner core

[Forthcoming text supporting gravity science investigation of the inner core]

Example measurements: gravity science

Implications for Exploration

Heat flow is particularly salient for landed missions near PSRs, as is planned for Artemis. In 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 to PSRs. This heterogeneous lateral heat flow may be a significant control on the distribution of buried ice. Local surface heat flow measurements will require regional context provided from orbit to reduce ambiguities in data interpretation.

[Forthcoming text supporting inner core investigation implications for exploration]

Findings

- **FINDING:** In order to ground truth surface heat flow measurements and extrapolate our understanding, orbitally-derived maps of heat flow require an accuracy comparable to Apollo at ~10 km spatial resolution.
- **FINDING:** Determining the bulk composition of the Moon requires estimates of heat flow at locations far from the Apollo zone.
- **FINDING:** Regional heat flow measurements at the poles are required to support interpretation of Artemis and other surface polar data, and to better understand the distribution of buried ice.
- **FINDING:** [Forthcoming finding(s) related to inner core investigation]

3.3.2 Lunar Volcanism and Magmatism

[Forthcoming text focused on volcanic and magmatic processes and products. The current text, specifically 3.3.6 includes limited descriptions related to observable volcanic products. This new section will bring together these and additional topics, including pre-mar volcanism, pyroclastic deposits, irregular mare patches, silicic volcanism, lava pits/tubes, etc.]

Transformative Investigations

[Forthcoming text describing transformative volcanism / magmatism investigations and example measurements]

Implications for Exploration

[Forthcoming text supporting volcanism / magmatism implications for exploration]

Findings

- **FINDING:** [Forthcoming finding(s) related to volcanism / magmatism]

3.3.3 Lunar Tectonics

LROC images documented small thrust faults throughout the highlands, including cross-cutting relationships with relatively fresh craters indicating on-going tectonism. Discoveries of landslides that occurred during the LRO mission show a spatial correlation of the landslides with 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. The recent Decadal Survey recognized this importance by directing: "Characterize the style and intensity of active tectonism occurring on rocky or icy worlds, through seismic and other geophysical measurements."

Transformative Investigations

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

Terrestrial long-time baseline measurements of small surface displacements (strain) reveal accumulating stress. Similar measurements on the Moon could revolutionize our understanding of lunar tectonism and would directly support the LGN.

Example measurements: Precision repeat laser topography, high-resolution visible imagery, interferometric synthetic aperture radar (InSAR)

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 of mass wasting with 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.

Example measurements: high-resolution visible imagery, LiDAR

Implications for Exploration

Recent studies have concluded that seismicity is a significant hazard to crew and infrastructure; evidence for on-going 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:** Measurements of accumulating stress should be carried out to understand the contemporary tectonic environment and better characterize the seismic hazard.
- **FINDING:** Detection of mass wasting events as result of on-going lunar seismicity should be continued.

3.3.4 Understanding the impact process at all scales

One of the most startling discoveries enabled by the 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 productive of secondaries a given primary impact might be, including the influence of the target site. The Decadal Survey noted: "... the contribution of secondary craters and sesquinary craters ... needs to be understood to fully analyze planetary crater populations."

Transformative Investigations

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

Continuous lunar observations address this need by coordinating two types of observations. 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. New imagery, 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 supports surface seismic measurements including the LGN.

Example measurements: impact flash monitoring; repeat high-resolution visible imagery or high resolution LiDAR repeated over years to decades, InSAR

Determine the secondary impact rate and efficiency of production of secondaries from primary impacts.

At the scales available with current observations, detected primary impacts are too infrequent to reliably assign detected evidence for secondaries to specific primaries. It is a safe assumption that the frequency of small secondary impactors, on the order of cm to tens of cm, is higher than observed splotches following 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: impact flash monitoring; repeat high-resolution visible imagery or high resolution LiDAR repeated over years to decades, InSAR

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

[Forthcoming text supporting the characterization of impact process producing cold spots]

Example measurements: infrared radiometry; high-resolution visible imagery

Implications for Exploration

The existence of likely secondaries with higher 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 a safe assumption that the frequency of small secondary impactors, on the order of cm to tens of cm, is higher than observed splotches (following a power law distribution), suggesting these events are a serious hazard. The cost of mis-estimating this hazard is potential loss of crew, thus direct measurement of the secondary impactor rate at the cm size range is a critical need.

Findings

- **FINDING:** 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:** Continuous monitoring at the >1 meter scale is required to refine the measurements of the primary and secondary flux and detect new impacts at the >>1 meter scale.
- **FINDING:** 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:** 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

The 21st century has seen significant strides in understanding the lunar regolith. Multifrequency radars have revealed subsurface structures at the 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 Lunar Radiometer data has shown the average compaction of the upper few centimeters varies across the Moon, and that this parameter correlates with crater age. 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 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 modulation of the solar wind by lunar magnetic anomalies will soon be tested on the ground by the CLPS Lunar Vertex 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.

The Decadal Survey noted the importance of the regolith and space weathering explicitly in their direction for strategic research: "Investigate the role of space weathering processes on airless rocky bodies using high-resolution imaging and spectroscopy of planetary surfaces..." and "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 regollith and megaregolith

Multi-mission multifrequency 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, only limited deeper probing is available from surface GPR and Apollo sounding measurements. The boundary between the regolith and megaregolith is virtually unmeasured, especially among the major terrains, so understanding how the developing crust evolved with respect to the impact flux is very poorly known. Improved understanding of regolith structure to kilometer depth globally and near landing sites specifically can affect site and traverse selection and inform sample analysis.

Example measurements: radar sounding; microwave radiometry

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, including formation of nanophase iron, agglutinates, and unique minerals associated with vapor deposition. Remote sensing has added hydroxyl (and possibly water) as well as hematite and other iron oxides. Other compounds that might occur are silanes and carbides produced in the illuminated Moon from solar wind gases. 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, visible and infrared remote sensing for products of solar wind interactions.

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

[Forthcoming text supporting the characterization of magnetic anomalies]

Example measurements: magnetic field measurements; neutral and ion mass spectroscopy of sputtered ions

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 reveal 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 ISRU. As yet undiscovered compounds may provide more efficient processing of key elements and chemical feedstocks.

Findings

- **FINDING:** 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:** 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:** Newly discovered compounds may provide resources for ISRU, such as carbon at the poles, and recoverable water in hydrated iron oxides.
- **FINDING:** Characterizing the three dimensional structure of magnetic fields associated with anomalies helps elucidate the relationship between surface anomalies and the heliospheric environment.

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. 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, 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 Procellarum KREEP Terrane (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 andcrater 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. And olivine in basin rings occurs in basin rings that hydrocode models have suggested sampled the mantle.

Many of the questions and strategic research areas listed by the most recent Decadal Survey would directly benefit from improved comprehensive global data: "Determine the compositional diversity of the terrestrial planets ... by obtaining mineralogical, geochemical, ... data from the surfaces ... [of the] Moon, and the less explored regions of the Moon ..." and "Evaluate the nature of early projectiles that struck the terrestrial planets and the Moon by analyzing regolith samples likely to contain remnant clasts from early bombardment impactors ...." and "Assess the contribution and effects of late accretion on the post-differentiation inner planets by analysis of ancient terrestrial materials, samples from regions of Mars and the Moon likely to be derived from each world’s mantle...." and "Determine the composition and depth of the materials, possibly lunar mantle, excavated by the South Pole-Aitken (SPA) basin formation... ;" " Probe the magmatic history of the Moon by conducting coordinated high-fidelity geochronology, geochemistry, and petrologic analyses...," and "Determine the origin of the Moon's volatile element abundances by completing additional stable isotopic analyses of volatile elements in lunar samples originating from the lunar interior as well as gamma-ray and neutron spectrometer measurements (e.g., K/Th ratios) by spacecraft."

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 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 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: Low altitude gamma ray, neutron and X-ray spectroscopy

Determine the mineralogical inventory of the Moon with high-quality, contiguous, global compositional measurements at <50-meter 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. Additional keys to these discoveries were the transition of sensing from multispectral imaging (targeted to capture specific spectral features defined prior to the mission) to hyperspectral imaging, and extending wavelengths from the visible to the near-infrared and thermal-infrared that provide much more generalized compositional sensing and enabling serendipitous discovery.

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, visible, near infrared, and thermal infrared hyperspectral imaging 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 exposure mantle material in some of their rings. Some rings (e.g. 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 meter 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, visible, near infrared, and thermal infrared hyperspectral imaging at the ~10-m scale. Multiband high resolution imagery or laser reflectance at the ~1 m scale. High-resolution monochrome imagery or laser reflectance at the <1 m scale.

Implications for exploration

The next phase of lunar exploration strongly emphasizes in situ analysis and sample return, as shown by many of the strategic research objectives outlined in the recent Decadal Survey. Improved remote sensing can make critical contributions to these new efforts. With spectroscopy at the 1 to 10 meter 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 sampling. Current compositional data sets, and those to be collected by missions in development, do not have the resolution 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 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 candidates 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 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 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:** 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 advances
- **FINDING:** Completing the compositional inventory of the Moon with high quality contiguous global compositional measurements at < 50 meter resolution is essential to ensure the mineralogic diversity of the Moon is captured.
- **FINDING:** Direct measurements of the compositional nature of the lunar mantle through detection and characterization of ultramafic lithologies at ~10 meter 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:** Compositional imaging of the Moon at ~1-10 meter or higher resolution is a priority to support surface operations.

3.3.7 Polar Region Microenvironments

The lunar polar regions contain unique microenvironments. One of these are permanently shadowed regions (PSRs) 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 microenvironment 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. These surfaces constitute a potential lunar permafrost zone with subsurface volatile stability. Small PSR's, called micro-cold traps, occur at scales of 10s cm to 10s of meters 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 micrometeorite 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 LRO LEND both found hydrogen in the upper meter of the polar regolith, and modeling suggests these deposits are primarily confined to PSRs, though their chemical form is unknown. Spectrometers on LRO, Kaguya, and Chandrayaan-1 detected patchy water ice at the surface, and 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 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 too low 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.

Previous community reports (e.g. SCEM, ASM-SAT) have noted that the understanding of the polar deposits is very immature. The most recent Decadal Survey noted; "Fundamental questions remain, however, regarding the transport, retention, physical and chemical alteration, and loss processes operating on such deposits over seasonal, diurnal, and precessional timescales." The Survey also directed: "Determine the amount and origin of water ice on the Moon and Mercury by sampling ice, determining its spatial distribution, measuring H and O isotopes, and determining the nature and abundance of contaminants within the ice as a means of understanding sources of water in the inner solar system," and noted "On airless bodies such as the Moon, Mercury, and Ceres, polar cold traps are of compelling interest to investigations of how volatiles inform the processes of prebiotic chemistry, as well as the history of volatiles throughout the age of the solar system." Furthermore, "Determine the origin, time of delivery, vertical and lateral distribution and current cycling of cold-trapped lunar volatiles via in situ analyses of isotopes (e.g., Deuterium/Hydrogen), sulfur, organics, abundance and distribution of volatiles, and local exospheric measurements." And "Evaluate possible sources of false positives for organic chemical biosignatures with ... remote sensing observations... from worlds unlikely to host life (e.g., the Moon...) ... in an effort to assess the production and/or delivery rate of abiotic organic molecules that might mimic biological organic molecules and establish a baseline against which measurements in habitable environments can be compared...."

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-meters

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, are limited to water ice, whereas understanding 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 maps at 100 meter scale or less 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; passive infrared hyperspectral imaging; imaging infrared radiometry; ultraviolet spectroscopy; active fluorescence spectroscopy; neutral and ion mass spectroscopy; neutron spectroscopy; mass spectroscopic dust analyzer

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

Dynamics of volatiles in the PSRs are inferred from the evidence for the presence 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; passive infrared spectroscopy; infrared radiometry; ultraviolet spectroscopy; orbital neutral and ion mass spectroscopy of activated molecules

Determine the distribution of volatiles to depths >10-meters to distinguish between hypotheses for volatile implacement, 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 should 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-meters or more, and hundreds of meters, while less accessible, would be especially valuable to understanding the extent of sequestered volatiles.

Example measurements: microwave radiometry; radar sounding, cosmic ray spectroscopy

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 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; passive infrared spectroscopy; active fluorescence spectroscopy; neutral and ion mass spectroscopy

Implications for exploration

The utility of maps of surface and shallow buried volatiles are obvious both for planning ISRU 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.

Findings

- **FINDING:** 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-meters) with context of surface temperature and temperature history.
- **FINDING:** 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:** Measuring the isotopic composition of ejecta lofted from contemporary natural or artificial impacts could provide the isotopic composition of sequestered volatiles.
- **FINDING:** The dynamics of water-ice at diurnal, seasonal and precessional timescales should be characterized with measurements sensitive to abundances well below 1%, and ice layer thicknesses much less than 1 micron.
- **FINDING:** Searches for buried water ice should be conducted to depths of 10 meters or greater to test emplacement hypotheses and to address the viability and sustainability of the water-ice resource.
- **FINDING:** Evidence should be sought in the exosphere for volatiles activated by loss mechanisms.
- **FINDING:** The abundance and distribution of methane and more complex organics should be characterized to define their scientific and resource potential.

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. 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 polars. 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 LAMP has made great strides in understanding exospheric hydrogen, though key energy ranges of atomic and molecular neutral hydrogen remain unmeasured.

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, does ballistic migration operate 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.

The Decadal Survey explicitly recognized the importance of the connection between surface and exospheric volatiles: "Derive the sources of exospheric volatiles by measuring the distribution, composition, and abundance of surface volatiles .... on solid bodies including the Moon...." and "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 "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 4D spatial and temporal behavior of volatiles 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 LADEE neutral mass spectrometer 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. 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 320K, which may decrease with increasing latitude. 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: neutral and ion mass spectroscopy, ultraviolet spectroscopy

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

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 3um, 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 infrared 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, and leads to major differences in interpretation of the temperature, latitude and diurnal behavior. Infrared measurements at 6 um capture the H-O-H bend of water uniquely, and airborne observatory measurements have detected emission from this feature and some of its variation, but analyses of a large survey dataset have just begun. However, this work demonstrates the technical potential to separate the behavior of hydroxyl from molecular water.

Example measurements: infrared spectroscopy; laser reflectance spectroscopy

Implications for exploration

[Forthcoming text supporting lunar volatile system implications for exploration]

Findings

- **FINDING:** 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 large spacecraft traffic.
- **FINDING:** The 3-dimensional 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:** Exospheric measurements of the abundance and dynamics of volatile species that may result from space-regolith interaction should be carried out, especially CO2 and ammonia.
- **FINDING:** The temporal behavior of hydration bands observed in the infrared should be characterized with definitive separation of reflected and thermal effects.
- **FINDING:** The abundance, distribution and dynamics of hydroxyl and water molecules should be unambiguously separated and characterized, including nightside abundances.

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 will be a necessary step on the way to human exploration of Mars or the moons of Saturn and Jupiter, which must be taken with as much knowledge and forethought as possible. This step will require orbital communications and navigation support globally, and especially for farside locations. It will also require appropriate platforms in appropriate orbits to host payloads that produce new resource maps derived from latest scientific instrumentation, and higher resolution topographical maps than are currently available. In addition to extending science return, a continuous lunar orbital presence at the Moon will directly support the exploration needs of the Artemis program.

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 continuous observation of the Moon, it will be possible to observe changes 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 as it happens, or soon after, when 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 the chemical composition of the surface at the location of the impact and the nature of impactors.
- New global datasets at high resolution (spectrally and spatially) 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. An LRO-2 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 from orbits to orbiters, but there are multiple stakeholders in our return to the Moon, including commercial and international partners, whose resources can be shared and leveraged to meet multiple 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 communication to Earth, to assets on the surface of the Moon, and to relay to cis-lunar assets with smaller transmitter/receivers.

While there are nearly infinite potential orbits around the Moon, we broadly classify a subset useful for lunar exploration as polar, equatorial, and distant. Distant orbits include Lagrange Points (e.g. L1, L2) and Near Rectilinear Halo Orbits (NRHOs).

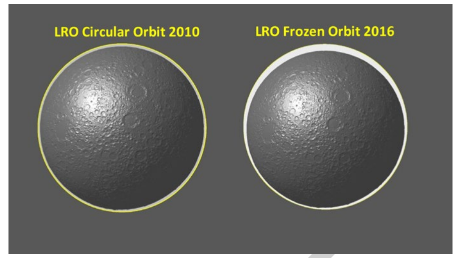


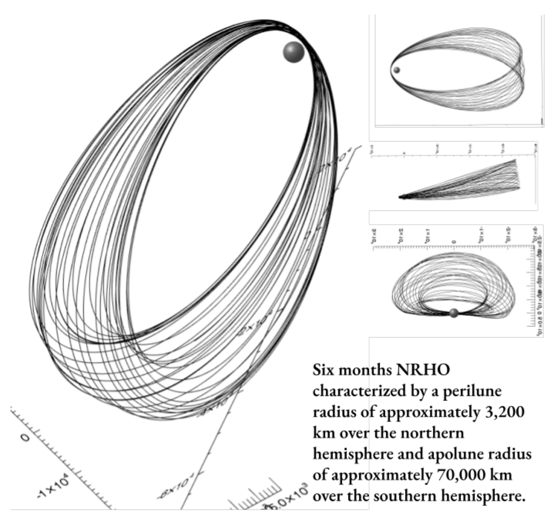
Figure 1 Example from the LRO mission illustrating the difference between the circular orbit LRO achieved early in the mission and the subsequent frozen orbit which was adopted to extend the mission

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. Where elliptical (or frozen) orbits do not require station keeping and allow an orbiter to remain active indefinitely, circular orbits must be maintained with frequent station keeping maneuvers, which will eventually deplete propellant. Since frozen orbits are stable and low frozen orbits will attract multiple missions over time, some consideration should be given to end-of-mission scenarios to prevent overcrowding. Potential options include deorbit with a controlled lunar impact or movement to a higher frozen orbit less likely to be occupied by future missions. Since either scenario will require use of reserve propellant, transition into the frozen orbit from circular orbit will need to be made sooner than what would otherwise be necessary. A controlled and targeted impact also provides an opportunity for an impact experiment such as performed by the LCROSS mission when vapors and dust in the impact plume might be monitored, crater dimensions documented, and temperature changes associated with the impact observed. The transition from circular to an elliptical frozen orbit should be planned carefully with enough remaining propellant to perform angular momentum adjustments and phasing maneuvers. Phasing maneuvers are necessary for optimal entry and exit from lunar eclipses and to time the position of the orbiter to observe events taking place on the surface, such as an impact experiment.

Highly elliptical orbits with low periapsis can be useful for 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. This approach has been adopted by the upcoming LunaH-Map cubesat mission.

- **FINDING:** Low altitude circular orbits are ideal for uniform high resolution measurements but require frequent station keeping maneuvers and are unsustainable without servicing.
- **FINDING:** 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.



Six months 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.

4.2.2 Polar vs. Equatorial Orbits

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

- **FINDING:** Polar orbits provide global coverage and should be adopted for long-term mapping orbits.
- **FINDING:** Equatorial orbits can be adopted for repeat (orbit to orbit) coverage over a selected area on the Moon 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 Near Rectilinear Halo Orbits (NRHOs), such as envisioned for Lunar Flashlight and Gateway. 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).

- **FINDING:** Distant orbits including orbits around Lagrange Points and Near Rectilinear Halo Orbits (NRHOs) have characteristics well-suited to support communication infrastructure and provide access to the lunar surface via Gateway.
- **FINDING:** Although most orbital science objectives will utilized low altitude orbits, distant orbits are ideal for monitoring for impact flashes and cis-lunar space weather.

4.3 Platforms

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

4.3.1 Larger Spacecraft

Throughout the modern era of planetary science, spacecraft capable of multiple extended missions with multi-instrument payloads have yielded scientific results that go far beyond the mission's original goals and objectives. Two examples are the Mars Reconnaissance Orbiter (MRO) and the Cassini missions. 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 to develop new modes of operations for both the spacecraft and instruments, and renew and extend science objectives that might otherwise require a completely new mission. Larger orbital platforms such as LRO, Kaguya and Chandrayaan-1/-2 enable the return of critical global coverage at high resolution and are able to observe changes on the surface over time. While the return on investment from long missions is considerable, instruments and spacecraft age. As spacecraft and instrument technology improves, a program that plans for the eventual replacement of long-lived orbiters and observations should be adopted.

- **FINDING:** 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:** 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

Smaller missions with only a few instruments that are narrowly focused on high priority objectives can quickly yield transformative science. Lunar examples include Clementine, Lunar Prospector, GRAIL, LADEE, and LCROSS. Medium-sized Lunar Trailblazer will use 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 mission launches or use smaller launch vehicles leading to lower overall costs.

- **FINDING:** Intermediate orbiters (e.g. LADEE, GRAIL, Lunar Trailblazer) are well suited for focused, short-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 LunaH-Map and Lunar Flashlight. Because these missions are low cost, require minimal resources and shorter development times, they enable higher risk approaches to test out new ideas and return valuable science quickly. Further, multi-spacecraft smallsat missions can be considered, such as tethered cubesats or swarms that return 3-dimensional distributed data sets of the lunar environment.

- **FINDING:** Cubesats (e.g. LunaH-Map and Lunar Flashlight) and other small platforms are low cost with rapid development and enable high risk, high payoff investigations and can involve constellations, tethered pairs and other configurations to be used to address unique science.

4.4 Communications and Navigation

Continuous orbital presence at the Moon will require Earth-based infrastructure including communication for commanding and data transfer and tracking for navigation purposes.

4.4.1 Communications

A continuous lunar presence using state-of-the-art and high resolution instrumentation will require commensurate advances in communication capabilities. High data rate communication will be a common need by all stakeholders at the Moon and a strategy of shared resources and commitments should be implemented. 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 lunar farside is shielded from earth-based radio transmission which provides an opportunity for radiowave 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:** Lunar surface and cis-lunar vicinity communications must be supported to advance science and exploration objectives.
- **FINDING:** Development of advanced, high data rate communication (e.g. laser-based, internet in space) should be pursued.
- **FINDING:** Strategies that preserve lunar farside radio astronomy opportunities must be implemented.

4.4.2 Navigation

Navigation about the Moon is aided by the considerable detail of the gravity field measured by the Grail mission. However improvements on tracking and spacecraft attitude control will enable more precise geolocation of observations from orbit of the surface. In the long term, orbital navigation services will aid activities on the lunar surface where precise geolocation is necessary.

- **FINDING:** No additional refinement of the lunar gravity field is necessary for navigation purposes (although advancements in gravity science are possible).
- **FINDING:** Improved geolocation technology can assist surface operations and in the long term global positioning satellites will enable precise (meter scale) location information for any asset on the Moon.

4.5 Operations and Ground Segment

Over the next decade and beyond considerable activity at the Moon will take place by NASA, other government agencies, international space agencies, and commercial interests. This may present a significant challenge for coordination and cooperation arising from a multi-agency, multi-mission space environment but also an opportunity to achieve common goals with lower costs as unnecessary redundant activities are eliminated.

4.5.1 Multi-Mission Operations

One possibility that should 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:** Multi-mission operation centers can save on costs, improve communications across missions, and reduce the demands on personnel and training should be considered.

4.5.2 Agencies and Entities

As activities at the Moon increase among diverse stakeholders, cooperation and communication will be essential. 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, spacecraft orbit altitude and orbit plane could be chosen partially on the basis of what other orbiters are doing or planning.

- **FINDING:** NASA should establish a single office tasked with coordinating across space agencies and within NASA for sharing resources and optimizing science return.

4.6 Planetary Data System

Advanced communication capabilities and the Moon's relative proximity will enable unprecedented planetary data collection and transfer to fulfill scientific needs for high resolution measurements. This may result in order of magnitude increases in data volume.

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

5. Measurement Approaches

5.1 Introduction and Scope

Since 2007, numerous orbital missions led by the U.S., India, China, and Japan 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 defined by U.S. and international priority documents, including the Planetary Decadal Surveys, the NRC Scientific Context for the Exploration of the Moon (SCEM) report, the ASM-SAT report, the LEAG Lunar Exploration Roadmap, and the Global Exploration Roadmap. In order to meet the scientific consensus 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 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. We outline 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 specific types of measurements that are needed to achieve high-priority science and exploration objectives while remaining agnostic on specific instruments 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 PSD, human exploration, and/or STMD; whether it would impose any mission-level requirements (e.g., communications, data rates, or orbits); and any known development cycle challenges.

The information used for this chapter is drawn primarily from previously concluded LEAG reports and White Papers submitted to CLOC-SAT. 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 that we do not cover, 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.

5.2 Breadth of Measurements of the Moon

We group measurements into several broad categories: Fields and Particles; Geophysical Measurements; Spectroscopic Approaches for Surface Characterization; Surface Geology and Geomorphology; and Subsurface Probes. Each category has a summary table for quick reference. The measurements discussed here are anticipated to have significant impacts for exploration and science objectives; however, the following list is intended to only provide examples of the types of measurements that could be employed in addressing science and exploration objectives, but it should not be considered complete and it should be expected to evolve as new technologies are developed and new discoveries are made.

5.2.1 Fields and Particles

Radiation and Plasma Environment

Continuous orbital measurements are required to monitor solar activity and the radiation and electromagnetic environment at the lunar surface and in cis-lunar space. 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 desireable. 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, 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/THEMIS measurements and providing a fourth dimension to these studies.

[additional text forthcoming on specific types of measurements for space weather, plasma observations, and radiation, with some info in white papers and ESF comments]

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 seek 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. 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. Surface and orbital platforms require 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 the anomalies. The orbital package should also include an energetic neutral atom detector which can monitor the solar wind reflected and neutralized upon impact with the surface.

[additional text forthcoming on specific types of measurements for magnetic fields]

Exosphere Components

Observations of the lunar exosphere by prior spacecraft including LADEE (NMS) and Kaguya/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. 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 lunar volatile cycle. Long-term orbital measurements should also include the exosphere's response to exogenous events including micrometeorite impacts and anthropogenic or robotic activities, and to observe possible transient 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.

[additional text forthcoming on exosphere measurements (e.g., neutral mass spectroscopy (NMS), and far-UV imaging ala LADEE example). To include ESF feedback, human/exploration relevance, potential ISRU locations and compositions]

TABLE 5-2-1: Measurements for Fields and Particles

Meas.	Objectives	Future Mission Support	Directorate Relevance	New or Advancement	Type of Obs	Mission-Level Req's	Readiness
Radiation and plasma detectors	Hazard mitigation; Flux variations over solar cycles	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	TBR
Magnetic fields	Space-surface interactions; Surface magnetic field strengths; Sources of magnetic fields; Hazard mitigation	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	TBR
Neutral and ion mass spectroscopy	Flux of different species; Volatiles cycle; Potential	All surface missions sensitive to exosphere composition	PSD, Human	Improves on LADEE and Kaguya/SELENE; Improved detection limits	Long-term, global	Polar orbit for volatiles	TBR

	resources			to expand study to additional components			

5.2.2 Geophysical Measurements

Tectonic Activity

The Moon is tectonically active, and orbital measurements of surface features associated with tectonic processes enable characterization of those processes and provide new information about the lunar interior. Additionally, quantifying current tectonic activity, including identifying zones of high activity, are important to understanding and defining potential tectonic hazards to surface missions. High-resolution imaging at scales of 10's of centimeters to a few meters provides one of the most direct methods to measure and characterize the surface geomorphic expression of tectonic activity on the Moon. Repeat imaging can be used to detect and measure surface changes.

[forthcoming text supporting important additional measurements including repeated interferometric radar or high precision swath lidar mapping to characterize the finite strain and associated stress fields over the lunar surface. Precise PNT (pointing/nav/timing) needed for some surface investigations.]

[text forthcoming describing global measurements required to calculate stress state of the Moon]

The Lunar Geophysical Network (LGN) mission is one of several New Frontiers concept missions recommended by the 2022 Astrobiology and Planetary Science Decadal Survey Report. 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. In addition, local measurements of crustal heat flow by LGN nodes would be enhanced by global spatially resolved heat flow measurements from orbit, for example, using long wavelength microwave radiometry.

Gravity Science

GRAIL provided an advanced global lunar gravity model from a co-orbiting spacecraft approach at an altitude of 50km, which is currently state-of-the-art. Improvement of the global gravity model is possible with additional measurements with a higher spatial resolution gravity gradiometer flown at low-altitude lunar orbit (<50 km).

[text describing state-of-art for gravity science and prospective improvements. Possible state of lunar core determinations?]

TABLE 5-2-2: Geophysical Measurements

Meas.	Objectives	Future Mission Support	Directorate Relevance	New or Advancement	Type of Obs	Mission-Level Req's	Readiness
Tectonic activity	Magnitude of waves; extent and areas of high tectonic activity as expressed by surface geomorphology; Hazard mitigation; Current stress state of the Moon	All surface missions to potentially active locations, particularly long-duration missions; LGN support	PSD, Human	Improves on LROC and topographic interpretations; Global view required to calculate stress state	Long-term; on-demand; global	Precise position and localization needed for some measurements; high-res and lower altitudes	TBR
Gravity Science	TBR						

5.2.3 Spectroscopic Approaches for Surface Composition

To address objectives related to the evolution of interiors and surfaces, compositions of interiors and surfaces, as well as human and robotic explorer scale mission support and planning, high spatial resolution spectroscopic characterization of the lunar surface is highly desirable. These measurements should address fundamental scientific objectives in lunar community documents, including those related to lunar volcanism, lunar magma ocean processes, space weathering, and the processes associated with lunar volatiles and organics. Highly beneficial products from these measurements include fine-scale to intermediate-scale maps of lunar surface chemistry, mineralogy, and volatiles. These measurements should also provide major contributions to exploration planning and resource definition for surface activities.

Mineralogy and Petrology

Advances in mineralogy and petrology should be enabled by improved spatial resolution of measurements (by at least 10x over current data sets) as well as through improved spectral resolution and new types of spectral information.

In the visible near-infrared (VNIR), which spans 0.6 to 4 microns, spectral features are used to investigate iron-bearing minerals with absorptions around 1 and 2 microns, as well as OH/H_2O absorptions near 3 microns. The UVVIS spectral region (0.3 to 1 micron) has been used to study glass, titanium, ilmenite and space weathering components on the Moon's surface. The spatial resolution of orbital UV data has been limited by available detectors and lenses. Clementine, LRO, and Kaguya/SELENE have provided some of the best UVVIS maps of the lunar surface to date at ~64 to 400 meters per pixel scales. High spatial resolution (e.g., 10 m/pixel) UVVIS and VNIR imaging spectrometers (either multispectral or hyperspectral) 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 the Moon Mineralogy Mapper aboard the Chandrayaan-1 spacecraft. Point spectrometers provide spectroscopic measurements for locations along a path made each orbit. With time, accumulated data gradually provides spatial coverage of the surface. Whereas imaging spectrometers use 2D-detectors paired with spacecraft motion to build up an image along the spacecraft's track. Imaging spectrometers are generally better suited for mapping purposes.

At longer wavelengths (typically 7 to 25 microns), high resolution (e.g., 10 m/pixel scales) thermal infrared (TIR) hyperspectral imaging would provide lithologic mapping complementary to UVVIS-VNIR measurements, especially of Fe-poor lithologies, as well as correlated temperature measurements useful to determine lunar surface thermophysical properties. A TIR hyperspectral imager has never been flown at the Moon; the current best TIR data is provided by LRO Diviner, with spatial sampling of ~500 m/pixel and 3 bands used for compositional analysis around 8 microns.

Between the traditional VNIR and TIR wavelength ranges, lies the "cross-over NIR-MIR region" (4 to 7 microns), which has recently been shown to provide a strong indicator of olivine and pyroxene solid solution composition as well as readily identifiable features due to quartz and other silica polymorphs. It also is sensitive to H_2O absorptions near 6 microns. Furthermore, it is relatively insensitive to space weathering, which can complicate interpretations of VNIR and TIR data. This is a new spectral region for planetary studies for which data have not yet been acquired.

The measurements (UV-VIS-NIR-IMIR-TIR at scales better than 50 m) enabling a global inventory of surface compositions should aim to improve on the spatial and/or spectral resolution of currently available data sets, with special techniques applied in low illumination (low signal) regions. 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, or volatiles. To assess large boulder compositions and mineralogy, measurements at scales better than 10 meters are needed. Meter-scale measurements from orbit are also highly desirable for robotic and human-scale planning and operations on the lunar surface, and for investigating microenvironments. Boulder and human-scale composition and mineralogic information, while highly beneficial in planning future missions, also provide key mineralogic and compositional context for localized surface activities and investigations.

Geochemistry

Lunar surface chemistry can be characterized through X-ray spectroscopy (XRS) and gamma ray and neutron spectroscopy (GRNS). Both techniques require long-lived orbital platforms to build sufficient counting statistics to make high SNR measurements. XRS requires strong solar activity, and timing of future XRS instruments should be optimized with the Sun's solar cycle in mind. 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/degree. Neutron spectroscopy (NS) further provides an independent quantification of H-abundance, which is highly complementary to UVVIS, VNIR, IMIR, and other techniques aimed at characterization of OH and H_2O.

[Additional text forthcoming about the spatial resolution advancements for GRS and NS. Note Chandrayaan-2 XRF for elemental composition of surface and other international missions].

Volatiles

Orbital remote sensing 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. In addition to VNIR and IMIR spectroscopy, there are other techniques to measure volatiles. For example, multispectral lidar measurements tuned to the 3 micron H_2O/OH^- bands could be used to search for surface-exposed H_2O in permanently shadowed regions (PSRs) and transiently shadowed regions (TSRs). The single-wavelength LRO Lunar Orbiter Laser Altimeter (LOLA) instrument demonstrated the use of active lidar (at 1064 nm) to detect surface reflectance changes in PSRs and TSRs that might be attributed to surface water-ice or frost. Repeat observations with active lidar would have the benefit of not being dependent on having sufficient solar illumination and could be used to detect changes over time, including those generated by volatile behaviors, seasonal changes, and robotic/human surface activities.

Lunar surface volatiles, especially water frost, would further be quantitatively characterized through hyperspectral ultraviolet (UV) imaging of the lunar surface. The Far-UV (FUV) is typically considered the wavelength range from 120 to 300 nm (0.12 to 0.3 microns) and contains the Lyman-alpha feature. A FUV hyperspectral imager would provide higher spatial and more spectral feature resolution than the LRO Lyman Alpha Mapping Project (LAMP) instrument, which characterized water frost and space weathering on the lunar surface. Measurement approaches that can retrieve H_2O abundances at the 1 wt% level and in surface thicknesses of 1 micron would be beneficial.

Organics

[text supporting organics forthcoming, including active fluorescence spectroscopy as a tool to detect organics from orbit.]

TABLE 5-2-3: Spectroscopic Measurements

Meas.	**Objectives**	**Future Mission Support**	**Directorate Relevance**	**New or Advancement**	**Type of Obs**	**Mission-Level Req's**	**Readiness**
UVVIS-VNIR imaging spectroscopy	Mineralogy, Volatiles, Space Weathering, Resources, Mission Planning	All, especially provides context for surface missions	PSD, Human	Improve spatial or spectral resolution over current data sets	Global coverage	High resolution imaging usually tracks with low altitude and high data rates	TBR
IMIR imaging spectroscopy	Mineralogy, Volatiles, Resources, Mission Planning	All, especially provides context for surface missions	PSD, Human	New type of measurement at the Moon	Global or regional	High resolution imaging usually tracks with low altitude	TBR

						and high data rates	
TIR imaging spectroscopy	Mineralogy, Mission Planning	All, especially provides context for surface missions		Improve on Diviner's compositional measurements in spatial and spectral feature resolution	Global or regional	High resolution imaging usually tracks with low altitude and high data rates	TBR
XRS, GRNS	Mineralogy, Volatiles, Resources, Mission Planning	All, especially provides context for surface missions	PSD, Human	Improve on Lunar Prospector and Kaguya/SELENE, Chang'e-1 measurements	Global, requires many orbits to build up coverage and signal	Altitude constraints	TBR
Lidar reflectance	Volatiles, Resources	All, especially provides context for missions investigating volatiles	PSD, Human	Improve and expand on the LOLA 1064 nm example	Global, requires many orbits to build up spatial coverage	Altitude constraints	TBR
FUV spectroscopy	Volatiles, Composition	All, especially provides context for missions investigating volatiles	PSD, Human	Improve on LAMP measurements	Global or regional	TBR	TBR
Active fluorescence spectroscopy	Organics	Provides context for missions exploring organics	PSD, Human	New type of measurement for the Moon	TBR	TBR	TBR

5.2.4 Approaches for Surface Geomorphology/Geology

Orbital observations provide the best opportunity for surface geology characterization while also providing key regional and global context for other missions as well as returned samples. High-resolution optical, spectroscopic, and radar imaging as well as LiDAR-based topography and thermal mapping are the established foundations for selecting and characterizing future robotic and human landing sites for safety, navigability, and scientific interest. These data and observations are also cornerstones of geologic investigations and investigations of geomorphologic features such as faults and fractures, impact craters, and volcanic features.

[text forthcoming on: potential improvements, including swath-mapping lidar/altimetry, high resolution infrared radiometer thermal mapping, thermal radiometry and boulders, porosity, layering of surface; high and medium resolution optical cameras, more radar, extreme high resolution imaging and topography data (10-cm scale).

- Very high spatial resolution (<10 cm/pixel?) images (visible wavelength, multispectral?, lidar?) of the lunar surface for planning of EVAs and robotic activities, including both identification of science targets as well as operational assessments of terrain (access/trafficability, hazards, operational limits) at spatial scales most relevant for human and robotic activities.
- Very high spatial resolution (<10 cm/pixel?) topographic data (derived from imagery and/or lidar). Add note about Chandrayaan 2 OHRC (image res of 0.3 m at 62 km alt, and possible DEM products from those)
- High radiometric resolution imagery to see into PSR/TSR areas
- Radar imaging improve on MRF, additional bands. Note: Chandrayaan-2 DFSAR

Detecting Surface Changes

[forthcoming text on: High resolution imaging, topography (lidar), thermal radiometry, and change detection monitoring

- Example for Impacts of all scales and impact cratering processes
  - Real-time monitoring of meteors and micro-impactors or other debris that could potentially impact the surface
    - Impact rate -Need data on sizes, ranges, velocities, and frequencies of impactors.
    - Used as inputs into shielding technologies for long-term surface activities.
    - Informs current impact production rates and impact cratering studies (science whys)
    - Real-time monitoring of meteors and micro-impactors or other debris that could potentially impact the surface
  - Impact flash monitoring
  - Study primary and secondary craters
    - Temporal imaging - present day flux
    - Topo for morphologies and formation processes (not much data yet for meter-scale and smaller craters)
  - Coldspot properties (IR radiometry, high-res VIS images, long-temporal imaging for changes over time, search for new coldspots)
- Effects of engine blast zones and monitor for changes over time and measure propulsion-driven ejecta - important for planning for resupply and building infrastructure on surface, rates of space weathering
- Mass wasting - montoriting for extent of changes, ongoing geologic activity
- Seismicity - monitoring for fault movements to understand current state of the Moon and determining hazard to surface activities

Geotechnical Measurements of Regolith

[forthcoming text on: regolith structure and properties

- Geotechnical measurements derived from blast zones and sites of surface activities (high sensitivity composition, thermal, high-resolution images)

- Regolith depth, density, grain size, slopes, rock and dust hazards for predictive models of surface development (e.g., construction or deployment of assets) and mobility, as well as sampling technique and tool development.
- Used for surface exploration planning. Need to develop 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.
- Related to advances in regolith and evolution science
- Data to potentially enable linkages between orbital observations and ground-truthed geotechnical properties, i.e. make estimates of things like grain size distribution, relative density, grain shape parameters, etc. using remotely-sensed proxies]

TABLE 5-2-4: Geomorphology and Geology Measurements [forthcoming]

Meas.	Objectives	Future Mission Support	Directorate Relevance	New or Advancement	Type of Obs	Mission-Level Req's	Readiness

5.2.5 Approaches to Investigate the Subsurface

Radar Sounding

[Text is forthcoming, to address:

- Radar sounding provides structural information at 10's-100 m depths. Sounding between 20-400 MHz provides information from ~5-100 m depth about volcanism, subsurface impact structures, and water ice.
- MARSIS and SHARAD examples provided electrical and physical information, including water-ice presence.
- 20 to 40 MHz optimum for upper regolith characterization; lower depths of penetration requires lower frequencies. Would potentially allow the deeper highlands megaregolith to be probed as well as the thickness of the mare basalts to be determined. Subsurface deformation of maria by wrinkle ridge thrust faults could be characterized.
- Kaguya Lunar Sounder, Chang'e Sounder examples]

Microwave Radiometry and Heat Flow

[forthcoming text on:

- Microwave radiometry combined with high resolution thermal mapping provides a mechanism to measure subsurface heat flow. It provides a measure of near surface rock abundance and composition (+/- ilmenite) and regolith thickness/depth to bedrock.

- cosmic rays as natural RF source]

TABLE 5-2-5: Subsurface Measurements [forthcoming]

Meas.	Objectives	Future Mission Support	Directorate Relevance	New or Advancement	Type of Obs	Mission-Level Req's	Readiness
Radar sounding							
Microwave radiometry and Heat Flow							

5.2.6 Environmental Conditions

Illumination

[forthcoming text on:

- Extended observations of illumination and temperatures from orbit
    - Extended orbital data enable detailed mapping of lunar poles (high resolution topography combined with extended-time surveys of illumination and temperatures)
    - Used to determine extent and age of cold traps, correlate with level of illumination and changes over time. (science whys)
    - Needed for planning surface activities for specific time periods (exploration whys), critical for determining polar power generation requirements for surface missions
    - Planning surface activities requires an evaluation of power generation methods at a site, and whether solar technologies are sufficient. Planning power (generation and storage) are needed for lunar nighttime stays and mobile systems as well.]

Surface Temperature

[text forthcoming]

5.2.7 Additional Exploration Support and Objectives

Lunar Geodesy and Navigation

[forthcoming text on:

- Measurements to improve the lunar geodetic grid and navigation

- Measurements that enhance overall accuracy and precision of lunar references and data tied to it - facilitates future exploration planning and data analysis for science = TBD]
- HLS, CLPS, etc. requirements]

Autonomous Landing Support

[forthcoming text on:

- Measurements to support autonomous and safe landings
  - Develop new autonomous capabilities to land safely and accurately, might require real-time onboard high resolution imaging or LIDAR processing and/or preflight data. Need to test hazard tolerant landing systems and avoidance technologies. Requires prior knowledge of hazards that cannot be tolerated
  - Very high spatial resolution (<10 cm/pixel?) images (visible wavelength, multispectral?, lidar?)
  - Very high spatial resolution (<10 cm/pixel?) topographic data (derived from imagery and/or lidar)
  - HLS, CLPS requirements?]

On-Demand Monitoring of Surface

[forthcoming text on:

- Continuous and on-demand communications and monitoring of surface assets (example high-resolution imaging in visible and thermal)
  - Coordinated communications between surface and other assets. (e.g., through line-of-sight, relays, high-band width, on-demand support or monitoring of surface assets for system health, safety, or political or regulation purposes)
  - Communicating activities with the population of Earth
- High temporal resolution to enable rapid/frequent/timely acquisition of images to capture EVA/robotic activities as they occur (or otherwise immediately afterwards). (Near) real-time capability will enable monitoring of human and robotic surface activities so as to make accurate determinations of locations visited, paths taken, and sequence of events (position/navigation/timing, PNT) and establish context for exploration activities and acquired datasets/samples.]

TABLE 5-2-6: Exploration Measurements [forthcoming]

Meas.	Objectives	Future Mission Support	Directorate Relevance	New or Advancement	Type of Obs	Mission-Level Req's	Readiness

5.2.8 Summary statements on breadth of measurement approaches

[summary statement of measurement approaches, including:

- Some future measurements could make advancements on prior measurements, complementing or enhancing our current data for the Moon.
- Some objectives and requirements for new measurements/data will drive communication stations and rates, data storage strategies, etc. Some of these might work best in certain architectures vs others.
- Spatial coverage (e.g., localized/patchy vs global)
- Temporal needs (e.g., instantaneous, repeated (e.g., for statistics), time-baseline; measurements at specific times (or many times) of day for variable solar illumination, temperatures, phase angle coverage, etc.
- These techniques have applications for both science and exploration objectives, including relevance to human programs.
- Examples requiring development to become flight ready in the near-future: sounding radar (20-400 MHz), swath LIDAR at sub-meter scales, hyperspectral TIR (5-25 microns) imaging, 'crossover' IMIR (4-8 microns) spectroscopy, etc.
- Mature instrument designs define flight requirements, such as power, volume, mass, data, and orbit for planned architectures, implementations, and class of mission (large orbiter, small orbiter, cubesat).

- **FINDING:** Appropriate and stable funding for maturation and flight-readiness of orbital instruments and measurements (e.g., DALI program) is essential to increasing the breadth of available measurement types for future missions.

5.3 Data Management Strategies

[forthcoming text on:

- Planned orbital measurements shape the architecture and implementation of missions (e.g., orbit geometry, altitude, duration, data volume, etc.) and the nature of data returned.
- Some examples of data return volumes?
- With multiple ongoing and future lunar activities (Artemis, CLPS, VIPER, and international instruments and missions), making data interoperable will maximize their benefits for all.
- Coordinate data collection and storage strategies across missions.
- This significant data return requires effective data management strategies. Are Landsat and other Earth observation programs a useful model, or commercial remote sensing satellite operations?]

- **FINDING:** 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.

5.4 Priority Measurements

[text that motivates the prioritization]

5.4.1 Long-term Orbital Measurements

[forthcoming text on:

- Temporal measurement needs include instantaneous, repeated (for validation), and measurements at different times of day to track variable solar illumination, temperature, phase angle effects, etc. over appropriate temporal baselines.
- Dynamic moon needs long temporal baseline obs
- Improved knowledge of variable surface environment, chemistry, and material properties is important for engineering design of surface hardware and mission and site architectures for long-duration activities including those within the polar regions (e.g., ISRU, power, and comm strategies that depend on a specific location).
- Additional example measurements: Extremely high-resolution imaging to document potentially hazardous impacts at 10-cm scales or better. Detection of strain displacements over a year baseline can be achieved by interferometric radar or swath mapping lidar at sub-meter spatial resolution. Microwave spectroscopy at or better than 10-km scales could provide spatially resolved measurement of heat flow similar to Apollo experiments.
- Context for future sample returns of soils, rocks, extracted volatile samples

- **FINDING:** 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, regolith chemistry, exosphere behavior, radiation, and space weather.

5.4.2 Global Context Uniquely Provided from a Long-Duration Orbital Platform

[forthcoming text on:

- Compositional measurements include high spatial resolution measurements (at 10-m scale or better) with high spectral resolution for key spectral features (e.g., VNIR/IMIR/TIR hyperspectral imaging).
- Additional examples of valuable measurements include microwave sounding for information about near-surface properties and thermal state (upper 10s of m) and low-altitude magnetic field patterns for information about ancient lunar dynamo and local space weathering environment.
- Priority measurements that can enhance CLPS science…
- Complementary to sample return
- Can provide on-demand obs. As well as follow ups on new discoveries

- **FINDING:** Additional orbital measurements are uniquely suited to providing the comprehensive global context that is critical to making further evaluations of the full compositional range of lunar materials.
- **FINDING:** Orbital measurements providing global and regional context are highly beneficial for mission planning and when choosing destinations for focused exploration or sample return.

5.4.3 Soil, Rock, and Rover-Scale Observations from Orbit

[forthcoming text on:

- Gap in connections from orbital data to lander-, rover-, human-, and individual rock-scales. Critical context for interpretations as well as planning missions. Site specific difference in soil properties.
- Landing site evaluations and selections; supporting surface activities including CLPS and planning for sample returns. Facilitate planning or lower risk for future surface missions
- Examples include high-resolution topography and composition for landing regions as well as time- and site-specific environmental conditions.
- Sub-meter spatial resolutions in topography and image data are often requested for hazard and landing site assessments, but such data and measurements are not currently available.

- **FINDING:** Additional lunar orbital measurements would provide highly beneficial information at a few-meters scale or better, which could be used to address key science tying regional to local and rock scale interpretations as well as to facilitate or lower risk for future missions.

5.4.4 Volatiles and Resources

[forthcoming text on:

- Near-term high-priority measurements include UV/VNIR/IMIR/TIR spectroscopy and imaging, orbital mass spectroscopy, multispectral laser reflectance and fluorescence, and neutron spectroscopy. Such data provide an essential framework for volatile cycles on the Moon.
- By improving coverage, spatial resolution and depth range, detection of species present, and dynamic behavior expanded measurements address the composition, distribution, classification, and quantification of volatiles and the materials that host them (e.g., long wavelength radar and passive R/F detection)
- Integrated measurements significantly aid in resource characterization and feed into resource uses and mission planning.
- Context for any future volatile sample returns.
- **FINDING:** 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:** 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.

5.5 Summary of Measurement Approaches and Findings

[text summarizing conclusions and findings]

6. Example Mission Scenarios and Summary

[This chapter is not included in the Draft Report. Suggestions for example mission scenarios to consider are welcome.]

Appendices

- *Appendix 1: Acknowledgements* [not included in draft report]
- *Appendix 2: List of All Findings*
- *Appendix 3: List of Acronyms*
- *Appendix 4: Glossary* [not included in draft report]
- *Appendix 5: References* [not included in draft report]
- *Appendix 6: Alphabetical List of White Papers*
- *Appendix 7: CLOC-SAT TOR* [not included in draft report]

Appendix 2: List of All Findings

Overarching Findings

The findings below are numbered for convenience and are not prioritized:

1. Continuous lunar orbital capabilities are essential to moving forward during the coming decades of international science and exploration. The next generation of orbital capabilities is required to enable more robust knowledge of the Moon and to provide communication and navigation support for both the lunar surface and cis-lunar vicinity.
2. Maintaining a path forward for emerging new instruments and capabilities enables new and unexpected discoveries.
3. Lunar science and exploration orbital needs through the next decades will benefit from diverse orbits and implementation approaches ranging from small exploratory satellites to modern instruments on long-lived LRO-class satellites.
4. The needs for lunar orbiter data storage, access, and retrieval must be regularly reviewed and upgraded so that data collections are readily available for new and ongoing analyses.
5. A variety of very high spatial resolution observations (< 1 meter) are essential for characterizing landing sites and surroundings and monitoring temporal variations as exploration activities expand.
6. Long temporal-baseline platforms enable critical monitoring of the surface and exosphere, including the effects of both natural and anthropogenic activities.
7. High-quality global-scale data provide valuable context for addressing current questions and long-term planning. As diverse orbital tools and information for exploration and science activities evolve, insight into and understanding of planetary-scale issues will result from orbital studies of the whole Moon.
8. The demonstrated value of an LRO-class satellite with diverse instruments operating collaboratively at the Moon cannot be overstated. Plans for a next generation lunar satellite with modern instruments that can replace the highly productive LRO (launched in 2009) are long overdue.

Topical Findings

The findings below are included in the order presented in 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
  - In order to ground truth surface heat flow measurements and extrapolate our understanding, orbitally-derived maps of heat flow require an accuracy comparable to Apollo at ~10 km spatial resolution.
  - Determining the bulk composition of the Moon requires estimates of heat flow at locations far from the Apollo zone.
  - Regional heat flow measurements at the poles are required to support interpretation of Artemis and other surface polar data, and to better understand the distribution of buried ice.
  - [Forthcoming finding(s) related to inner core investigation]
- 3.3.2 Lunar Volcanism and Magmatism

    - [Forthcoming finding(s) related to volcanism / magmatism]
- 3.3.3 Lunar Tectonics
    - Measurements of accumulating stress should be carried out to understand the contemporary tectonic environment and better characterize the seismic hazard.
    - Detection of mass wasting events as result of on-going lunar seismicity should be continued.
- 3.3.4 Understanding the impact process at all scales
    - 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.
    - Continuous monitoring at the >1 meter scale is required to refine the measurements of the primary and secondary flux and detect new impacts at the >>1 meter scale.
    - 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
    - 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
    - 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.
    - 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.
    - Newly discovered compounds may provide resources for ISRU, such as carbon at the poles, and recoverable water in hydrated iron oxides.
    - Characterizing the three dimensional structure of magnetic fields associated with anomalies helps elucidate the relationship between surface anomalies and the heliospheric environment.
- 3.3.6 The composition of the Moon through the lens of its surface deposits
    - 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 advances
    - Completing the compositional inventory of the Moon with high quality contiguous global compositional measurements at < 50 meter resolution is essential to ensure the mineralogic diversity of the Moon is captured.
    - Direct measurements of the compositional nature of the lunar mantle through detection and characterization of ultramafic lithologies at ~10 meter 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.
    - Compositional imaging of the Moon at ~1-10 meter or higher resolution is a priority to support surface operations.
- 3.3.7 Polar Region Microenvironments
    - 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-meters) with context of surface temperature and temperature history.

- 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.
- Measuring the isotopic composition of ejecta lofted from contemporary natural or artificial impacts could provide the isotopic composition of sequestered volatiles.
- The dynamics of water-ice at diurnal, seasonal and precessional timescales should be characterized with measurements sensitive to abundances well below 1%, and ice layer thicknesses much less than 1 micron.
- Searches for buried water ice should be conducted to depths of 10 meters or greater to test emplacement hypotheses and to address the viability and sustainability of the water-ice resource.
- Evidence should be sought in the exosphere for volatiles activated by loss mechanisms.
- The abundance and distribution of methane and more complex organics should be characterized to define their scientific and resource potential.

- 3.3.8 The Lunar Volatile System
  - 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 large spacecraft traffic.
  - The 3-dimensional 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.
  - 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.
  - The temporal behavior of hydration bands observed in the infrared should be characterized with definitive separation of reflected and thermal effects.
  - The abundance, distribution and dynamics of hydroxyl and water molecules should be unambiguously separated and characterized, including nightside abundances.

Chapter 4 Implementation Approaches and Architectures

- 4.2.1 Circular vs. Elliptical Orbits
  - Low altitude circular orbits are ideal for uniform high resolution measurements but require frequent station keeping maneuvers and are unsustainable without servicing.
  - 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 provide global coverage and should be adopted for long-term mapping orbits.
  - Equatorial orbits can be adopted for repeat (orbit to orbit) coverage over a selected area on the Moon and these orbits provide high local time resolution measurements.
- 4.2.3 Distant Orbits
  - Distant orbits including orbits around Lagrange Points and Near Rectilinear Halo Orbits (NRHOs) have characteristics well-suited to support communication infrastructure and provide access to the lunar surface via Gateway.

- Although most orbital science objectives will utilized low altitude orbits, distant orbits are ideal for monitoring for impact flashes and cis-lunar space weather.
- 4.3.1 Larger Spacecraft
  - 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.
  - 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
  - Intermediate orbiters (e.g. LADEE, GRAIL, Lunar Trailblazer) are well suited for focused, short-duration investigations that address compelling scientific objectives using the most advanced and capable instrumentation.
- 4.3.3 Smaller Spacecraft
  - Cubesats (e.g. LunaH-Map and Lunar Flashlight) and other small platforms are low cost with rapid development and enable high risk, high payoff investigations and can involve constellations, tethered pairs and other configurations to be used to address unique science.
- 4.4.1 Communications
  - Lunar surface and cis-lunar vicinity communications must be supported to advance science and exploration objectives.
  - Development of advanced, high data rate communication (e.g. laser-based, internet in space) should be pursued.
  - Strategies that preserve lunar farside radio astronomy opportunities must be implemented.
- 4.4.2 Navigation
  - No additional refinement of the lunar gravity field is necessary for navigation purposes (although advancements in gravity science are possible).
  - Improved geolocation technology can assist surface operations and in the long term global positioning satellites will enable precise (meter scale) location information for any asset on the Moon.
- 4.5.1 Multi-Mission Operations
  - Multi-mission operation centers can save on costs, improve communications across missions, and reduce the demands on personnel and training should be considered.
- 4.5.2 Agencies and Entities
  - NASA should establish a single office tasked with coordinating across space agencies and within NASA for sharing resources and optimizing science return.
- 4.6 Planetary Data System
  - The Planetary Data System must be appropriately scaled over time to accommodate the expected increases in data returned from the lunar surface and orbit.

Chapter 5 Measurement Approaches

- 5.2.8 Summary statements on breadth of measurement approaches
  - Appropriate and stable funding for maturation and flight-readiness of orbital instruments and measurements (e.g., DALI program) is essential to increasing the breadth of available measurement types for future missions.
- 5.3 Data Management Strategies
  - 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.

- 5.4.1 Long-term Orbital 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, regolith chemistry, exosphere behavior, radiation, and space weather.
- 5.4.2 Global Context Uniquely Provided from a Long-Duration Orbital Platform
    - Additional orbital measurements are uniquely suited to providing the comprehensive global context that is critical to making further evaluations of the full compositional range of lunar materials.
    - Orbital measurements providing global and regional context are highly beneficial for mission planning and when choosing destinations for focused exploration or sample return.
- 5.4.3 Soil, Rock, and Rover-Scale Observations from Orbit
    - Additional lunar orbital measurements would provide highly beneficial information at a few-meters scale or better, which could be used to address key science tying regional to local and rock scale interpretations as well as to facilitate or lower risk for future missions.
- 5.4.4 Volatiles and Resources
    - 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.
    - 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.

Appendix 3: List of Acronyms

A3SDT	Artemis III Science Definition Team Report
Artemis	Artemis Program
ARTEMIS	Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun
ASM-SAT	Advancing Science of the Moon Specific Action Team
CLOC-SAT	Continuous Lunar Orbital Capabilities Specific Action Team
CLPS	Comercial Lunar Payload Services
Diviner	Diviner Lunar Radiometer Experiment
FUV	Far ultraviolet
GCR	Galactic cosmic ray
GRAIL	Gravity Recovery and Interior Laboratory
GRNS	Gamma ray and neutron spectroscopy
GRS	Gamma ray spectroscopy
HCN	Hydrogen cyanide
IMIR	Intermediate infrared
InSAR	Interferometric Synthetic Aperture Radar
ISRU	In Situ Resource Utilization
ITT	Investigation Traceability Tensor (see Table 1)
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
LGN	Lunar Geophysical Network
LiDAR	Light Detection and Ranging
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
MRO	Mars Reconnaissance Orbiter
MTT	Measurement Traceability Tensor (see Table 2)
NIR	Near infrared
NMS	Neutral Mass Spectrometer
NRHO	Near Rectilinear Halo Orbit
NS	Neutron spectroscopy
OWL	Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032
PKT	Procellarum KREEP Terrane
PRISM	Payloads and Research Investigations on the Surface of the Moon
PSR	Permanently Shadowed Region
SCEM	The Scientific Context for Exploration of the Moon
STM	Science Traceability Matrix
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TIR	Thermal infrared
TSR	Transiently shadowed regions
UV	Ultraviolet
UVVIS	Ultraviolet visible
VNIR	Visible near-infrared
XRS	X-ray spectroscopy

Appendix 6: Alphabetical List of White Papers

The Case for Orbital Lidar Swath-Mapping at the Moon

A Case for Passive Microwave Wavelength Measurements From Lunar Orbit

Advanced UV Water Frost and Adsorption Signature Orbital Mapping Instrument Concepts

Characterization of Lunar Surface Thermal Environment and Physical Properties using Advanced Thermal Imagers

The Contribution of Active Spectroscopy to Orbital Remote Sensing of Lunar Volatiles

Cross-Over Infrared Spectroscopy: A New Tool for Remote Mineral Detection and Compositional Determination in the 4-8 μm Wavelength Range

Hydrogen Prospecting at the Lunar Poles: Orbital Mission Concept with Neutron Spectroscopy Measurements

Lunar Volatiles and Solar System Science

Lunar Volatiles Orbiters

The Need for Better Characterization of the Primary Anorthositic Crust with New Orbital Observations

The Next Lunar Orbiter: Some Observations and Programmatic Perspectives

Orbital Capabilities to Support Upcoming CLPS Lunar Surface Exploration

Why Radar Sounding is Crucial for Future Orbital Observatories

Why Orbital Magnetometer Instruments are Crucial for Future Improved Lunar Magnetic Observations