Lunar Surface Science Workshop (LSSW) Session VIII: Structuring Real-Time Science Support of Artemis Crewed Operations

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1. Overview

The Lunar Surface Science Workshops (LSSW) were organized to invite community input to determine science objectives and directives for the Artemis crewed missions to the lunar south pole. The 8th LSSW met from February 24th to 25th, 2021, to discuss scientists' integration in and among flight directors and controllers, engineers, and the astronaut crew to provide real-time scientific support during crewed missions. The program, abstracts, and on-demand recordings of presentations for the 8th LSSW are available at the following links:

Program and Abstracts:
https://www.hou.usra.edu/meetings/lunarsurface2020/pdf/lunarsurface8_program.htm

On-Demand Recordings:
https://lunarscience.arc.nasa.gov/lssw/srts

Primary topics for discussion included the lessons learned from historical and current missions, the architecture of science support in analog and historical missions, and the infrastructure necessary for science support success. Four "breakout" discussion sessions addressed these topics and elicited the opinions of meeting attendees. The results — including key recommendations and outstanding questions — of these breakout sessions are summarized in Sections 2-4. For context, mission (historical, current, and analog) overviews are detailed below in Sections 1.1-1.4.

1.1 Apollo

The Apollo program (1963-1972) included six crewed lunar landings. The Apollo 11-17 missions had a "Science Support Room" (SSR), which was informally called the "Science Backroom" (see Appendix B1). The SSR was located separate from mission control and had access to near-live video and transcribed audio of the mission to facilitate scientific support (e.g., sampling recommendations) during lunar surface EVAs (extravehicular activities). In addition to real-time science support during missions, the Apollo SSR personnel helped plan landing sites and mission traverses. Many SSR members participated in simulation-based training (in and out of the field) with the crew and mission control (see Appendix A1). Engineers worked in a separate backroom to provide support for ALSEP (Apollo Lunar Science Experiments Package) instrument deployment. During the Apollo program, there was a siloed approach for gathering and understanding mission data. For example, the CAPCOM (Capsule Communicator) was the only individual in mission control with the ability to directly communicate with the astronauts. In addition, each instrument had its own engineering and science team looking at information on their own console. These data were primarily designed to be useful after the crew left the surface. During the mission, these teams reported up within Mission Control through the Experiments Officer. The Apollo program did not have a designated plan for the archival of instrument data (e.g., ALSEP). As a consequence, for the past ~15 years, there has been a NASA effort to find, recalibrate, analyze, and archive ALSEP data that was sent directly to instrument investigators. Documentarians filmed some SSR operations, and archived footage (including available tools, room arrangements, and team dynamics) was presented at the 8th LSSW.

1.2 Mars Exploration

The surface of Mars has been explored continuously *in situ* by rovers since January 2004. All of the rovers (Spirit, Opportunity, Curiosity, and Perseverance) have included international teams overseeing multiple instruments for the scientific exploration and analysis of Mars. Composed of hundreds of scientists and engineers (e.g., approximately 450 for *Curiosity* and 350 for *Perseverance*), the mission teams have each also included graduate students and early-career participants. Before landing on Mars, the entire mission team performed multiple mission simulations. Simulations of mission activities (e.g., landing, drilling, discovery-based surface operations, etc.) provided an opportunity for the entire team to practice mission roles, build rapport with team members, and become familiar with the mission timeline and tools. The distance from Earth to Mars creates a time delay between 5 and 20 minutes, significantly influencing the mission operations architecture. After landing, the *Curiosity* team would shift their 18-hour operations timeline to account for the 40-minute difference between an Earth day and a Mars day (sol). Throughout a martian night, participants analyze downlinked data and prepare uplink plans for the coming sol. During the three months after landing the Curiosity rover, the entire team worked in person at the Jet Propulsion Laboratory. Each instrument team had individual workrooms, and there were also designated meeting spaces for meetings on the tactical timeline. As the rover missions evolved, as did the mission infrastructure and architecture. The timeline for creating a single or multiple sol plan was reduced to about 6 hours during regular business hours. After 90 sols, scientists returned to their home institutions, reducing the need for physical space. Today, the *Curiosity* and *Perseverance* mission operations continue remotely using virtual platforms, including Webex, Slack, chat channels, a web documentation interface, and multiple phone lines. Each of the Mars rover missions since

Pathfinder has operated with an established management structure (see Appendix A1) and constantly changing, qualified team members have filled key operational roles for each planning cycle. These operational roles have addressed strategic (long-term) as well as tactical planning of observations, drive path, instrument health, and sequence preparation. All the Mars rovers, past and present, have operated within their long-term mission objectives, but sol-to-sol activity can be discovery-driven, adding to mission success and scientific return.

1.3 Space Shuttle and International Space Station Operations

In the decades since the Apollo Program, the Flight Operations Directorate (FOD), in conjunction with International Partners (IPs) and Marshall Space Flight Center's Payload Operations Integration Center (POIC), have successfully executed missions with the Space Shuttle and to the International Space Station (ISS), including both intra-vehicular (IV) activities (i.e., science payloads) and EVAs. Specifically, FOD uses lessons learned and best practices from each mission and EVA to refine and improve the Flight Control Team (FCT) structure, protocols, and products. The United States On-orbit Segment (USOS) FCT is led by Mission Control Center Houston (MCC-H) and provides the real-time operations expertise to support the USOS ISS systems. The MCC-H ISS FCT has a number of console positions, led by Houston Flight (the Flight Director), which has overall responsibility for mission integration and execution and is supported by a group of certified backroom Flight Controllers (see Appendices A1 and B1). Specifically for EVA operations, there have been many valuable lessons learned for Artemis EVA operations. During an ISS EVA, a Ground IV controller directly communicates with the EV crew, while CAPCOM remains the prime communicator for the IV crew. If operations are proceeding as expected, the EVA FCT operates to both provide guidance to the EV crew when needed on the EVA procedures and to monitor data such as consumables, telemetry, suit health, etc. During off-nominal operations, the FCT is standing ready to provide guidance and input to the EV crew when necessary, responding based on prepared crib sheets for pre-determined issues, as well as providing an interface between hardware and specialty backrooms with flight controllers and the MCC-H front room. As noted in Kagey et al. (this workshop), the ISS and Space Shuttle EVA FCT structure is a successful model from which Artemis mission planning can evolve. A major takeaway is that clear direction, structure, and decision-making authority is critical in ensuring safe and productive EVA operations.

1.4 Overview of Analog Work

Analog missions provide significant capacity for testing new mission support technologies and strategies, as well as answering critical science questions. These missions are often used as preparatory campaigns to test newly developed procedures and to discover needed improvements and research techniques to implement in the final mission. The analogs we consider here are highly integrated so as to address mission structure in addition to science, and both answer science objectives while maintaining an integrated flight team. Though these campaigns do not typically mimic the lengths and breadths of exploration missions, analogs still simulate various aspects of space exploration ranging from hardware to integrated mission operations and safety margins. Analog campaigns can often run over several years, with multiple missions conducted over that time, allowing for an iterative design and testing process in proving hardware and mission requirements. The NASA Desert Research and Technology Studies (Desert RATS), Extreme Environment Mission Operations (NEEMO), and Biologic Analog Science Associated with Lava Terrains (BASALT) are examples of NASA analog missions that have simulated living and working on a spacecraft and EVA procedures while also serving as training mechanisms for astronaut explorers. Appendices A2 and B2 summarize the organizational structures for some examples of past analog campaigns. While there is no perfect analog location, nor is there an analog mission profile that can perfectly simulate an extraterrestrial exploration environment, a combination of work in multiple analog environments will help the Science Team, the broader Flight Control Team, and future Artemis crews build toward Artemis surface missions, while also bringing together the broader exploration workforce in the time prior to each mission. Chosen analog sites should include a variety of extreme environments, including but not limited to underwater environments, locations near the North and South poles, volcanic flows, and impact craters.

2. Recommendations from Historical Missions, Current Missions, and Analog Experience

The breakout sessions on the first day of the 8th LSSW and several plenary invited and contributed talks on both days focused on relevant lessons learned from Apollo, Mars exploration, and International Space Station operations, as well as analog investigations on Earth. Recommendations from analog missions are based on high-fidelity analog missions in which science operations and mission command are integrated and EVA teams operate in extreme environments. The following are the key recommendations (see also Appendices A3 and B3).

1. **Involvement of early career researchers, the broader science community, and the general public will ensure Artemis program longevity**.
    a. Early career participation on a science support team at each stage of the mission will guarantee its scientific robustness and provide training to future leaders in Artemis science.
    b. The broader scientific community, potentially including international collaborators, must be invited to participate in mission preparation, support tool development, and provide science support for long-duration missions.
    c. Public support is vital for a sustained lunar exploration program, and the Artemis science support team can play a role in "winning the hearts and minds" of the American public.
        i. The lunar science community can engage the public with outreach programs to garner support, possibly by utilizing human exploration, orbital reconnaissance missions such as the LRO, etc.
        ii. Crowdsourcing and community science can be essential tools for engaging the public, especially for drawing the attention of decision-makers with regard to new and ambitious ideas.

2. **Adapt to discovery.** A science support team must adapt to discoveries made by the crew rather than rigidly prescribed to predetermined mission objectives. There should be plans for mission priorities but the flexibility to meet challenges and address new findings. Flexible mission *objectives* answer to Artemis program *goals*, which are top-level and immutable. Alternatively, procedural *tasks* (i.e., steps for instrument set-up) should be unalterable, particularly for mission-critical tasks, to ensure the crew's safety.

3. **We must practice and enforce the integration of teams.**
    a. It is necessary to conduct fieldwork in analog environments (using hardware and protocols as close as expected to flight products) with the entire team (mission controllers, science support, engineers, documentarians, and crew) to improve mutual trust and communication.

   b. Maintaining integrated teams (e.g., engineers working with scientists) for the mission's duration will ensure cross-disciplinary communication.

4. **Analog tests and simulations are needed to prepare all team members for their roles.** Simulations will play a critical role in unifying science and operations teams prior to the flight and prepare large science teams who may be split into operational and non-operational roles prior to crew deployment to the lunar surface.

5. **There need to be rigidly defined roles within the science support team.** Role definition, differentiation, assignments should occur in advance of the mission. Simulation of assigned roles and responsibilities is imperative among those actively participating in real-time during crewed EVAs (extravehicular activities). However, those roles and responsibilities can and should evolve with the expanding needs of the Artemis program.

6. **Maximizing efficiency of operations in accomplishing science objectives is critical to mission science return.**
   a. Communication to the astronaut crew from the ground must be carefully considered, and simultaneous communications streams should be minimized to avoid confusion and potentially conflicting commands (see Section 4.2).
   b. Experience gained from fully-integrated analog tests (e.g. NEEMO, Desert RATS, etc.) suggests that establishing a SCICOM (science communicator) role separate from the CAPCOM/Ground IV may help reduce noise while maintaining more direct contact between the science support team and the astronaut crew (see Section 4.2).

7. **The crew must be prepared to operate semi-autonomously.** EVAs are risky and costly, demanding concise communication by the FCT with the astronaut crew. Some level of crew autonomy must exist during nominal lunar surface operations, particularly as we prepare for time-delayed communications expected for Mars missions.

8. **Mission products must be well-documented and available to all personnel throughout the mission.**
   a. Prior to missions, flight rules and products must be well-documented.
   b. During missions, mapping must be conducted by dedicated mapping staff and made accessible to all support teams.
   c. During missions, astronaut observations, data, images, and sample science must be displayed meaningfully and in real-time.

   d. After each mission, data and data products should be consistently archived and made available to the science community. Given the dearth of original ALSEP instrument data archives, we find that this would save costs and time for future data analysis and mission science return.

9. **Documentarians are a necessity.** Having access to historical mission images, videos, and audio recordings has proven enormously beneficial in planning future missions but is also socially significant. Documentation during Artemis lunar surface operations is critical to preserving information for future generations. Documentarians should have subject matter expertise and participate in mission training simulations to produce higher-quality documentation of operations activities and real-time decision making.

3. Infrastructure

The infrastructure breakout session on day 2 focused on the physical space, facilities, equipment, tools, hardware, software, communications, data streams, etc., desired for real-time operations support during Artemis to enable science objectives. Driving questions for the session were:

- What sort of physical space is required to support the Backroom/Science Operations Center during Artemis missions? Where should this be in relation to other mission support?
- What are the computing resources, including software and visualization tools, that the Backroom/Science Operations team will need during Artemis missions?
- What communications infrastructure, as well as other tools deployed on the lunar surface, will specifically enable the science support team to do their work in supporting Artemis missions?

3.1 Recommendations for Infrastructure

1. **Physical space is imperative for the scientific support team.**
    a. There should be multiple physical spaces that can be divided by specialty, instrument, and/or mission objective.
    b. Physical spaces will need to have the infrastructure to support communication between the on-site physical spaces and other auxiliary locations.
    c. Modular, reconfigurable spaces with individual workstations and larger shared screens have proven beneficial in analog mission scenarios.

2. **All physical spaces need to have the technological capabilities to include people not physically present.**
    a. Infrastructure should leverage video, voice, and text chat systems, as well as virtual forum spaces (i.e., Microsoft Teams, Slack, etc.) to support remote participation and engagement in mission operations.

3. **More development is needed to design a virtual communications platform capable of supporting real-time surface operations.**
    a. The virtual platform should have a common infrastructure that can be accessed in real-time by team members, both physically present and remote.
    b. Data returned from lunar surface instruments, and investigations should be included and streamed into the platform, as well as archived for later reference.
    c. The platform should include the ability to communicate and add/edit documentation in real-time (e.g., chat, version control, timeline, etc.).

4. **Physical spaces should be designed based on mission objectives.**
    a. Ergonomic designers can assist in making functional, sustainable, and healthy workspaces.
    b. The length and type of mission may change the physical space needs and, therefore, should be adjustable.
    c. The physical location of the science support room should be proximal to the primary mission control room.

5. **Create a common communication language across the team**
    a. Training for missions should include all mission team members (astronauts, scientists, engineers, documentarians) to develop a shared language.
    b. Virtual collaboration and communication platforms should be conducive to using this shared mission language.
    c. A glossary of terms and acronyms should be built and available to all team members.

6. **Real-time transcription is helpful for keeping track of communication.**
    a. Transcription would need to be done by a person or Artificial Intelligence (AI) system that understands technical jargon and the communication style.
    b. Transcription should be tested and trained alongside the mission team and astronauts.
    c. Real-time transcription would need to be immediately available to mission team members. The transcriptions should be indexed in a way that allows them to be searchable.

7. **The development of Virtual Reality (VR) and Augmented Reality (AR) tools should be considered a supplement to the Flight Control and Science Support Teams.**
    a. The development of a VR environment would enable scientists on the ground to work in the "same location" as the crew and any remote science teams.
    b. VR capabilities would provide a backdrop for EVA planning and later data analysis.
    c. AR technology can provide enhanced situational awareness for both astronauts on the lunar surface and science support team personnel using smaller virtual overlays that do not limit a user's connection with the physical world around them.

8. **Establish cross-instrument data compatibility.** Artemis surface operations will include a diverse set of scientific instruments that produce large amounts of data. Additionally, engineering data from other systems (e.g., suits, mobility systems, spacecraft) will also be

collected and returned for analysis. Data types will range from closed, proprietary formats to standard, open-data formats, and data will likely vary in the timing and amount of data collected. Real-time science support requires the ability to gather and understand all this mission data in a real-time environment. Ideally, suits and instruments involved in the Artemis program should be able to transmit data in real-time. As the long-term goal of NASA is to establish a sustained human presence on the lunar surface, real time data transfer will be a necessary architecture that can and should be established as part of the early Artemis missions.

a. A proposed solution is for data and metadata standards to impose a top-down approach. Therefore, all systems, instruments, and payloads will become components of the Artemis missions and will be subject to the same standards and requirements for compatibility and interoperability.
b. Telemetry from Artemis components should be gathered and housed within a single, centralized data system as a natural extension to the methods currently employed when funneling multi-instrument data through a single downlink. Each instrument's engineering and science team would retrieve copies of their data from the central data system.
c. Having the mission data in an interoperable, compatible format that is housed in a central location will enable the use of advanced real-time data visualization and analysis systems that enable science support room operations in addition to mission operations overall. Such systems improve situational awareness, speed up decision-making, etc., and preserve the mission context of each mission's science and operations data for later analysis.
d. The science community should be integrated into the decision-making and design process of data formats/compatibility early on in planning for Artemis missions.

3.2 Outstanding Questions for Infrastructure

1. **How should communication between the Flight Control Team, Science Support Team, and within the Science Support Team be structured?** Will there be a multi-tier communication system for selected representatives from different groups to specific meetings and communication channels, similar to Mars Rover operations? Will a layered communication structure add to the amount of physical and virtual meeting spaces required? How does the number of channels necessary change to the overall communication infrastructure?

2. **Should the audio stream with CAPCOM/Ground IV and/or SCICOM be the only point of communication with the astronauts?** Should the science support team be able to directly

send to the crew, for example: visual imagery and maps accessed on a tablet; updated text checklists viewed on a heads-up display; updates or short briefings (via video, voice, or text); etc.? How much additional data and technology support would be required by adding multiple communication streams to/from the astronauts?

3. **Are multiple communication pathways to the astronauts needed, or should communication with the crew always be located in the same physical space and occur through the same individual and via the same modality?** If there is a change in who is the active communicator with the crew (e.g., from CAPCOM/Ground IV to SCICOM or to objective/instrument specific team member, etc.; see Sections 2.6 and 4.2), would it be productive or valuable to change the physical location of the communication station, for example, to the science support team for science tasks?

4. **How can the physical spaces and infrastructure be designed to allow adjustments as the mission objectives evolve?**

5. **Will the data collected be easily PDS compatible?** Data preparation should include a plan for PDS compatibility and archival. What methodology and system would be created for archiving data that is not an instrument output (e.g., communications, sketches, timelines, etc.)?

6. **Who (crew, Flight Control Team, Science Support Team) needs what type of data (audio, video, images, instrument, etc.)?** Would it be useful to have a system that would allow annotated images between scientists on the ground and astronauts on the surface? Would visible imagery streams inform sampling strategies, geologic context, or in-situ discovery-based analysis? Can data from instruments be streamed real-time to Earth to allow adjustments and calibrations? When instruments are being used or deployed, would it be productive to allow the astronauts to speak directly with the instrument team if needed?

7. **What communication infrastructure is needed on the Moon and Earth?** To maintain the required level of information and communication, would there be a need to set up hotspots, antennas, etc. on the lunar surface? How does determining these needs play into mission planning?

8. **Does there need to be hardware and software development?** What constraints (e.g., power, bandwidth, size) and requirements would fit the needs of the real-time surface operations?

9. **Would the developed VR and AR tools require specific facilities (e.g., specific rooms, computing and display hardware, different lighting, dedicated networking infrastructure, communication tools)?**

10. **How will the missions' evolving architecture (e.g., number of astronauts, eventual parallel surface investigations, etc.) affect the number and type of communication channels needed?**

11. **Are there significant differences in costs and gains between different infrastructure styles?** How and when would budget decisions occur? Is there an opportunity to invest in communication infrastructure that will be a basis for missions to Mars?

12. **What new mission control positions will be needed, and how can we leverage the existing mission control structure?** How will these console positions be physically organized (e.g., linear, modular, circular)?

4. Architecture

The Architecture breakout session on day 2 focused on the organizational structure desired for real-time operations support during Artemis to enable science objectives. Driving questions for the session were:

- How should the Backroom/Science Operations Center be structured during Artemis lunar surface exploration (i.e., team structure, physical location, interfaces to support infrastructure, etc.)?
- What should roles and responsibilities look like in the Artemis science support team? What kind of positions should exist? How should the science support team be selected, and what backgrounds are needed?
- What role will the 'Science Operations Center' play in real-time surface operations (crew autonomy versus the decisions the science support team will want to feed input into)?
- What is the role of strategic versus tactical science support teams? How would the shift structure and staffing roster look?

4.1 Recommendations for Architecture

1. **The Artemis pre-mission training (field, analog) program should include astronauts, mission control team members, science support team personnel, and documentarians.** This early integration is necessary to facilitate better communication, teamwork, and a sense of trust during mission operations. Analog deployments and simulations provide opportunities to work out the best internal and external communication architecture before mission operations begin.

2. **Dedicated documentarians with some subject matter expertise are critical for recording audio, visual, and text-based records in real-time during mission operations.** Clear documentation of discussions and the decision-making process is valuable within the context of a single mission, allowing team members to refer back to records and inform the next series of decisions. Clear and concise documentation is imperative within the Artemis program to serve as a historical record and inform future exploration programs.

3. **The science support team should be involved in site selection, traverse planning, and EVA planning as much as the timeline allows, especially once high-resolution data is available for the landing site(s) and operational field area(s) on the lunar surface.**

4. **The science support team should include dedicated members responsible for identifying and tracking features of interest and crew activities during mission operations in real-**

time. Identifying, cataloging, and ranking potential targets and locations from which the astronauts would collect geologic samples could contribute to the planning of consequent EVAs.

5. **The science support team should include positions dedicated to creating and updating both interpreted geologic maps and tactical maps in near-real-time as new data becomes available.**

6. **The science support team should include representatives for each instrument being used by astronauts on the lunar surface.** Science support team members will be needed to interpret and synthesize multiple data points, instrument and data calibration, and troubleshooting should any issues arise with the instruments during a mission.

7. **Efficient communication and effective collaboration during scientific investigations with ground-based subject matter experts in the loop will depend on two-way near-real-time audio and one-way near-real-time high definition video from the Moon to mission control.** Shared viewing of the near-live video feeds and monitoring of communication loops will allow multiple members of the science support team to maintain situational awareness and simultaneously view, listen to, and discuss ongoing mission activities.

8. **The scientific and situational awareness of both the astronaut crews conducting lunar surface EVA's and the subject matter experts participating from mission control would be enhanced by implementing Virtual Reality (VR) and Augmented Reality (AR) data visualizations.** High-resolution remote sensing and in-situ mission data could be used to create immersive VR renderings of the lunar surface field site, providing mission control personnel with a more immersive first-hand view of the field site and potential science targets. 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. These approaches to shared data visualization could foster more efficient communication between astronauts and mission control and streamline the decision-making process regarding features of interest and sample locations. Similar to analog missions, a virtual environment is unable to provide a full experience of the flight environment. Condition-specific implementation of mixed reality systems is therefore critical to productive use of any immersive environment, both for improving situational awareness and increasing scientific return.

9. **All mission-related data should include accurate and clearly accessible timestamps.** Timestamps will enable horizontal integration of data from disparate and overlapping

sources and help overcome any disconnect between those responsible for collecting data and those responsible for analyzing that data. Timestamps should be accurate to the *second,* allowing all datasets to be connected using time as a common factor and clarifying the full mission timeline for future reference.

10. **Elements of the mission control and communication structures developed for International Space Station and Mars rover operations can be adapted to lunar surface operations**. However, the unique time delay and operational environment need to be taken into account. Current and past Mars rovers operate in a mostly unknown natural environment and execute commands over a time span of hours to days between contacts with the ground. Astronauts on the ISS operate in a known/engineered environment and execute commands in real-time with live input from the ground. Astronauts on the Moon will operate in a mostly unknown natural environment and will execute commands in near-real-time with the potential for live input from CAPCOM/Ground IV and/or SCICOM (see Sections 2.6 and 4.2).

11. **Communications within and between the Artemis Science, Engineering, and Operations teams could be optimized by organizing these teams into separate physical spaces, with shared virtual spaces.** Using separate but nearby physical spaces will allow for specialized discussion without interruption of unrelated tasks. The proximity of these separate spaces will allow for quick communication or meetings between groups should the need arise. Internet-based video, voice, and text chat systems, as well as virtual forum spaces (i.e., Microsoft Teams, Slack, etc.), could be implemented to support remote participation, engagement, and collaboration between science support, engineering, and operations team members, including those who are otherwise unable to be physically present for mission operations.

12. **Including a diverse and equitable group of current and next-generation scientists is key to the overall quality and longevity of lunar surface operations and the Artemis program.** Including early career training opportunities as part of the Artemis program mission control structure is essential to training future generations of scientists and likewise promotes the longevity of lunar surface science operations.

13. **Carefully consider the roles of strategic vs. tactical real-time science support.** The nature of human spaceflight EVA operations requires a small group of experts in their various fields, each trained in flight operations, to work together in a carefully orchestrated communication hierarchy to make each EVA a success. Contrasting this, Artemis will include a large community of scientists, all experts in their fields, that can add

insight and value into the gathering of Artemis science data during operations. In some respects, these two needs are conflicting. To address this, it is recommended that two modes of real-time science support systems be implemented: Strategic and Tactical.

a. Strategic real-time science support operations should be modeled around what we have learned from Mars rover operations. Mars rover operations include an extensive science team that is facilitated to participate and provide input. The Strategic group's problems and decisions will be higher level and larger in scope than those of the Tactical group.
b. Tactical real-time science support operations can be modeled around how task flight controllers support EVA flight controllers during ISS EVAs. An EVA Science Officer (ESO) position included in MCC would operate within the hierarchy of the EVA flight controller who, in turn, communicates with CAPCOM/Ground IV (or SCICOM; see Section 4.2). The ESO should be a trained scientist, preferably with a field geology background and an operational skillset, who trains with and becomes a peer within MCC flight control and the science support team. The ESO would be supported by their own team (if needed) and by information software systems that provided real-time situational awareness of all science data and operations.
c. Strategic and Tactical real-time science support will work in harmony. The Strategic group establishes goals, intent, and objectives of activities via the creation and modification of EVA task plans. The Tactical (ESO's) role is to attempt to facilitate the achievement of science objectives during the EVA.

4.2 Outstanding Questions for Architecture

1. **Should communication with lunar astronauts take place through a CAPCOM/Ground IV position or through a SCICOM position?** The idea of designating a member of the science support team to serve as the primary communication link between astronauts on the lunar surface and mission control, or a SCICOM position, was suggested several times throughout the workshop. Ideas varied as to whether the proposed SCICOM would either replace or work alongside the traditional CAPCOM/Ground IV position. Arguments for both approaches were presented throughout the workshop. During the Apollo missions, a CAPCOM was used as the point of contact between mission control and the lunar astronauts. A CAPCOM allowed for focused communication but occasionally led to some confusion when plans changed or where detailed science questions arose. Implementing a SCICOM would put a subject matter expert in direct contact with astronauts on the lunar surface for assistance with science goals, instrument operation, and data collection and analysis, but may result in additional confusion related to communication hierarchy and the clear communication of operational necessities.

It is important to note that there can be a continuum of modalities for communication between FCT, the science support team, and the astronauts, and these modalities may shift from one to another during a single mission depending on what operations are underway. At one end are maintenance/engineering-centric activities (both IV and EVA) where a traditional CAPCOM/Ground IV flight controller will always be the appropriate person to fill the role. At other times, for example, when interacting with specialized science hardware or an experiment (both IV and EVA), an objective-/instrument-specific member of the science team may be more appropriate to directly interact with the crewmembers. For EVAs centered on field science, analogs suggest that a dedicated SCICOM may be a particularly effective way of aiding crewmembers in accomplishing their mission objectives. In every case, however, it is critical that whoever fills the CAPCOM/Ground IV/SCICOM position at any given time is sufficiently cross-trained and supported by other personnel to assist the crew with any contingency, whether operational or scientific in nature.

The CAPCOM/Ground IV/SCICOM role will evolve with the changing and increasingly complex nature of lunar surface operations. For example, additional communication roles may be necessary to manage potentially unrelated yet parallel tasks during later missions, for example, to support multiple teams of astronauts on EVA simultaneously at different locations or IV operations concurrent with EVA operations. Flexibility in who communicates with the astronauts and how will accommodate evolution and refinement of EVA operational procedures for planetary surface exploration as distinct from those which have evolved for orbital EVAs.

2. How will a detailed communication structure for the Artemis missions look?

Several outstanding questions are related to the nature of the exact communication structure between the science support team and the Artemis astronauts. Suppose direct communication between astronauts and the science support team, at least during science-centric EVAs, is implemented. Would the best approach limit communication to an individual SCICOM position, or would the opportunity for post-EVA debriefs involving the full science support team be more beneficial? What combination of voice, text, and video communication will be established between astronauts and mission control as well as between individual members of the science support team? What is the most efficient combination of these communication methods? Can concurrent text, voice, and video streams be utilized in mission control to effectively communicate among science support team members? Advancements in live high-resolution video streaming and VR/AR technology could enable multiple science support team members (e.g. documentarians, SCICOM, ESO, etc.) to participate as “over-the-shoulder” observers during lunar surface EVA’s. To what extent can/should these “over-the-shoulder” observers be able to interact with the crew in real time, keeping in the increased amount of communications traffic associated with this approach could prove confusing or taxing to members of the Science Support Team or the astronaut crew.

3. **How many console positions should be present in the Artemis Mission Control and Science Support Rooms, and how will they be organized?** Multiple different approaches to Mission Control and science support team structures have been implemented during the Apollo, ISS, Shuttle, and Mars rover missions. The Artemis program will require a diverse and adaptable science support team capable of analyzing data from all instruments taken to the lunar surface and troubleshooting for that same equipment should the need arise. A clear outline of expertise and experience needed to successfully fulfill the role at each console position should be developed. In addition to the wealth of knowledge gained from flight missions, analog missions have proven to be an invaluable tool for testing multiple different approaches to console and personnel arrangement in various mission scenarios. A list of probable Artemis console positions with brief explanations derived from previous mission analog mission work can be found in Appendix A, and a list of analog mission architectures presented at the workshop can be found in Appendix B.

5. Summary

The field of planetary science has evolved considerably since the Apollo era and now includes various subdisciplines that require distinct instruments and data products. By leveraging lessons from historical, current, and analog missions, we can better prepare for a new generation of diverse scientists to participate in the crewed exploration of the Moon. We must anticipate the infrastructural needs of an evolving support science architecture to meet the increasing complexities of the Artemis program. To do so, we recommend that future LSSW sessions seek to formally distinguish between strategic (long-term) and tactical (real-time) mission support. Furthermore, future workshops may address Earth-based exploration in extreme environments, such as in the mining industry, the Arctic/Antarctic, and the deep ocean. Also, we recommend an additional workshop plan for Artemis data product archiving and distribution, particularly finding what data might be cross-instrument compatible. Future work on preparing for science support must address the outstanding questions in Sections 3.2 and 4.2 in this document. This generation of planetary scientists, and the next, is poised to make enormous strides in exploration, and we must provide them the tools they need.

Appendix A: Console Positions

A.1 Historical and Current Mission Console Positions

Apollo Missions

- ***Artemis Science Support Room***. Schmitt, H.H. et al. (this workshop).
    - Science Support Room (SSR), Apollo 11-17
        - Group of scientists providing science trade-off support to CAPCOM and Flight Directors
        - Staffed by geologists who had trained or planned with the crew prior to a mission
        - Tasks included finding the Apollo 11 landing site and troubleshooting experiments. Also conducted reactive planning of future missions following EVAs

- ***Structuring Real-Time Artemis Surface Science Support: Perspectives from Apollo Mission Operations***. Head, J. (this workshop).
    - Science Support Room (Apollo 11-17)
        - Located in ALFGE Backroom in MCC
        - Consisted of the following:
            - Field Geology Team: mapped crew traverses real-time, monitored crew activity and dialogue, documented sample collection, and observations
            - One person granted communication with mission control and CAPCOM
            - Maintained open communication with instrument deployment and monitoring staff in a separate room.

- ***Lunar Extra Vehicular Activity (EVA) Science Support Operations - Learning from Apollo and Shuttle for Application to Artemis***. Feist, B. F. et al. (this workshop).
    - Science support for missions designed around instrument deployment and support
        - Experiments Officer (EO): monitored deployment and evaluated function of field experiments in all phases of EVA planning and execution
            - Maintained contact with instrument PI (Primary Investigator) in the event of off-nominal instrument function and contingencies
        - Field Geology Science Support: functioned under the EO to support field geological exploration by the crew; were only non-engineering support

- Surface Mission PI: added with science support expansion by Apollo 16 and 17

Shuttle and ISS

- ***Lunar Extra Vehicular Activity (EVA) Science Support Operations - Learning from Apollo and Shuttle for Application to Artemis.*** Feist, B. F. et al. (this workshop).
    - Payload Officer (PLO) and Multi-Purpose Support Room (MPSR): integrated shuttle and payload, planned flight rules
    - Payload Operations Control Center (POCC): where PLO conducts planning with payload community; may have direct communication with Payload Specialist astronaut (not during high-risk operations or EVAs)

- ***Lessons Learned from Space Shuttle and International Space Station Operations.*** Kagey, J. (this workshop).
    - Flight Control Team (FCT): grew to encompass international partners, hardware owners, payload specialists as additions were added to the vehicles
    - United States On-orbit Segment (USOS) FCT: flight team lead by MCC-H, directs the use of USOS systems in adherence to flight rules
        - Consists of: ISS MER (headed by MER Manager), IMC, POIC (headed by POD), HOSC
        - Partners include: CSA, ESA, JAXA, Orbital ATK, ROSCOSMOS, Space-X
    - Mission Control Houston (MCC-H): leads the USOS FCT, integrates and executes mission, ensures safety real-time of the crew and ISS
        - Consists of: ADCO, CAPCOM, CRONUS, ETHOS< EVA, SURGEON/BME, GC, HSG, ISE, ISO, OPS PLAN, OSO, PLUTO, POINTING, PAO, RIO, ROBO, ISS SPAN, SPARTAN, TOPO, VVO
        - All disciplines may have backroom flight controller support positions

- ***Incorporating Historic Lessons Learned into an EVA Execution Model for Artemis.*** Kanelakos, A. (this workshop).
    - Exploration ExtraVehicular Activity (xEVA) Operations Team:
        - Plans operations and develops operational products for flight
        - Trains astronauts, flight controllers, instructors, Mission Evaluation Room (MER), and Mission Management Team (MMT)
        - Develops execution systems architecture, executes mission from MCC-H, provides troubleshooting

Mars Rover Missions

- ***Spatial Context is for Astronauts: Spatial Products, Tools, and Staff for Human Surface Operations based on Mars In Situ Missions Experience***. Calef III, F. J. et al. (this workshop).
    - Localization Scientist ("Keeper of the Maps"): position dedicated to locating a Mars rover in XYZ space along a traverse, providing a map base for community mapping, and overseeing the creation of map products
        - MSL: one Localization Scientist and two interns for the initial 30 days of instrument testing and later surface analysis
        - Mars2020: three dedicated Localization Scientists

- ***The Value of Integrating Science and Engineering Teams in the Operation of NASA's Curiosity Rover***. Vasavada, A. (this workshop).
    - Entry, Descent, and Landing (EDL) System Engineers: engineers and atmospheric scientists who identified uncertainties during landing and developed a landing system for the Curiosity rover
    - Science Operations Working Group: consists of systems engineers, instrument operators, science team members, all of whom oversee tactical uplink planning
        - Tactical Uplink Lead oversees the process of tactical uplink planning
        - Engineering liaison: a geologist who works with robotics engineers to provide scientific input for rover arm use

A.2 Analog Mission Console Positions

- ***Tactical and Strategic Science Support for Crewed Artemis Missions: Lessons Learned from the BASALT Research Program*.** Lim, D. S. S. et al. (this workshop).
    - Mission Support Center: consists of all console positions (including students and early career professionals) to support crew during operations; monitors EVA operations priorities to help direct sample selection.
    - Mission Support console positions included:
        - Leaderboard Lead, Science Lead
        - SCICOM, CAPCOM/EV (Playbook)
        - Science Lead (Geology): oversees the following consoles
            - Situational Awareness, Image management/Situational awareness
            - Instrument Lead, Science Tactical
        - Science Lead (Biology): oversees the following consoles
            - Physio Monitor
            - Ethnographer, Situational Awareness
        - Software Team (2 consoles)
        - Flight Communications (2 consoles)
        - Communications Team (2 consoles)

- ***Mission Control Structure and Strategies: Lessons from the CanMoon Sample Return Analogue Mission*.** Osinski, G. R. et al. (this workshop).
    - Science Team: led by a Science Lead, and consisted of Tactical Science Team and Science Interpretation Team.
        - Tactical Science Team: consisted of instrument leads, GIS & localization specialists, image specialists, and a documentarian
            - Conducted quality control of science data, determined uplink commands for rover operations; aided Science Interpretation Team when not busy.
        - Science Interpretation Team: interpreted downlinked data during processing; led by Interpretation Manager and consisted of specialists in pertinent disciplines (e.g., mineralogy, remote sensing, etc.)
    - Planning Team: conducts long- and short-term planning based on discussion with Science Processing Team, and uplinks commands, monitors traverse, and manages data; overseen by Planning Lead
    - Science and Planning Integrator (SPI): conducted real-time communication between Planning and Tactical Science teams to prioritize instrument use or analyses

- ***ILEWG EuroMoonMars Field Campaigns: Lessons for Artemis Crew and Science Support Collaboration*.** Foing, B. H. et al. (this workshop).
    - Mission Support Roles: Flight director, CapCom, MCC, Safety Officer
    - Logistics Support: included specialists in habitats, consumables, safety, and EVA expertise
    - Research support officer: connected with PIs and Co-Is of the investigation by mail or direct voice communication
    - Remote scitech: created maps of traverses, monitored space weather, monitors instruments.
    - Post-mission support: create database, curate and analyze samples, publish research

A.3 Recommended Console Positions for Artemis Mission Science Support

- ***Artemis Science Support Room***. Schmitt, H.H. et al. (this workshop).
    - EAE: Experiment Anomaly Evaluation; includes investigators on deployed instruments, support engineers, working to evaluate problems with experiments
        - Located in a separate room.
        - Members must be engineers familiar with deployed instrument design and use
    - RTT: Real-Time Transcripts; provides transcripts of crew's conversations in near-real time
    - Sub SSR: Sample and Feature Documentation (SFD), Discovery Response Team (DRT), Sample Identification Team (SIT)
        - SFD: small team to identify samples and compile all documentation (images and descriptions provided by crew); should be lead by a lunar surface geologist
        - DRT: three field geologists; helps redirect crew activities in response to unexpected discoveries in the field
        - SIT: small team to monitor verbal descriptions of samples as made by crew in real-time, compare sample descriptions to EVA plan and mission objectives and provide real-time information pertinent to sample collection to SSR

- ***Lunar Extra Vehicular Activity (EVA) Science Support Operations - Learning from Apollo and Shuttle for Application to Artemis***. Feist, B. F. et al. (this workshop)
    - Exploration Science Officer: flight control position (in addition to an Experiments Officer, EO) to oversee science support and hold direct communication with MCC

- ***Incorporating Historic Lessons Learned into an EVA Execution Model for Artemis***. Kanelakos, A. (this workshop).
    - EVA Science Officer (ESO): Leads EVA Science Operations Team, will integrate all EVA data and train with the crew and MCC in advance of the mission

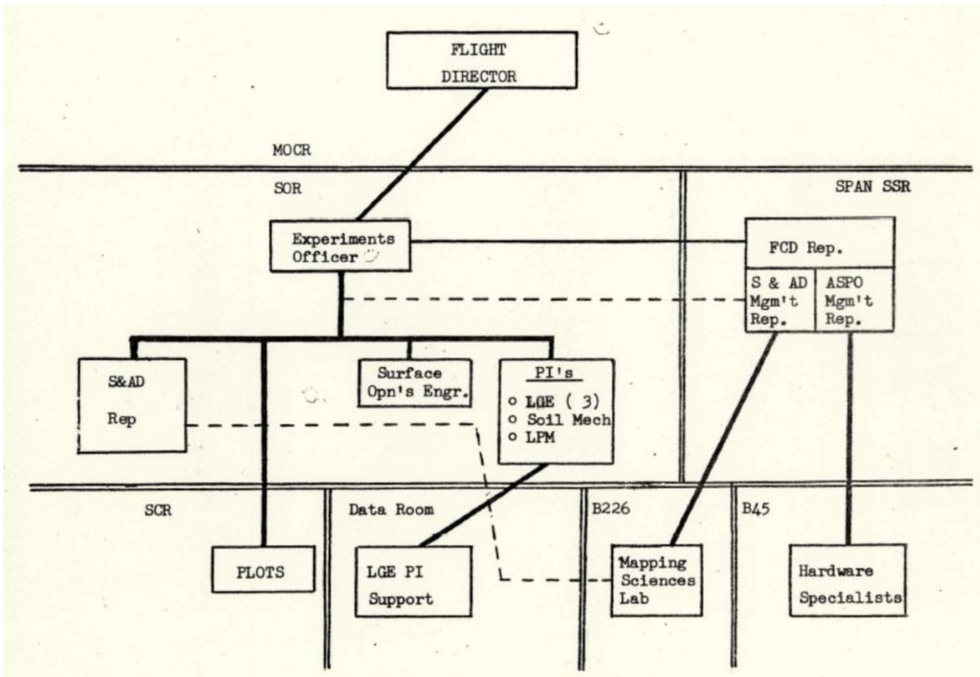
- ***Guiding Principles to Optimize Real-time Scientific Productivity During Artemis Crewed Missions to the Moon***. Heldmann, J. et al. (this workshop).
    - Science Lead: console position to communicate Science Center discussions to crew and flight ops.

- ***Surface Operations Real-Time Replanning During Apollo 17: Examples of Rapid Decision making and Implications for Artemis.*** Petro, N. E. et al. (this workshop).
    - Artemis Project Scientist: a science support team lead with direct contact to a crew member who acts as a field PI; helps to debrief observations and make changes to EVA plan depending on EVA discoveries.

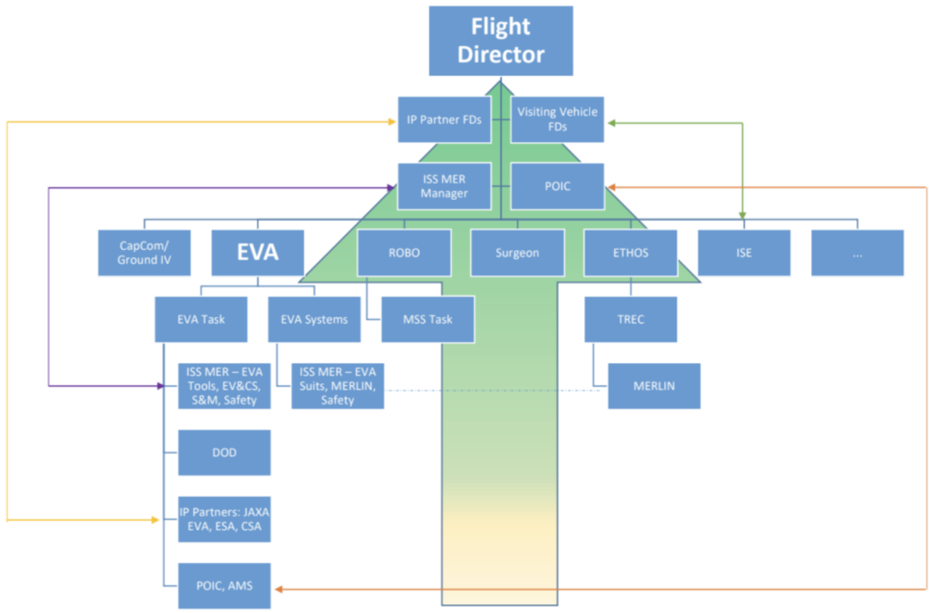
Appendix B: Organizational Charts

B.1 Historical and Current Mission Organizational Charts

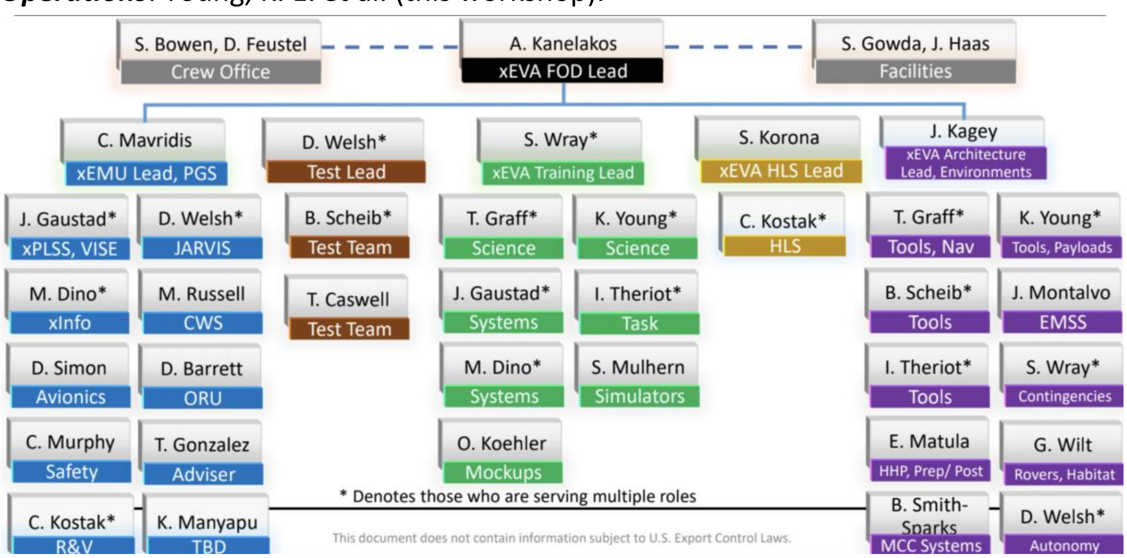
Lunar Extra Vehicular Activity (EVA) Science Support Operations - Learning from Apollo and Shuttle for Application to Artemis. Feist, B. F. et al. (this workshop).



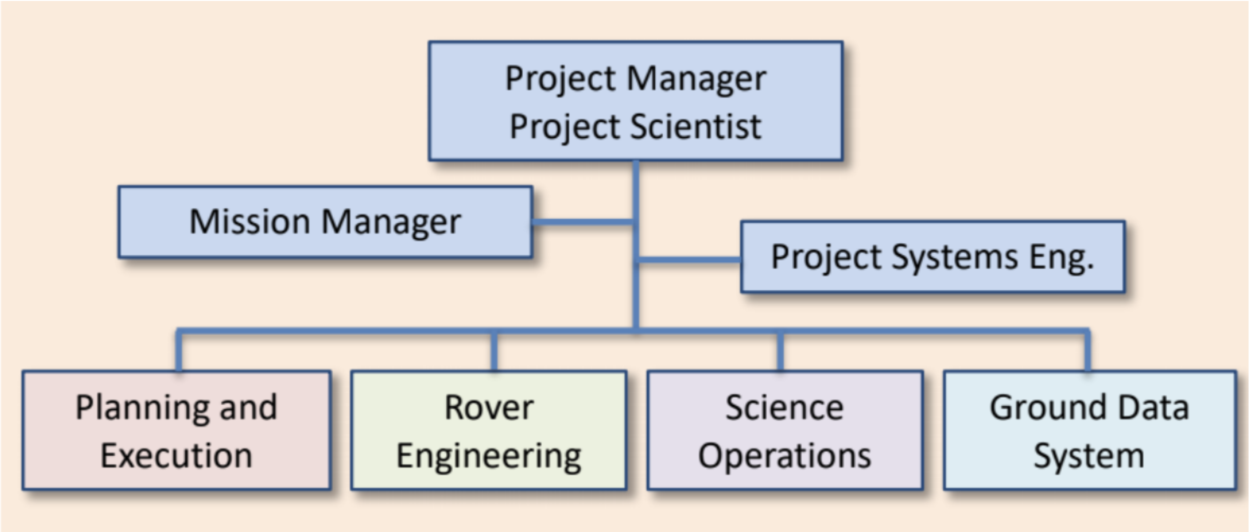
Lessons Learned from Space Shuttle and International Space Station Operations. Kagey, J. (this workshop).



Incorporating Historic Lessons Learned into an EVA Execution Model for Artemis. Kanelakos, A. (this workshop). Also presented in ***NASA Testbed Environments for Artemis Lunar Surface Operations***. Young, K. E. et al. (this workshop).

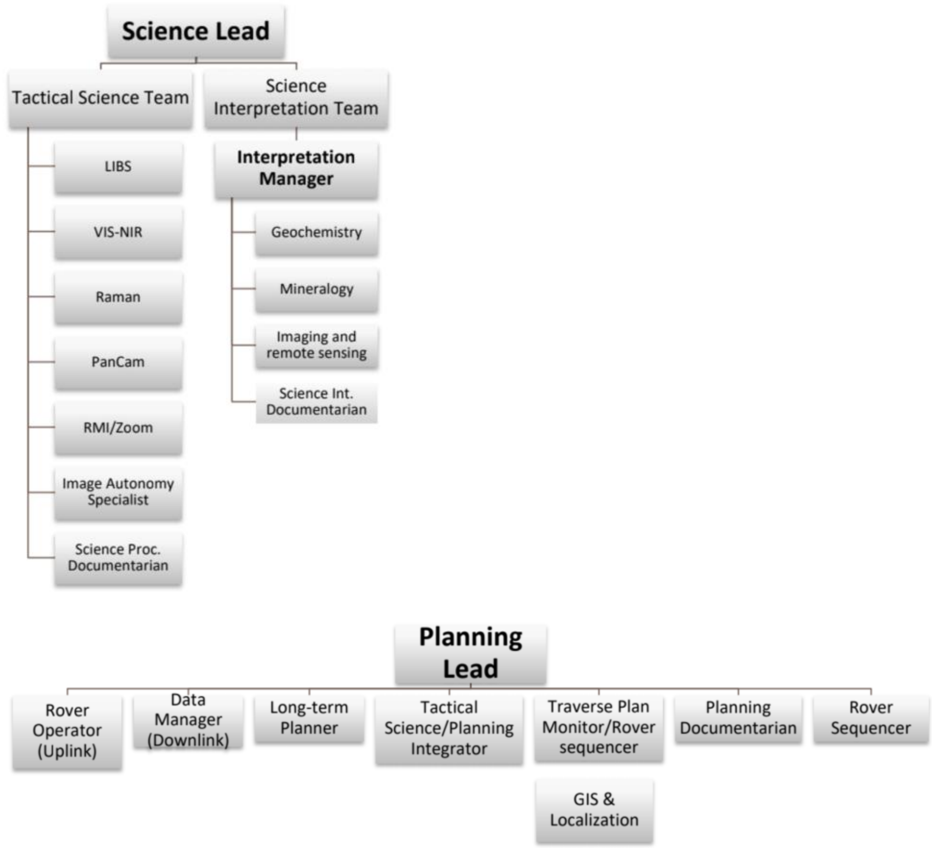


The Value of Integrating Science and Engineering Teams in the Operation of NASA's Curiosity Rover. Vasavada, A. (this workshop)

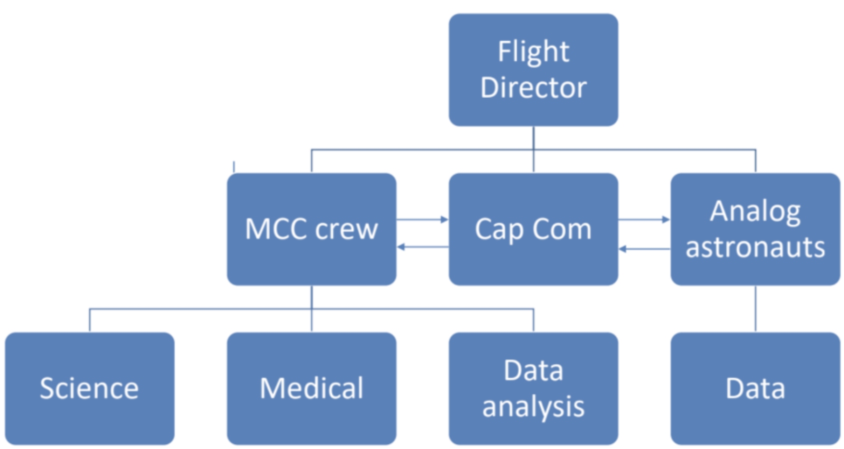


B.2 Analog Mission Organizational Charts

Mission Control Structure and Strategies: Lessons from the CanMoon Sample Return Analogue Mission. Osinski, G. R. et al. (this workshop).

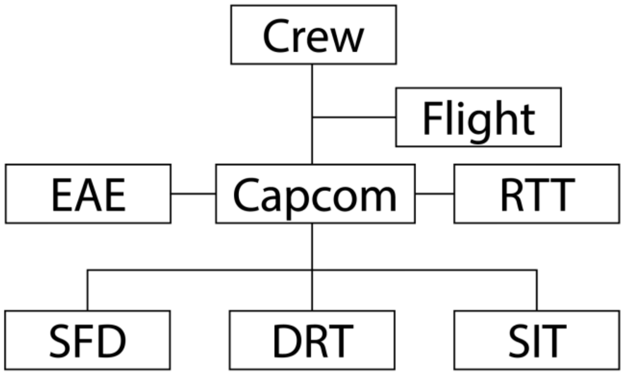


***EMMPOL (Euro Moon Mars POLand) Moon Analog Mission*.** Perrier, I. R. et al. (this workshop).



B.3 Recommended Organizational Charts for Artemis Mission Science Support

***Artemis Science Support Room*.** Schmitt, H.H. et al. (this workshop).



Incorporating Historic Lessons Learned into an EVA Execution Model for Artemis*.** Kanelakos, A. (this workshop) Also presented in ***NASA Testbed Environments for Artemis Lunar Surface Operations. Young, K. E. et al. (this workshop)