Analog Objectives for Artemis (AOA) Specific Action Team (SAT)
A Lunar Exploration Analysis Group (LEAG) Activity

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Introduction

As NASA and its partners seek to land astronauts on the Moon with its Artemis missions, terrestrial analog studies can be a valuable method to investigate the science questions to be addressed during lunar crewed exploration and the science operations and technology necessary to enable this exploration. Specifically, analog activities that prepare for astronaut extravehicular activities (EVAs) and the crew-enabled science that will occur during these EVAs are numerous. Such activities range from large, integrated operational field tests such as Desert Research and Technology Studies (DRATS) and NASA Extreme Environment Mission Operations (NEEMO) to smaller, focused activities at field locations as well as at onsite NASA and institutional facilities.

Analog studies and missions have long been successfully used to investigate scientific processes across the Solar System as well as to prepare for robotic and crewed exploration. NASA is now seeking to capture and describe Artemis-relevant analog objectives in order to provide oversight and strategic coordination for analog activities designed to impact and inform future lunar surface exploration. This is vital to ensure that the needs of all stakeholder communities, including the lunar science community, are being met.

To address this goal, the NASA Science Mission Directorate (SMD) established the Analog Objectives for Artemis (AOA) Specific Action Team (SAT). The task of the AOA SAT is to catalog and prioritize the objectives for science and science operations in preparation for Artemis human missions that can be achieved through analog activities. This report will summarize these objectives, including:

- Priority: How necessary is each objective, i.e. is it critical for mission planning or merely useful? Is it **Mission Required**, **Mission Enabling**, or **Mission Enhancing** for both Artemis Sortie Missions and Artemis Base Camp Missions?
- Time Criticality: Is the objective required for the **first crewed Artemis surface mission**? For **Artemis Sortie Missions**? For the **Artemis Base Camp Missions**?
- Candidate Analog Scenario(s): Are specific hardware, software, facility, personnel, etc. needed to achieve the stated objective? Can addressing the objective be accomplished in a local facility or small-scale analog environment, or would the work benefit from a more integrated, high-fidelity mission analog? Though the AOA SAT will suggest candidate analog scenarios to address different science, technology, and operations objectives, future investigators evaluating these objectives may devise different methods to conduct these studies.

For any analog activity designed to address the objectives outlined in this report, it is critical that fundamental science questions or a mission architecture designed around science objectives underpin each activity. Including this science backbone increases the fidelity of the analog activities results and findings and ensures that the analog activity includes a comprehensive assessment of future lunar surface EVAs. Conclusions drawn from analog activities that do not include this science backbone risk ignoring the complete picture of future lunar surface EVAs. As Artemis mission constraints are evolving, this report addresses the two expected endmember mission constraints: (1) shorter Artemis Sortie Missions and (2) Artemis Base Camp Missions with longer surface stays (see Key Definitions, below, for mission constraint summaries). Additionally, as downmass constraints are unknown at this time, we do not consider them here. However, as this downmass picture becomes clearer, future analog work can incorporate those estimates if possible.

Finally, the objectives outlined in this report address primarily Solar System science. Future comparable efforts may address activities designed around human health and performance research, biological and physical sciences, heliophysics, astrophysics, in-situ resource utilization (ISRU), and/or other parallel efforts, but those objectives are not included in this study.

Resources

In addition to the many compelling and informative publications stemming from prior analog activities, there are many resources for the community to consider when designing Artemis-relevant analog activities. These include, but are not limited to:

- Artemis III Science Definition Team Report [NASA/SP-20205009602]: Document outlining high priority science objectives, along with recommendations, for the Artemis III lunar surface mission, which is expected to be NASA's first crewed lunar landng since the Apollo Program.
  https://www.nasa.gov/sites/default/files/atoms/files/artemis-iii-science-definition-report-12042020c.pdf
- Exploration EVA System Concept of Operations [EVA-EXP-0042]: NASA/EVA Program document summarizing the Concept of Operations for planetary surface exploration.
  https://ntrs.nasa.gov/citations/20205008200
- Lunar Surface Science Workshop (LSSW) Report from 'Structuring Real-Time Science Support of Artemis Crewed Operations' LSSW Session: Summary report from the 8th LSSW session which addresses community consensus from that activity on several topics highlighted in this report.
  https://lunarscience.arc.nasa.gov/lssw/downloads/LSSW-8-Report-FINAL.pdf

Analog Objectives

As discussed above, this report will outline analog objectives necessary to prepare for the crewed exploration of the lunar surface through NASA's Artemis plan. Objectives outlined below are categorized and include a rationale for inclusion in this report, priority, time criticality, and candidate analog scenario(s) for each objective. All objectives should include robust science questions or a fundamental science architecture during analysis to ensure outcomes include the required fidelity. The ordering of objectives and categories of objectives in this report is not an indication of priority.

A. Science Support Room Integration and Structure

By combining lessons learned from Apollo missions, decades of International Space Station (ISS) and Shuttle missions, numerous robotic missions to other planetary bodies, and a variety of analog activities, it is clear that the Artemis Mission Control Center (MCC) structure will need to include a robust Science Team that provides support to crewed missions in real-time during EVAs and possibly across multiple missions. How the Science Team is integrated with the rest of MCC, and specifically the EVA Flight Control Team (FCT), is still being evaluated. The objectives outlined below seek to constrain how the Science Support Room (SSR), or the real-time Science Team, should be structured to support real-time operations and how the SSR should integrate with the rest of MCC and the FCT to support crewed operations.

Objective A.1: Define the ideal structure and composition of an SSR Science Team to support lunar EVAs and geologic traverses, both for the Artemis Sortie- and Base Camp-style missions (including the number of people, areas of expertise, team roles, responsibilities, etc.). Establish how this SSR should integrate with the broader EVA FCT in order to support real-time crewed operations.

Description: Prior lessons learned highlight the criticality of an SSR during real-time crewed operations. However, several unknowns remain about how this SSR should be structured and how the SSR should integrate with the rest of the FCT and MCC. Although the SSR members will be expected to integrate into existing MCC structures and protocols, more work is needed to determine the ideal structure by which the SSR can feed recommended science priorities, plans, and changes up through these protocols in the way least impactful to crew safety and operational efficiency. Work on this objective should consider both how the SSR should be structured (physical infrastructure, areas of expertise, roles/responsibilities of each SSR team member, etc.) as well as provide recommendations on how the SSR can provide the EVA FCT with updated science guidance throughout a lunar mission.

Priority: Mission Required for all crewed surface missions.

Time Criticality: Required for the first crewed surface mission.

Candidate Analog Scenario(s): Include mission simulations with at least an SSR during real-time operations and, if possible, high-fidelity mission constraints (i.e. aspects of broader MCC and/or EVA FCT, rigorous mission timeline, etc.).

Objective A.2: Determine the utility, roles and responsibilities, and integration of a possible SCICOM role within the broader FCT and SSR.

Description: During Apollo missions, the FCT communicated with the EVA crew via a CAPCOM position, the sole person in MCC responsible for direct crew communications. A Ground IV is the sole person responsible for crew communications on current ISS EVAs, while a CAPCOM retains communications with the crew inside the ISS during an EVA. For Artemis missions, the role of a designated SCICOM during lunar EVAs should be explored (i.e. a second person in MCC who communicates with the crew during EVA activities, with Ground IV/CAPCOM handing off to the SCICOM during science operations such as sampling, science instrument operations, etc.), as should the relationship between the SCICOM and Ground IV/CAPCOM. For example, is it feasible/efficient to pass off communications between SCICOM and Ground IV/CAPCOM within one EVA? Within one station? If a SCICOM position is recommended, what should the extent of their responsibilities be, and how should they integrate with the rest of the FCT (i.e. Flight Director, EVA Team, CAPCOM/Ground IV, SSR)?

Priority: Mission Enhancing for Artemis Sortie Missions. Mission Required for Artemis Base Camp Missions.

Time Criticality: Important for first crewed surface mission, Required for Artemis Base Camp Missions.

Candidate Analog Scenario(s): Include high-fidelity mission analog simulation, including integrated SSR with broader FCT (including Ground IV/CAPCOM).

Objective A.3: Determine the utility of remote and/or distributed SSR(s) during real-time crewed operations and/or in periods between crewed surface missions. If remote SSR(s) are recommended, define requirements/recommendations to provide connectivity between the remote team(s) and any team(s) onsite at the larger MCC.

Description: Though an onsite SSR is expected for the first crewed Artemis mission, it is possible that later missions could provide more flexible SSR architectures, including a remote and/or distributed SSR either in lieu of or in addition to an onsite SSR in MCC. The utility, functionality, and structure of any recommended remote SSR should be evaluated here, as well as any recommendations on how to link the remote SSR(s) with onsite MCC facilities.

Priority: Mission Enhancing for Artemis Sortie Missions and Artemis Base Camp Missions.

Time Criticality: Increasingly important for Artemis Base Camp Missions.

Candidate Analog Scenario(s): Include mission simulations with at least an SSR (located separately from any simulated MCC facility) during real-time operations and, if possible, high-fidelity mission constraints (i.e. aspects of broader MCC and/or EVA FCT, rigorous mission timeline, etc.).

Objective A.4: Define the requirements for SSR physical infrastructure necessary for the spectrum of Artemis mission constraints (Artemis Sortie Missions and Artemis Base Camp Missions).

Description: Physical infrastructure can include but is not limited to, quantity and size of the room(s) where the SSR and any science payload teams operate (including remote infrastructure if this is recommended), requirements for reconfigurable space, technological capabilities needed to support science teams (i.e. computers, shared screens, communications), etc.

Priority: Mission Required for all crewed surface missions.

Time Criticality: Required for the first crewed surface mission.

Candidate Analog Scenario(s): Include mission simulations with at least an SSR during real-time operations and, if possible, high-fidelity mission constraints (i.e. aspects of broader MCC and/or EVA FCT, rigorous mission timeline, etc.).

Objective A.5: Determine how the SSR should be structured to support longer, sustained Artemis missions. Determine the role of tactical (real-time, during an EVA) versus strategic (longer-term, across a mission) subteams.

Description: During longer-duration Artemis Base Camp missions, the crew may be on the surface for far longer than early, Artemis Sortie Missions, even possibly living and working out of a facility equipped with more advanced scientific capability. These missions will likely enable a higher volume of collected science data (samples, observations, *in situ* analyses, habitat analyses, etc.) to be returned during the lifetime of a mission. Prior work has shown the potential for a distinction in SSR function between a tactical and strategic team. The former is responsible for real-time operations during an EVA, and the latter is responsible for planning across an entire mission, including between EVAs. Additionally, the division of labor between strategic and tactical science planning has been used to good effect in remote geologic exploration of Mars by robotic assets for over a decade. This objective should investigate the utility and structure of this distinction and provide recommendations on how to incorporate it, if indeed two sub-teams are recommended.

Priority: Mission Enhancing for Artemis Sortie Missions. Mission Required for Artemis Base Camp missions.

Time Criticality: Required for Artemis Base Camp Missions.

Candidate Analog Scenario(s): Include high-fidelity mission constraints, including a mission of sufficient duration to adequately investigate the distinction between tactical and strategic teams.

B. Software to Support Real-Time Operations

The Apollo Program solved many specific science support communication, planning, and replanning management problems encountered during the Apollo missions largely without the benefit of computer software. Today we find ourselves with the opposite challenge: we have a seemingly infinite number of software solutions that could be used in the name of science support activities and already employ a multitude of software solutions that sometimes themselves introduce confusion and new management challenges.

Analog activities in support of Artemis have the opportunity to help to unravel the challenges introduced by the nature of these interdependent and interconnected solutions by providing clear findings and subsequent software requirements. We can assess how existing software systems can inform and enable the establishment of science support Concept of Operations (ConOps) and, conversely, allow a firm definition of the intended ConOps to dictate the requirements of the supporting software systems.

Objective B.1: Determine the requirements for, develop, or assess existing software solutions that support real-time science operations.

Description: Using science support ConOps as a starting point, define, create, or assess existing software solutions that solve aspects of the ConOps such as enablement of communication amongst the SSR and the broader FCT, adding/editing scientific activity documentation during EVA, viewing videos/photos from the lunar surface both in real-time and throughout the mission, viewing the planned vs. executed EVA timeline, etc. Produce specific, documented results that can be directly acted upon by software engineers or procurement staff.

Priority: Mission Required for all crewed surface missions.

Time Criticality: Required for the first crewed mission.

Candidate Analog Scenario(s): Include mission simulations with at least an SSR during real-time operations and, if possible, high-fidelity mission constraints (i.e. aspects of broader MCC and/or EVA FCT, rigorous mission timeline, etc.).

Objective B.2: Assess Geographical Information Systems (GIS) software solutions to support the ConOps of SSR operations as defined in EVA-EXP-0042 section 7.2.8.3 - Science EVA Tasks.

Description: Commercial and custom NASA GIS software packages can create mapping products for mission operations planning and execution. Investigate how GIS software systems can best facilitate the science support ConOps. The outcome of this effort should articulate the advantages and disadvantages of the software packages with the goal of providing input to software engineering teams for product improvement.

Priority: Mission Enhancing for all crewed surface missions.

Time Criticality: Required for Artemis Sortie Missions.

Candidate Analog Scenario(s): Perform high fidelity analog EVA with flight controllers and SSR participants using GIS software solutions.

Objective B.3: Investigate the use of software systems and data visualizations to enable rapid flight controller decision-making as well as SSR science analysis and recommendations regarding mission science operations.

Description: Individual Artemis science instrumentation will produce a variety of raw and derived datasets. Certain data products can be used to inform tactical surface operations. Providing flight controllers and SSR participants with timely, easily digestible data and derived data visualizations is key to enabling rapid decision-making during mission operations. We seek a better understanding of how software solutions and data presentation formats can reflect and enable the flexibility required by the ground support team and assist EVA participants in making rapid and informed decisions when presented with unexpected events.

Priority: Mission Required for all crewed surface missions.

Time Criticality: Required for the first crewed landed mission.

Candidate Analog Scenario(s): Analog field testing to assess improvements to situational awareness and science data collection for specific scientific investigations, development, and test of advanced technology software platforms, integration of mission operations and science support teams with the surface crew in a high fidelity analog environment.

C. Instrumentation

Artemis surface operations will include a diverse set of scientific instruments that produce critical datasets for addressing high priority science objectives over a wide range of scientific disciplines. The data will have a range of formats depending on instrument type, formats and the timing of data acquisition and the volume of data acquired will likely vary. Instrumentation can be deployed or carried on space suits, in hand by crew, mounted on the habitat or spacecraft, operated by robotic assets, carried or deployed by rovers, etc. A key activity is determining specific instrumentation and associated ConOps to optimally achieve high-priority Artemis science objectives.

Objective C.1: Determine Artemis science investigation priorities and associated required instrumentation. Develop criteria for determining associated instrument deployment priorities and requirements driven by science needs.

Description: Each Artemis science payload must be tied to specific mission science objectives. The type of data required to address these science objectives will be essential for establishing when and where measurements will need to be collected. For example, some science payloads may require specific measurement environments or locations that tie back into surface operations and timing, and thus must be established within a priority structure. Some instrumentation may require special measurement conditions that cannot be achieved without affecting other instruments or mission operations. Work should also address standards for deployment, e.g., establishing background parameters that may affect instrument performance and data collection quality.

Priority: Mission Required for all crewed surface missions.

Time Criticality: Required for the first crewed Artemis lunar landing.

Candidate Analog Scenario(s): Utilization of instrumentation in a relevant analog environment to address specific scientific investigation(s).

Objective C.2: Map science investigations to associated instrumentation and determine the optimal deployment method(s) to achieve these science goals (e.g., handheld instruments; tripod-, cart-, rover-, or lander-mounted; robotic asset-deployed, etc). Define a ConOps, an expected data volume, mass and power requirements, and an approximate amount of time required for crew hands-on time per data collection opportunity.

Description: Defining the science investigations, supporting instrument payloads, and their optimal deployment methods during mission operations will be crucial for optimizing crew efficiency and science investigation success. Science payloads will be deployed in a variety of ways during the Artemis missions depending on science needs and instrument or payload suite. Each individual instrument will uniquely draw on mission resources and must be integrated into the science and operational planning, including infrastructure required for instrument deployment and operations as well as the requirements for crew surface time.

Priority: Mission Required for all crewed surface missions.

Time Criticality: Required for the first crewed Artemis lunar landing.

Candidate Analog Scenario(s): Requires science-driven analog deployment with appropriate instruments to conduct analog science investigation(s).

Objective C.3: Determine the data accessibility and visualization requirements for science payloads, including real-time and delayed data download and display. For a given payload or measurement type, determine science data volumes and data types that would be optimally viewed by science and operations teams, and methodologies and software solutions to facilitate real-time operations, data downloads, data storage, and handling, etc.

Description: Science payloads will collect data at the Moon and depending on the science needs, specific data may need to be monitored in real-time and readily accessible for science analysis, mission operations, and decision making both on Earth and by the crew on the Moon. Instrument datasets must be assessed for science prioritization in terms of data download, display, and availability, and an appropriate support infrastructure developed to facilitate the required real-time operations and data visualization and analysis needs for science.

Priority: Mission Enabling for all crewed surface missions.

Time Criticality: Required for first crewed Artemis landing and subsequent real-time operations.

Candidate Analog Scenario(s): Science-driven analog deployment with relevant science instrument(s) integrated with mission software to enable real-time data visualization and analysis.

Objective C.4: Determine relevant metadata required to enable subsequent scientific analysis of instrument datasets by providing appropriate calibration, mission telemetry (time stamps, georeferencing information, etc.) of instrument raw data and derived data products.

Description: Data-generating instruments being considered for Artemis operations can improve the value of their data by producing data products that are contextually referenced to the overall Artemis mission operations (e.g., master clock time-stamped or geospatially referenced metadata). Instruments should be evaluated for the ability to incorporate metadata that references the primary data payload to the overall mission context and mission telemetry streams.

Priority: Mission Enabling for all crewed surface missions.
Time Criticality: Required for first crewed Artemis landing.
Candidate Analog Scenario(s): Can be conducted in an office or laboratory setting.

D. Human/Robotic Partnerships

A major change since the Apollo missions is the advancement of robotics. The partnership and interplay of humans and robots for space exploration has received considerable attention, particularly in the context of ISS operations. Human-assisted sample return, for example from the Lunar Gateway, has also been discussed. In contrast, significant questions remain as to the utility and benefit(s) of such partnerships for lunar surface operations. There are three main human - robotic partnership phases that can be envisaged on the lunar surface: 1) *robotic precursor* activities, whereby a rover is sent to the site of future astronaut surface operations some time (weeks to months) in advance of the human mission; 2) the use of a *robotic assistant* during astronaut surface operations; and 3) *robotic postcursor* activities, whereby the rover continues operations after the astronauts leave the lunar surface. Lessons learned from analog mission activities highlight the benefit of robotic precursor and postcursor mission activities. Questions remain as to the best practices and requirements for a robotic assistant.

Objective D.1: Define ConOps for human/robotic partnerships that are precursory, synchronous with crewed operations, and/or for follow-on activities (postcursor) to crew on the ground. Determine the recommended science objectives and data types required for these operations.

Description: The Apollo missions did not employ human/robotic partnerships, so ConOps must draw from analog mission experience. Such lessons learned have shown that precursor and postcursor operations can be structured in a similar fashion to purely robotic missions (e.g., MER, Curiosity, etc), with the caveat that the primary motivation of the precursor activities is to collect data to maximize the scientific return of, and enable better planning of, astronaut surface operations. However, a number of unknowns remain about how the SSR should be structured and how the SSR for this purely robotic phase should integrate with the rest of the FCT and MCC for crewed operations. Based on previous lessons learned, postcursor activities enable the hypothesis testing to continue following the departure of the astronauts, both through the collection of further data from locations visited by the astronauts as well as by extending the rover's travel network to new sites under the direction of MCC. The structure of SSR and the interplay of MCC during this phase remains to be determined. For robotic assistant activities, the operations have an added layer of complexity as there will be both robotic and human operations occurring concurrently and in parallel and exactly who and how the SSR, FCT, and MCC will be structured and involved needs to be addressed. For these activities, robotic platforms of any type may be employed (smaller robotic platforms, unpressurized rover platforms, pressurized rover platforms, etc.) as Artemis constraints are still unknown.

Priority: Mission Enhancing for Artemis Sortie Missions. Mission Required for Artemis Base Camp Missions.

Time Criticality: Required for Artemis Base Camp Missions where additional robotic platforms are expected.

Candidate Analog Scenario(s): Include mission simulations with a robotic platform (smaller robotic platforms, unpressurized rover platforms, pressurized rover platforms, etc.), at least an SSR during real-time operations, and, if possible, high-fidelity mission constraints (i.e. aspects of broader MCC and/or EVA FCT, rigorous mission timeline, etc.).

Objective D.2: Define recommended science instrumentation and associated data and transmission requirements for robotic precursor, assistant, and postcursor platforms.

Description: Rovers for planetary exploration have increased in sophistication and complexity since their inception, with the evolution of NASA's Mars rovers from Sojourner to Perseverance being a prime example. These platforms, however, were not designed for human/robot partnerships, nor were their mission and science goals defined with supporting crewed exploration in mind. Lessons learned from previous analog missions have suggested that stand-off imaging payloads (e.g., visible and multispectral cameras and LiDAR) are sufficient for robotic precursor activities. However, substantial questions remain about the optimum use of a robotic assistant (see Objective C2) in deploying and operating science instruments. Thus, the outcome of Objective C2, and whether a requirement is to use the same robotic platform for the three phases of human/robot partnerships, will have implications for the instrumentation requirements for robotic precursor and postcursor platforms. Whether these robotic precursor, assistant, and postcursor platforms need to be teleoperated and with real-time data transmission, or if some level of pre-planned and/or autonomous operations could occur, needs to be investigated and has implications for data and transmission requirements.

Priority: Mission Enhancing for Artemis Sortie Missions. Mission Required for Artemis Base Camp Missions.

Time Criticality: Required for Artemis Base Camp Missions where additional robotic platforms are expected.

Candidate Analog Scenario(s): Include mission simulations with a robotic platform (smaller robotic platforms, unpressurized rover platforms, pressurized rover platforms, etc.), at least an SSR during real-time operations, and, if possible, high-fidelity mission constraints (i.e. aspects of broader MCC and/or EVA FCT, rigorous mission timeline, etc.).

Objective D.3: Determine what assets are needed in the SSR to enable human and robotic partnerships.

Description: As noted above, the addition of robotic assets, particularly as field assistants, adds complexity to mission operations as there will be times when both robotic and human operations will be occurring concurrently and in parallel. Investigations should evaluate if these operations require a separate SSR for the robotic and human assets, investigate how the coordination and integration of robotic assets and crews will occur, and/or evaluate if the software developed to support real-time human operations can be adapted for human-robotic operations. The overlap and/or coordination of instrumentation and imaging for these human/robotic partnerships should also be addressed.

Priority: Mission Enhancing for Artemis Sortie Missions. Mission Required for Artemis Base Camp Missions.

Time Criticality: Required for Artemis Base Camp Missions where additional robotic platforms are expected.

Candidate Analog Scenario(s): Include mission simulations with a robotic platform (smaller robotic platforms, unpressurized rover platforms, pressurized rover platforms, etc.), at least an SSR during real-time operations, and, if possible, high-fidelity mission constraints (i.e. aspects of broader MCC and/or EVA FCT, rigorous mission timeline, etc.).

E. Operations in Complex Lighting Environments

The Apollo surface EVA experience demonstrated that walking or driving up- or down-Sun greatly reduced visibility and impeded maneuverability. Artemis will explore the Moon in a very different illumination regime than most of the Apollo experience. The inclination of the Moon's rotational axis relative to the ecliptic pole ensures the polar regions never exceed a Sun angle of a few degrees, causing complex and potentially challenging illumination conditions for operations. Only the first EVA of Apollo 12 briefly approximated this condition, when the Sun was 7.4° above the horizon. These polar low-angle illumination conditions coupled with topography produce areas of near-permanent illumination, as well as permanently (or persistently) shadowed regions (PSRs). Operational strategies and hardware for successful Artemis exploration must be determined, evaluated, and tested for the complex lunar polar lighting environment.

Objective E.1: Determine and test efficient and effective strategies for conducting scientific operations in complex and challenging illumination conditions including near-complete darkness and low-angle sun conditions.

Description: Exploration of the lunar polar regions will encounter complex and harsh illumination conditions. Comprehensive strategies for Artemis science operations in these challenging lighting environments need to be determined and tested for efficient and effective exploration of the lunar poles. Orientation effects, topographic roughness, color perception, and other factors will play a key role in Artemis mission planning, training, and execution. Science operations in analogous lighting conditions, including low-angle sun, fully dark, effects of Earth-shine, and various other lighting conditions, require comprehensive evaluation and analog testing.

Priority: Mission Required for all crewed surface missions.

Time Criticality: Required for first crewed surface mission.

Candidate Analog Scenario(s): Requires an analog simulation and/or environment with high-fidelity methods to simulate the range of lighting conditions expected.

Objective E.2: Evaluate the operational needs and viable options to provide artificial lighting for lunar south pole exploration. Determine system requirements through

evaluation and testing for primary and supplemental lighting to support observational, imaging, sampling, instrument deployment, and other science tasks in dark and low-angle sun conditions.

Description: Artificial light source(s) will be used to mitigate the unique illumination challenges for lunar exploration. Lander-mounted, suit-integrated, cart/vehicle-mounted, handheld, stationary deployed, naturally reflected, and other primary and supplemental lighting options have been proposed. These concepts and methods require further evaluation for their effective use during Artemis scientific operations. Lighting output/flux, level/intensity, brightness, distance, spread, color temperature/index, power/efficiency, and other key lighting parameters will play a role in Artemis mission planning, training, and execution. System requirements for primary and supplementary lighting can then be derived to support lunar scientific activities and objectives.

Priority: Mission Required for all crewed surface missions.

Time Criticality: Required for the first crewed surface mission.

Candidate Analog Scenario(s): Requires an analog simulation and/or environment with high-fidelity methods to simulate the range of lighting conditions expected.

Objective E.3: Evaluate and test advanced technologies and techniques to facilitate operations in complex lighting environments.

Description: Advancing technologies and techniques that may aid lunar operations in complex lighting environments should be evaluated. Advancements in multispectral imaging, LIDAR, depth cameras, augmented heads-up displays, and other emerging hardware and software technologies should be tested for their direct application to facilitate operations in complex lighting environments. Unique techniques for operating in challenging lighting environments also need to be evaluated in appropriate analog environments for their potential applications.

Priority: Mission Enabling for all crewed surface missions.

Time Criticality: Required for Artemis Sustained Missions.

Candidate Analog Scenario(s): Requires an analog simulation and/or environment with high-fidelity methods to simulate the range of lighting conditions expected.

F. Imaging

Cameras have been, and will continue to be, a fundamental instrument type for planetary exploration, and the resulting images are a foundational data product upon which most other science investigations are built, either by recording context or by providing observational and/or quantitative data. Similarly, images are critical for providing and maintaining the situational awareness necessary for achieving mission success. For Artemis, two specific circumstances pose a number of questions related to imaging that will require analog research to answer. First are the unique illumination conditions presented by the lunar south pole exploration area. Second are the tremendous advancements in imaging technologies that have been made in the decades since Apollo. The objectives enumerated below highlight some of these open questions.

Objective F.1: Determine the performance specifications and other requirements for cameras to be used for lunar surface exploration, particularly for use in complex lighting conditions.

Description: Cameras deployed on the lunar surface in support of Artemis exploration missions may operate in different modes (e.g., autonomous or crew-operated), may be deployed in different ways (e.g., vehicle-mounted, suit-integrated, or handheld) and may be used for various purposes (e.g., science data collection or operations support). Each of these possibilities – as well as the lunar surface environment (i.e. illumination) and mission constraints – will place performance requirements on these imaging systems. Among the specifications to explore are: form factor (e.g., mass and volume); deployment method (e.g., vehicle, suit, or handheld; fixed or movable; static or gimballed); image capture mode (e.g., still or video); frame rate; spatial resolution; field-of-view; lens type(s) (e.g., fixed or interchangeable; macro, wide-angle, zoom, etc.); sensor type and size; sensor sensitivity and dynamic range (i.e., radiometric resolution); spectral sensitivity and spectral resolution; exposure settings (i.e., aperture, shutter speed, ISO) for various environmental conditions and use cases; calibration (e.g. need for a metric camera; color calibration); file formats; data storage, communications, and processing; and power requirements. Given the possible use cases and other constraints, it is possible that no single camera may satisfy all requirements, so an additional outcome of this objective is to determine the ideal number and types of cameras to be available.

Priority: Mission Required for all crewed surface missions.

Time Criticality: Required for first crewed Artemis surface mission and subsequent missions.

Candidate Analog Scenario(s): Include an analog simulation and/or environment with high-fidelity methods to simulate the range of lighting conditions expected.

Objective F.2: Explore the operational implications and utility of capturing digital video and digital still images of science and other exploration activities on the lunar surface, including an assessment of camera hardware for the ability to enable real-time operations (by providing image data in real time in addition to preserving data for post-EVA analysis) and the ability to preserve contextual metadata products.

Description: A key difference between Apollo and Artemis exploration activities, particularly EVAs, is the modern capability of capturing still images and video using digital cameras. This opens possibilities not feasible during Apollo, and understanding the utility of these new capabilities, and their operational costs, will be important. For example, investigations should evaluate questions such as: the recommendation for real-time video streaming; the recommendation for real-time upload/download of still images; and recommendations for requirements of video and still image resolutions (as well as frame rate, etc.) for real-time image (as opposed to images intended for later use). Additionally, digital cameras are very capable of acquiring images automatically. Investigations should consider if this is a good approach, as opposed to having crewmembers shoot images manually. Without the constraint of film stock, there will be no physical limit on the number of photos or videos; analog activities should consider what the effect will be on data storage/communications. Additionally, without the need to develop film, there is no lag between when images are taken and when they can be available for viewing and analysis. Studies should investigate what effects on data storage/communications and on tactical and strategic science and operations this has. Finally, digital image data can be readily manipulated with computers. Studies should investigate what new ways of using image data (in real-time or not) including 3D, spectral, and other image processing will be useful to support mission operations.

Priority: Mission Required for all crewed surface missions.

Time Criticality: Required for first landed mission.

Candidate Analog Scenario(s): Include an analog simulation and/or environment with high-fidelity methods to simulate the range of lighting conditions expected.

Objective F.3: Test hardware and ConOps for capturing and utilizing context images (both still and video) of EVA operations, particularly sample collection, from the first-person perspective.

Description: Suit-mounted or crew handheld cameras will be important tools for capturing first-person perspective views of EVA activities, particularly sampling and rock- to outcrop-scale science observations. Analog investigations here should consider: the camera type (i.e., still or video or both) and deployment method (e.g., helmet-, chest-mounted, or other) that is optimal for science operations; the optimal artificial lighting configuration; the crew time/attention, if any, that will be required to operate the camera(s); the methods that should be used to obtain stereo (or 3D) images, *in situ* microscopic images, and outcrop scale images; the best technique(s) for integrating first-person perspective image data be integrated with other data types (e.g., to provide spatial context for handheld analytical tools, etc.); the best technique(s) for integrating first-person perspective image data with Virtual Reality/Augmented Reality (VR/AR) capabilities for use by the crew and by mission/science support personnel; and finally, the utility of first-person perspective digital still/video for science context and operational situational awareness.

Priority: Mission Enabling for all crewed surface missions.

Time Criticality: Relevant for first crewed landed mission. Critical for Artemis Sortie and Artemis Base Camp Missions.

Candidate Analog Scenario(s): Include an analog simulation and/or environment with high-fidelity methods to simulate the range of lighting conditions expected.

Objective F.4: Test hardware and ConOps for capturing and utilizing context images (both still and video) of EVA operations, including science activities, from a stand-off distance from the EVA crew (i.e. from the 3rd-person perspective).

Description: One way of maximizing situational awareness of crew activities on the lunar surface is to establish a stand-off imaging capability so that EVAs can be monitored and recorded from a third-person perspective. Additional work is needed to evaluate: the optimal camera type (i.e, still or video or both) and deployment method (e.g, tripod or rover or other; static/panoramic, motion-tracking, or other); the optimal artificial lighting configuration; the required crew time/attention (e.g. for set-up, etc.); the ideal technique(s) for obtaining outcrop scale images and traverse scale images; the strategy for integrating third-person perspective image data with other data types (e.g., to provide spatial context for close-range remote sensing, area survey data such as geophysics, etc.); the strategy for integrating third-person perspective image data with VR/AR capabilities for use by the crew and by mission/science support personnel; and finally, the utility of third-person perspective digital still/video for science context and operational situational awareness.

Priority: Mission Enabling for all crewed surface missions.

Time Criticality: Relevant for first crewed landed mission, critical for Artemis Sortie and Base Camp missions.

Candidate Analog Scenario(s): Include an analog simulation and/or environment with high-fidelity methods to simulate the range of lighting conditions expected.

Objective F.5: Determine and prioritize the range of other use cases (i.e., deployment modality, data capture concept of operations, data types) for modern digital imaging instruments in support of either science or operations.

Description: Depending on the constraints of specific science objectives and/or operational requirements, example use cases may include but are not limited to: vehicle-mounted (rover, aerial platform) cameras; cameras on articulated masts or robotic arms (for overhead views, precision pointing/positioning, repetitive and time-consuming image acquisition campaigns, etc., either autonomously or in concert with crew); multi-scale imagery (microscopic to panoramic scale; “gigamacro” to “gigapan”); 3D imaging (360, stereo, depth cameras, SfM); spectral imaging, etc.

Priority: Mission Enabling for all crewed surface missions.

Time Criticality: Relevant for first landed mission, critical for Artemis Sortie and Base Camp Missions.

Candidate Analog Scenario(s): Include an analog simulation and/or environment with high-fidelity methods to simulate the range of lighting conditions expected.

Objective F.6: Determine the type of sample markers, ground-control points, and/or calibration targets (radiometric, geometric, or both) needed for lunar surface imaging given expected lighting conditions at the lunar south pole.

Description: For both science and operations applications, images will need geometric or radiometric calibration, or both. During Apollo EVAs, these calibration requirements were met by using a deployable target called the gnomon that integrated a scale bar, a color scale, and a rod that showed both local vertical as well as illumination direction. To meet calibration goals for Artemis, more work is needed to determine if all elements of the Apollo gnomon will be required or if any additional (or alternative) capabilities (e.g., color chips, standardized graphics) be needed for modern digital imaging. Additionally, investigations should consider what ground control tools and/or concepts of operations will be needed for modern photogrammetric applications, including stereo, structure-from-motion/multi-view stereo (SfM/MVS), and other methods. Studies should also evaluate what tools are needed to provide the required size and color scale and other contextual annotations (e.g., sample number, location, orientation, illumination conditions, etc.) in-frame so that images, particularly of samples and outcrops, are of optimal archival utility. Finally, investigations should consider what ConOps will be required for radiometric image calibration in the complex lighting environment of the lunar south pole (i.e., timing and cadence of when calibration is performed, etc.).

Priority: Mission Required for all crewed surface missions.

Time Criticality: Required for first landed mission.

Candidate Analog Scenario(s): Include an analog simulation and/or environment with high-fidelity methods to simulate the range of lighting conditions expected.

Objective F.7: Test beyond-visible wavelength imaging (multispectral ultraviolet, infrared, thermal infrared, etc.) for obtaining science images, context images, and situational awareness images, particularly in complex lighting conditions.

Description: Unique geologic information exists across the electromagnetic spectrum, and improved technology means that low-mass, low data volume instruments that capture information in various wavelengths may be available to crews. In addition to multispectral instruments, other available instruments might include low-light imaging technologies (FLIR, photomultiplier cameras, etc.) as well as integration with other spatial instrument data, such as LiDAR, which can operate in darkness and provide 3D data.

Priority: Mission Enabling for all crewed surface missions.

Time Criticality: Relevant for first landed mission, critical for Artemis Sortie and Artemis Base Camp Missions.

Candidate Analog Scenario(s): Include an analog simulation and/or environment with high-fidelity methods to simulate the range of lighting conditions expected.

Objective F.8: Test motion-compensation and image stabilization techniques and technologies, particularly for still/video cameras mounted to mobile platforms such as suited astronauts, rovers, etc.

Description: Image data, particularly video, obtained by moving cameras suffers from motion-related artifacts and degradation (i.e. motion blur, frame jitter, etc.). This was the case for the footage acquired with the Maurer 16-mm motion film cameras and the TV footage acquired with the Ground Commanded Television Assembly (GCTA) during Apollo. Much, but not all, of this can be mitigated by post-processing with motion-compensating software, but software and hardware (e.g. gimbals, etc.) approaches to image stabilization while the imagery is collected are superior. To the extent that video will be an important image dataset for Artemis, and also for still images acquired (automatically and continuously) from a moving/movable (e.g. crew- or rover-mounted) camera, investigating ways of avoiding, reducing, and removing motion-related image degradation will be important, particularly for cameras operating in complex lighting conditions (e.g. handheld photography with long exposure times in low-light conditions, etc.).

Priority: Mission Enabling for all crewed surface missions.

Time Criticality: Relevant for first landed mission, critical for Artemis Sortie and Artemis Base Camp Missions.

Candidate Analog Scenario(s): Include an analog simulation and/or environment with high-fidelity methods to simulate the range of lighting conditions expected.

Objective F.9: Explore the training and operational requirements associated with astronauts obtaining image data during EVAs.

Description: In addition to having to operate cameras with pressurized gloves, a challenge faced by the Apollo astronauts was aiming cameras and framing shots "in the blind" since their Hasselblad cameras were chest mounted and were without viewfinders. In addition, the Apollo astronauts had to be trained to make real-time assessments of lighting conditions, without the use of a light meter, so that they could choose from the limited exposure settings available on their cameras. This objective includes understanding the human factors and ergonomics of operating camera hardware while in the Artemis spacesuit (i.e. with pressurized gloves), interfaces for viewing/manipulating imagery and targeting/controlling cameras (e.g., voice, tactile controls, heads-up displays), and training personnel in general photographic techniques, particularly for tackling challenging lighting conditions, as well as in mission- and instrument-specific procedures.

Priority: Mission Required for all crewed surface missions.

Time Criticality: Required for first landed mission.

Candidate Analog Scenario(s): Include an analog simulation and/or environment with high-fidelity methods to simulate the range of lighting conditions expected.

G. Sampling

Samples are required to address scientific and engineering knowledge gaps. Samples collected during the Apollo missions have been studied for over fifty years and continue to be investigated by researchers across the globe. The success of Apollo has been in part owed to the careful curation of returned materials. Artemis will provide a unique opportunity to build on and complement the success of Apollo sample science. During Artemis, astronauts will collect samples from the lunar surface far outside of the Apollo-sampled regions and return them to Earth for curation and analysis. The candidate sites for Artemis exploration pose new challenges to sampling, curation, and safety that analog activities can help address.

Objective G.1: Determine procedures and best practices for collection of diverse samples and sample types (soils, rocks, rocklets, cores, trench, solar wind, etc).

Description: Apollo collected a diverse lunar sample collection both in terms of lithological diversity and sample type. Lithologies range from basalt of various chemical compositions (very-low, low, high-Ti; low- and high-K, high-Al; KREEP), highlands rocks (troctolites, norties, granite, felsite, anorthosite), and breccias (impact melt, fragmental, polymict, monomict, regolith). In addition, regolith samples contain abundant lithic and mineral fragments, and agglutinates. Sample collection during Apollo included collection of samples by pick-up (rocks/rocklets), rake, trench, core, and double drive tube. Given the geological differences between the Apollo and Artemis landing sites, and new tools available for sample collection, this objective includes investigation of how to collect a diverse sample suite (see also Objectives B1/B2).

Priority: Mission Required for all crewed surface missions.

Time Criticality: Required for first crewed surface mission.

Candidate Analog Scenario(s): Include an analog simulation and/or environment with access to geological diversity (soils, boulders, outcrops).

Objective G.2: Define a ConOps for how to collect sample context data (imagery, descriptions, location, time, sampling numbering, tracking, etc.) during EVAs.

Description: There is a need to understand the geologic setting of future Artemis landing sites, surrounding regions, and the locations from which returned samples are collected. Definition of this ConOps should include documentation of the geology on the ground with astronaut descriptions, photographs, etc. to understand the geologic context of the collected samples from these regions. This should also include investigation of the use of new technologies to enhance sample context preservation.

Priority: Mission Required for all crewed surface missions.

Time Criticality: Required for first crewed surface mission.

Candidate Analog Scenario(s): Include an analog simulation and/or environment with access to geological diversity (soils, boulders, outcrops).

Objective G.3: Define a ConOps for how best to coordinate robotic/crew sampling with *in situ* measurements.

Description: Compared to the Apollo era, there now exist a multitude of robotic/handheld/portable analytical (e.g. handheld x-ray fluorescence) equipment for field data collection. This objective should include investigation of strategies to couple sample collection (see objective H-1) with *in situ* measurements to maximize science return and to aid with prioritization of samples for return to Earth.

Priority: Mission Required for all crewed surface missions.

Time Criticality: Required for first crewed surface mission.

Candidate Analog Scenario(s): Include an analog simulation and/or environment with access to geological diversity.

Objective G.4: Test and evaluate advanced protocols, techniques and technologies for the effective collection and containment of volatile bearing materials (includes ices and ice-regolith mixtures).

Description: Our understanding of lunar polar volatiles has been significantly improved over the past decade through new data and analyses. Lunar volatiles are of high priority for both science and exploration objectives. The lunar polar cold traps provide an unprecedented record of Solar System volatiles delivered from numerous sources (comets, asteroids, solar wind interactions, interior outgassing, etc.) over an extended period of time. Artemis will visit polar locations that have the potential to host surface and subsurface volatiles, frost and ice, respectively. Many of the science priorities concerning volatiles (Artemis SDT report) will require combined *in situ* measurements (see Objective G-3) with sample return objectives to fully address the identified science priorities. This objective should include investigations of the temperature and pressure limits for the collection and containment of volatile-bearing regolith; definition of strategies to monitor and quantify volatile and or contaminant loss during sample collection and transport; and investigations of the potential for space suits to contaminate volatile-bearing samples during sample collection and development of monitoring/mitigation strategies.

Priority: Mission Enabling for all crewed surface missions.

Time Criticality: Required for first crewed surface mission.

Candidate Analog Scenario(s): Include an analog simulation and/or environment with access to volatile (ice) bearing simulant.

H. Tool & Tool/Sample/Payload Management

Essential to the success of Apollo was the design, fabrication, and operation of tools and containers for collecting, transporting, and preserving lunar samples. Tools were built to meet stringent scientific requirements to reduce contamination of samples while remaining within the constraints of size, weight, power, and operability. Tools and containers matured from lessons learned over the course of the Apollo missions. Additionally, the methods and mechanisms to transport and manage tools, samples, and payloads to various workstations matured with increasing capabilities and exploration distances. Geologic sampling is a key component of the Artemis science objectives, thus sampling tools and their management must be defined and tested. Though concrete science objectives for each mission have not been defined, the Artemis III Science Definition Team Report and other community documents can provide guidance on high priority science objectives for Artemis missions.

Objective H.1: Define the sampling tools needed to address desired lunar south pole science objectives.

Description: Following the Apollo-era sampling tool suite it is envisioned that Artemis crewed missions will carry rock hammer, rake, scoop, tongs, extension handles, drive tubes, contingency sample containers, and sample bags. There will also be new "tools" available for Artemis compared with Apollo, specifically for cold sampling of volatiles. Investigations here should include defining which tools are needed for south polar exploration and should include the tool type, number of tools, and utilization.

Priority: Mission Required for all crewed surface missions.

Time Criticality: Required for first crewed surface mission.

Candidate Analog Scenario(s): Include an analog simulation and/or environment with appropriate Artemis science scenarios and objectives for which to test sampling tools.

Objective H.2: Investigate the relationship between tool materials and procedures for tool deployment, their potential for contamination, and desired lunar south pole science objectives.

Description: Apollo-era sampling tools and sample containers, storage, and curation tools were made almost entirely of Teflon, aluminum, and stainless steel. The Artemis missions will take advantage of the advancement in new materials available for flight that were not available during Apollo. To maximize the science gain now and into the future, it

is necessary to weigh the potential for tool/instrument contamination on returned samples and to determine the potential for tool/instrument/containment degradation during sampling (e.g., when sampling volatile-rich deposits that could contaminate in-situ measurements/returned samples). This objective should include the definition of a ConOps for how contamination knowledge would be obtained and monitored during the lifetime of a sample (pre-flight, flight, EVA, return, curation).
Priority: Mission Required for all crewed surface missions.
Time Criticality: Required for first crewed surface mission.
Candidate Analog Scenario(s): Requires documented curation requirements.

Objective H.3: Determine and/or test equipment, procedures, and best practices for the management and transport of tools, instruments, samples, and payloads.

Description: Management and transport of scientific equipment (tools, instruments, payloads, etc) and collected samples to/from lander(s) to their worksite(s) or storage location(s) is a complex challenge. Efficient and effective procedures, mechanisms, tracking tools and best practices need to be determined and tested.
Priority: Mission Required for all crewed surface missions.
Time Criticality: Required for first crewed surface mission.
Candidate Analog Scenario(s): Requires an analog simulation and/or environment with appropriate Artemis science scenarios and objectives for which to test management and transport of tools, instruments, samples, and payloads.

Objective H.4: Define a ConOps for the cleaning of sampling tools and handheld instruments.

Description: Sampling tools and handheld instruments may be used multiple times and or at multiple distinct locations during a given mission. This increases the possibility of sample/measurement cross-contamination. This might be different than was used during Apollo depending on the materials used for tool and instrument construction. As such, a strategy for effective cleaning of tools and instruments used on the lunar surface is needed.
Priority: Mission Enabling for all crewed surface missions.
Time Criticality: Important for first crewed surface mission.
Candidate Analog Scenario(s): Requires documented curation requirements.

I. Documentation

The timeline and linkage between key activities (e.g., sampling, *in situ* analysis, tool use, photography, instrument deployment and use, etc.) is captured by properly documenting a wide variety of parameters that can be defined through analog study. Documentation results in a large number of products that accompany the specific activity of any mission and is critical for capturing the mission activities for posterity. These products include metadata (data about the data), specific data collected solely for the purpose of documentation, and any information that is necessary to put specific activities into proper context with each other across the mission.

Protocols are designed to standardize documentation, and ensure that specific needs for mission documentation take place.

Objective I.1: Determine what documentation requirements are for science activities and science payload deployments during real-time Artemis operations. These can be instrument or activity specific.

> **Description:** During Apollo, documentation was achieved through written transcripts of audio interactions, images, metadata, astronaut notes, audio and video recordings of astronaut activities, and instrument specific metadata. With Artemis, it is expected there will be abundant documentation and metadata that span a large range of formats that expand upon the Apollo model. New products that were not collected by Apollo will also be available. The definition of these documentation elements is necessary to ensure that this information is captured and available for real-time operations during the mission.
> **Priority:** Mission Required for all crewed surface missions.
> **Time Criticality:** Required for first crewed surface mission.
> **Candidate Analog Scenario(s):** High fidelity field testing of equipment to identify documentation needs and define requirements for the Artemis lunar landings.

Objective I.2: Determine requirements for how documentation is accomplished during real-time Artemis missions. Establish the order of priority, time costs, and provide training on how to document mission activities. Define the software and instrument requirements for documenting metadata.

> **Description:** Documentation activities can be accomplished with automation, independently as a separate task, or synchronously alongside the data. Documentation activities are expected to occur alongside deployment and operation of science payloads, and an order of priority and crew time spent on these activities is needed to place them in a mission timeline. The Apollo missions included significant training exercises and checklists that prepared astronauts for documentation activities, and how this would be accomplished under each task.
> **Priority:** Mission Enhancing for all crewed surface missions.
> **Time Criticality:** Important beginning with first crewed surface mission.
> **Candidate Analog Scenario(s):** Preparation of training exercises that demonstrate or test how protocols effectively capture relevant documentation data.

Objective I.3: Assess the ability of data generated by candidate science instruments to provide documentation support for other instrument data and crew activities.

> **Description:** Science instruments flown to the lunar surface may collect data that in addition to its primary purpose, supports the documentation of mission events. For example, a LiDAR system primarily used to provide detailed views into PSRs could also provide before-and-after information useful for documenting sample collection. Instruments data products should be assessed in the search of such opportunities.
> **Priority:** Mission Enhancing for all crewed surface missions.
> **Time Criticality:** Will inform all crewed surface missions with science instruments but not required.

Candidate Analog Scenario(s): Post exercise assessment of produced data products assessing whether additional documentation goals were inadvertently achieved.

J. Advanced Technologies

The scientific and situational awareness of both the astronaut crews conducting lunar surface EVAs and the subject matter experts participating from the FCT and SSR would be enhanced by identifying and implementing effective advanced technologies, including Virtual Reality (VR), Augmented Reality (AR), and/or mixed reality (XR) data visualizations. Shared and immersive data visualization technologies are currently being used to improve scientific assessment and target triage for Mars surface operations; such technologies could be applied in a lunar environment as well. Unique applications would also include enabling more efficient communication between astronauts and the ground support team, as well as advanced concepts for immersive mission support centers and unique data visualization capabilities.. AR integrated into astronaut heads-up displays (HUDs) can provide rapid and relevant synthesis of scientific data to inform decision making and science operations. The use of VR/AR/XR can also enable remote operations and provide a collaborative work environment for personnel not co-located in one physical space through the development of virtual mission control and science support rooms.

Objective J.1: Determine the utility that AR/VR/XR could provide to Artemis astronauts and real-time Artemis science and operations teams. Determine optimal use cases and evaluate the effectiveness of AR/VR/XR systems to enhance surface science productivity and mission operations.

Description: The development of an AR/VR/XR environment(s) would enable scientists and operations personnel on Earth to work in the “same location” as the crew and any remote ground support teams. AR/VR/XR capabilities can provide key data visualization and analysis tools to enable EVA planning, execution, and subsequent data analysis. AR technology can provide enhanced situational awareness for both astronauts on the lunar surface and science support team personnel using virtual overlays that do not limit a user's connection with the physical world around them. The use of such advanced technologies could foster more efficient communication between astronauts and ground support teams and streamline the decision-making process regarding features of interest and sample locations.

Priority: Mission Enhancing for Artemis Sortie Missions, Mission Enabling for Artemis Base Camp Missions.

Time Criticality: Useful for Artemis Sortie Missions, increasingly important for Artemis Base Camp Missions.

Candidate Analog Scenario(s): High fidelity analog campaign including surface astronaut crews, FCT, and SSR components, integrating VR/AR/XR technologies including computing and display hardware and software, appropriate networking infrastructure, and communications tools.

Objective J.2: Determine the scientific value that AR could provide to Artemis surface crews for use on the surface, including EVA. Determine how AR could be used to maximize crew scientific efficiency and science return, including providing recommendations on what type of scientific information could be used by the crew (i.e., procedure viewing, science payload procedures and data, sampling identification, map overlays, data product visualization, etc).

Description: The scientific and situational awareness of the astronaut crews both on EVA and IVA and the science and operations teams on Earth would be enhanced by implementing VR, AR, and/or XR data visualizations. Augmented reality data visualizations could be overlaid on an astronaut's field of view using an in-helmet head's up display (HUD) to facilitate communication of targets or navigational waypoints from mission control. High-resolution remote sensing and in-situ mission data could be used to create immersive VR renderings of the lunar surface field site, providing team members with a more immersive first-hand view of the field site and potential science targets. VR, AR, and/or XR have significant potential to enhance the science productivity of the mission both at the Moon and on Earth and increase situational awareness.

Priority: Mission Enhancing for Artemis Sortie Missions, Mission Enabling for Artemis Base Camp Missions.

Time Criticality: Useful for Artemis Sortie Missions, increasingly important for Artemis Base Camp Missions.

Candidate Analog Scenario(s): Analog field testing to assess improvements to situational awareness and science data collection for specific scientific investigations, development and test of advanced technology software platforms, integration of mission operations and science support teams with surface crew in high fidelity analog environment.

Objective J.3: Assess the feasibility of using low-cost COTS (Commercial off the Shelf) camera systems and instruments to provide science measurements and situational awareness compatible with AR/VR/XR systems for optimizing scientific return from Artemis missions.

Description: Technical improvements in terrestrial instrumentation have followed an exponential path in recent decades, but such instruments currently lack the appropriate rigorous testing for extreme space/lunar environments that would allow them to be used for science without undue risk to spacecraft/instrument hardware. Investment in identifying and testing COTS instruments that could provide high science return would greatly increase the breadth and depth of portable, inexpensive instruments available to ground crew. Examples of COTS instruments include, but are not limited to, static goPro-type cameras, depth cameras, 360 cameras, etc.

Priority: Mission Enhancing for Artemis Sortie Missions, Mission Enabling for Artemis Base Camp Missions.

Time Criticality: Useful for Artemis Sortie Missions, increasingly important for Artemis Base Camp Missions.

Candidate Analog Scenario(s): Environmental testing facilities for Technology Readiness Level (TRL) advancement, analog field testing to assess improvements to situational awareness and science data collection for specific scientific investigations, development and testing of advanced technology software platforms.

K. Communications Architecture

Effective communications among key elements of any Artemis mission will be critical to optimizing science productivity and ensuring mission success. For both Artemis Sortie Missions and Artemis Base Camp Missions, a communications architecture must be developed to integrate the Artemis astronaut crews on the lunar surface (EVA and IVA) with the SSR and FCT on Earth. Analysis and testing of communication platforms (e.g., voice, video, text chat, data visualizations, virtual platforms, etc.), protocols for communications and lines of communication within the mission hierarchy, real-time versus delayed relay of different information types, and considerations of bandwidth limitations on data relay and communication must all be considered.

Objective K.1: Determine the ideal communications structure to support Artemis Sortie Missions and/or Artemis Base Camp Missions. This architecture can include how the SSR communicates internally (including any science payload teams) as well as how the SSR communicates with the FCT. Communication methods may include voice, video, and text chat systems, as well as virtual platforms.

Description: The communication architecture between the FCT, SSR, astronaut crews, and within the SSR must be developed and tested. Considerations include possible use of a multi-tier communication system for selected representatives from these different groups to specific meetings and communication channels (similar to Mars rover operations) while considering the number of channels necessary to operate the overall communication infrastructure. Analog testing should address the operations of the audio stream with CAPCOM/Ground IV and/or SCICOM with the astronauts to determine optimal procedures. For example, investigations can evaluate if the SSR should be able to directly send information to the crew (e.g., visual imagery and maps accessed on a tablet; updated text checklists viewed on a HUD; updates or short briefings (via video, voice, or text)) and/or consider how much additional data and technology support would be required by adding multiple communication streams to/from the astronauts, and/or is this communication better streamlined through one point of contact on the ground with the SSR or FCT. The communication between the SSR and FCT must also be addressed and an optimal hierarchy and line of communication established to enable efficient and accurate communications to relay science information and ensure optimal surface operations in terms of science productivity. The SSR must also develop an internal communications strategy to effectively analyze and interpret data to provide meaningful feedback for operations in an efficient manner consistent with the overall ConOps.

Priority: Mission Required for all crewed surface missions.

Time Criticality: Required for both Artemis Sortie and Base Camp Missions**.**

Candidate Analog Scenario(s): High-fidelity integrated field campaign including surface astronaut crew, SSR, and FCT.

Objective K.2: Develop recommendations on alternate forms of communication between the crew and the SSR besides the traditional voice communications. For example, consider if a HUD should be used to push imagery, text, etc. to the crew or if rapid transcriptions should be made available to ground and/or astronaut crews (and where possible in multiple formats (text, braille, etc.)). Consider the utility of advanced technologies such as AR/VR/XR as tools for interpreting and relaying information among personnel.

Description: Development and testing is needed to assess the operations and utility of additional forms of communication beyond the traditional voice communications used as a primary communications method during Apollo. Technological advances over the past several decades have resulted in additional communications options such as HUDs, transcriptions of audio transmissions, virtual platforms (AR/VR/XR), etc. More development is needed for each of these technologies to integrate into an overall ConOps which should be based on a common infrastructure that can be accessed in real-time by team members, both physically present and remote. Data returned from lunar surface instruments and investigations should be included and streamed into the platform as appropriate, as well as archived for later reference. The ability to communicate and add/edit documentation in real-time (e.g., chat, version control, timeline, etc.) should also be considered.

Priority: Mission Enabling for all crewed surface missions.

Time Criticality: Useful for Artemis Sortie Missions, increasingly important for Artemis Base Camp Missions.

Candidate Analog Scenario(s): Analog deployment with astronaut crew and SSR to conduct scientific investigation and assess various forms of communications.

Objective K.3: Determine the amount of data bandwidth required (both to the Moon and to Earth) for communicating data (voice, imagery, instrument data, etc.). Assess the proportion of this communication which requires real-time transmission to support real-time operations and investigate methods of enabling the required communications bandwidths.

Description: Efficient communication and effective collaboration during scientific investigations with ground-based subject matter experts in the loop is vital to optimizing scientific productivity of Artemis missions. Several outstanding questions are related to the nature of the exact communication structure between the science support team and the Artemis astronauts. Analog testing can inform the utility of an assumed two-way near-real-time audio and one-way near-real-time high definition video from the Moon to Earth, and/or modifications to this ConOps. Analog testing can also address various communication scenarios to develop best practices. For example, investigations should evaluate if direct communication between astronauts and the SSR is preferred during science-centric EVAs, and if so, what the best approach to limit communication with crew to an individual SCICOM position is, or would the opportunity for post-EVA debriefs involving the full science support team be more beneficial. Additionally, investigations should determine what combination of voice, text, and video communication should be established between astronauts and ground teams as well as between individual members of the SSR and if concurrent text, voice, and video streams can be utilized by the SSR to effectively communicate among science support team members. In addition, the use of VR/AR/XR platforms for various science support activities (e.g., data analysis and visualization, situational awareness, traverse and EVA operations planning and updates, etc.) may be beneficial before, during, and after EVAs. To enable these types of communication activities, the required communication infrastructure on the Earth and Moon must be assessed (e.g., is direct to Earth communication sufficient? Is a lunar relay satellite(s) required? Are lunar hotspots or antennas required to enable communications?).

Priority: Mission Required for all crewed surface missions.

Time Criticality: Useful for Artemis Sortie Missions, increasingly important for Artemis Base Camp Missions.

Candidate Analog Scenario(s): Test simulating communication bandwidth constraints and capabilities with communications between a simulated lunar surface crew and Earth-based Science Support team.

Objective K.4: Determine appropriate standards for communication (shared language) and expectations for communication content and interactions among surface crew, the FCT, and the SSR. Provide opportunities for learning protocols and assessments for improving communication.

Description: A common language across all aspects of each Artemis mission is required to ensure efficient and accurate communication. All collaboration and communication platforms should adhere to this shared mission language and mission personnel should undergo appropriate training to ensure its proper usage. Developing this shared language and implementing its use across all Artemis communication platforms can be addressed through analog testing. A glossary of terms and acronyms available to all team members as well as the availability of accurate transcriptions of voice transmissions may be conducive to maintaining appropriate standards and interpretations of communications.

Priority: Mission Required for all crewed surface missions.

Time Criticality: Required for both Artemis Sortie and Artemis Base Camp Missions.

Candidate Analog Scenario(s): Integrated field testing with Artemis-relevant science objectives including astronaut crew, SSR, and FCT variables to determine and standardize most relevant shared language attributes and test integration and use of this language in mission communication platforms.

L. Crew Autonomy

Interviews with Apollo astronauts resulted in several recommendations for future exploration missions. A recurring theme is that future missions should not be as rigidly scheduled as Apollo and that the crew should have greater autonomy, with respect to judging safety, in day-to-day planning, and in executing EVAs. A related comment was the frustration expressed by many Apollo astronauts that there was never enough time to properly investigate a given site. More work is needed to evaluate the degree of crew autonomy that best enables mission science success and how to enable that autonomy by defining the relationship between the crew and the SSR.

Objective L.1: Determine the ideal balance of crew autonomy versus support from the SSR during Artemis sortie missions as well as Artemis Base Camp Missions in order to maximize science return and crew efficiency.

Description: Based on the recommendations of the Apollo astronauts, Artemis crews should have greater autonomy; however, the amount of crew autonomy versus the amount of involvement of the SSR remains a critical open question. There is likely to be some form of "happy medium" between a largely SSR- and MCC-driven operations (or the Apollo model) versus a completely autonomous crew (which is what will later be required on Mars due to the long communications latency). Furthermore, the flexibility to change the amount of crew autonomy for different missions is likely important as drivers such as duration and location on the lunar surface (which has implications as to whether real-time communications will always be possible) will also dictate the level of crew autonomy.

Priority: Mission Enabling for all crewed surface missions.

Time Criticality: Important for first crewed surface mission, critical for Artemis Base Camp Missions.

Candidate Analog Scenario(s): Requires high-fidelity mission analog simulations, including integrated SSR with broader FCT (including CAPCOM).

M. Analog Science Training

An important role of analogs is providing operationally- and scientifically-relevant locations and scenarios for training mission personnel in field science and operations. These training activities will ensure that all individual components and team members of Artemis missions are prepared for their missions, and, equally important, ensure that the integration of those components and team members is as complete and seamless as possible. Analog science training activities, while critical, are not the only component of mission development, training, and preparations. It is, therefore, also important that analog science training activities be well-integrated with other analog test and training activities as well as with all other aspects of Artemis missions.

Objective M.1: Develop curriculum and training activities to prepare SSR participants for missions, including how to foster teamwork, build trust, and familiarize the SSR with infrastructure and protocols for missions.

Description: It will likely often be the case that some or all SSR team members for a given mission will not have experience working in the SSR for a crewed mission. Familiarization with nominal operations in MCC during crewed flight operations is critical for SSR members, including principles of flight operations (i.e. teamwork, trust, communication, decision making) and how MCC infrastructure and protocols are structured. Additionally, if SSR members do not have experience working on active missions (crewed, robotic, etc.), developing strategies to work across, not just science, but also engineering and operations is critical to mission success.

Priority: Mission Required for all crewed surface missions.

Time Criticality: Required for first landed mission.

Candidate Analog Scenario(s): Include a team including multiple disciplines to adequately evaluate strategies across science, engineering, and operations.

Objective M.2: Identify and develop analog training sites of various types (scientific process, scale, terrain, illumination, etc.) to meet planned Artemis and lunar science and operations objectives defined in key science documents (i.e. Artemis 3 Science Definition Team Report, Planetary Science Decadal, etc.).

Description: During Apollo, a variety of analog sites in North America and other locations throughout the world were visited for use as analog test and training sites. Since Apollo, some of these sites have continued to be used for planetary science and planetary mission studies, others have not, and new analog sites have been identified. As preparations for Artemis continue, analog sites for both science and operational testing and training need to be developed, to include understanding their science, operational, and logistical characteristics and the definition, design, and implementation of specific training and/or test activities at those sites.

Priority: Mission Enabling for all crewed surface missions.

Time Criticality: Important for first landed mission.

Candidate Analog Scenario(s): Include science-driven (and potentially instrument-enabled) analog campaigns (from reconnaissance trips to large-scale, integrated tests) at sites with relevant geologic diversity in environments that simulate lunar terrain and mission scale. The level of fidelity required in these respects will depend on the scope of the training activity.

Objective M.3: Develop and implement curricula, training activities, and protocols to train the EVA and IVA crew, the SSR, and the FCT to support lunar field science operations, including geologic observations, sample collection, instrument deployment, and other planned lunar surface activities.

Description: Artemis mission participants including crew, SSR, and FCTs must be invested in optimizing the success of scientific investigations on the lunar surface. To that end, all participants must understand the science operations and requirements for science activities on the Artemis missions for optimal operations and integration into the overall mission architecture. Field exercises will provide astronauts, as well as SSR members and the FCT, with a commonality of experience, terminology, and expectations with regard to activities, autonomy, and decision making. Analog work should determine the levels of training required of all personnel to ensure adequate understanding of the science objectives, goals, and tasks.

Priority: Mission Required for all crewed surface missions.

Time Criticality: Required for first landed mission.

Candidate Analog Scenario(s): Include a science-driven analog campaign at a site with relevant geologic diversity in an environment that simulates lunar terrain and mission scale. The level of fidelity required in these respects will depend on the scope of the training activity. Work should include a team including multiple disciplines to adequately evaluate strategies across science, engineering, and operations. Include mission simulations with high-fidelity mission constraints and with at least an SSR (and, if possible, aspects of broader MCC and/or EVA FCT with CAPCOM).

Objective M.4: Define recommendations for how to provide crew, SSR, and FCT with appropriate experience and analog training to facilitate autonomous science decision-making during lunar surface EVAs.

Description: As the length and complexity of Artemis missions increase, it will be necessary to investigate the level of crew autonomy to be expected during science operations (during either nominal or contingency operations) and devise analog science training activities to develop the requisite ConOps and skills to enable this degree of expected and desired autonomy. The task here is to develop training activities to prepare the mission team (crew, SSR, FCT) to meet that level of autonomy (see Objective L.1).

Priority: Mission Enabling for Artemis Sortie Missions, Mission Required for Artemis Base Camp Missions.

Time Criticality: Relevant for first landed mission, critical for Artemis Sortie and Artemis Base Camp Missions.

Candidate Analog Scenario(s): Include science-driven mission simulations of sufficient duration and with high-fidelity mission constraints (e.g. comm. limitations, etc.) and with at least an SSR (and, if possible, aspects of broader MCC and/or EVA FCT with CAPCOM).

N. Location/Navigation

Apollo EVAs, rover operations, and a variety of analog activities provide ample evidence that mission objectives and crew safety require accurate location and navigation knowledge and capabilities. The operational strategies, system requirements, and hardware for efficient and effective location and navigation during Artemis EVAs must be determined and tested. The objectives outlined below seek to constrain these parameters for conducting safe and successful tasks and traverses while exploring the lunar surface.

Objective N.1: Determine optimized strategies for operational and science navigation and situational awareness in Artemis-like mission, terrain, and lighting conditions.

Description: In order to support the Artemis mission goals of returning the crew safely and completing the science objectives, there is a need for EVA navigation capabilities on the lunar surface. A navigation system(s) will enable the crew to find and document the science objectives, and will allow them to safely return to their vehicle. Navigation capability for Artemis will likely evolve in a phased approach, with basic capabilities for early Artemis missions advancing to more capable/precise systems as missions progress. Optimized strategies for science and operational navigation need to be tested in Artemis-like mission, terrain, and lighting conditions.

Priority: Mission Required for all crewed surface missions.

Time Criticality: Required for first crewed surface mission.
Candidate Analog Scenario(s): Requires an analog simulation and/or environment that simulates lunar terrain and mission scale.

Objective N.2: Determine navigation and location requirements for conducting science tasks and operations (imaging, sampling, subsurface operations, traversing, instrument deployments, etc.).

Description: For each science objective and/or task (imaging, sampling, subsurface operations, traversing, instrument deployments, etc.), navigation requirements and/or location accuracies need to be determined/justified and tested. System requirements for primary and supplementary navigation can then be derived to support lunar scientific activities and objectives.
Priority: Mission Required for all crewed surface missions.
Time Criticality: Required for first crewed surface mission.
Candidate Analog Scenario(s): Requires an analog simulation and/or environment that simulates lunar terrain and mission scale.

Objective N.3: Determine and evaluate effective map and other navigational aids for surface operations.

Description: Effective navigation during Artemis missions will likely utilize a variety of navigational aids and strategies for both primary and contingency navigation on the lunar surface. Effective map products (hardcopy and/or digital displays) need to be determined and tested for Artemis operations. In addition, other navigational aids (markers, beacons, lights, tracks, etc.) require evaluation and testing in Artemis-like mission, terrain and lighting conditions.
Priority: Mission Enabling for all crewed surface missions.
Time Criticality: Required for first crewed surface mission.
Candidate Analog Scenario(s): Requires an analog simulation and/or environment that simulates lunar terrain and mission scale.

O. Test Design

In addition to designing effective tests to address the analog objectives listed above, it is also critical to design analog objective testing effectively by designing or selecting effective metrics with which to compare technologies, protocols, operations concepts, etc., as well as by choosing ideal analog testing locations (field, onsite, etc.) and test conditions.

Objective O.1: Develop and test an effective set of metrics designed to assess analog missions (i.e. a system with which to evaluate ConOps, science operations hardware and software, etc.).

Description: When considering many of the foci of the objectives described in this document, it has historically been challenging to define a set of metrics to rigorously compare one test parameter or variable against another. It is challenging to move beyond the descriptive and qualitative to definitively prove that one system or technique

is better than another. This objective seeks to develop a new system of metrics with which to draw these distinctions that can be used in analog testing moving forward.
Priority: Mission Enhancing for all crewed surface missions.
Time Criticality: Metrics not required for any phase of lunar exploration, though the development of these systems will make subsequent analog testing more impactful.
Candidate Analog Scenario(s): The set-up of an analog test designed to test newly developed metrics must include all variables present in that metric system.

Objective O.2: Define a set of criteria with which to select an ideal facility (field site, controlled testing location, combination of facilities, etc.) for science and science operations fieldwork and testing.

Description: When seeking to select a site (or sites) to address a specific analog objective, it can often be challenging to ensure the selected site will adequately meet the needs of that test. This can include scientific process(es), logistics, safety constraints, and many other variables. This objective seeks to constrain a set of criteria and/or construct a rubric with which analog investigators can select the best site or facility (or combination thereof) with which to perform their future analog studies.
Priority: Mission Enhancing for all crewed surface missions.
Time Criticality: Analog selection criteria not required for any phase of lunar exploration, though the development of these rubrics will make subsequent analog testing more impactful.
Candidate Analog Scenario(s): None.

Conclusions

The objectives contained in this AOA SAT report are intended to capture the highest priority analog testing objectives necessary to prepare for the Artemis generation of crewed lunar surface science and exploration. Each objective outlined above includes a description and rationale for including this objective, priority of the objective in mission preparation, time criticality/necessity of the objective for each Artemis Program phase, and any requisite requirements the designed analog test should have in order to address the objective. As stated above, science objectives relevant to this report do not include those pertaining to human health and performance research, but rather those relevant to Solar System science (for example, those contained in the Artemis III Science Definition Team report). Finally, this document is intended to be a resource for those hoping to conduct analog research in preparation for future Artemis lunar surface scientific exploration.

Key Definitions

Artemis Sortie Mission: Short-duration missions with two crew on the lunar surface for less than 7 days. The initial Artemis missions shall be capable of supporting *at least* two lunar surface EVAs, each lasting at least four hours nominally with a one hour contingency.

Artemis Base Camp Missions: Long duration missions with prepositioned habitable assets (e.g. a surface habitat or a pressurized rover) that enable crew to remain on the lunar surface up to 32 days. Crewed Artemis Base Camp operations can begin with the delivery of the first prepositioned habitable asset and may include either 2 or 4 crew on the lunar surface. These missions shall enable *a minimum of* 24 hours of cumulative surface EVA time per crewmember per 7 Earth-day period.

Flight Control Team (FCT): The Team responsible for providing real-time support during crewed missions. This includes a number of functionalities, including but not limited to Flight Director (FD), the EVA team, CAPCOM/Ground IV, etc.

Mission Control Center (MCC): The physical facility housing primary mission support functionalities (i.e. the primary Flight Control Team).

Science Support Room (SSR): The science team that will provide real-time support during crewed lunar operations.

SCICOM: A possible FCT or SSR role that would be the communicator in MCC responsible for communicating directly to the crew during any science activities during an EVA.

Tools: Astronaut-deployed implements used for physical geologic sampling (i.e. hammer, tongs, scoop).

Instruments: Astronaut-deployed scientific implements used to collect advanced *in situ* data (i.e. spectrometers, geophysical payloads).

Metadata: Data that describes the data. Metadata should enable the discovery, identification, and selection of data; facilitate the management of resources, and describe the relationships among various parts of a resource.

Samples: Any lunar materials that are analyzed in-situ or collected, the latter refer to materials that remain on the lunar surface or are brought to Earth.

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