

EVA Development in Exploration-Driven Human Spaceflight

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I. Introduction

Since the Apollo program completed lunar surface operations in 1972, NASA astronauts have performed hundreds of Extravehicular Activities (EVAs) in support of Skylab, Space Shuttle and International Space Station missions. These EVAs were primarily driven by engineering objectives, such as the installation or repair of hardware. As a result, the tasks to be performed were generally well-constrained by the engineering of the hardware involved (barring, of course, unexpected hardware failures), and products guiding these EVAs were highly detailed and directive.

When astronauts return to the Moon, EVAs will include a significant component of scientific, discovery-based exploration. Mission planners will have knowledge of topography and large (>1m) features but cannot predict the nuances of terrain and geology that the astronauts will find on the lunar surface. The plan for Artemis EVAs must therefore enable sufficient flexibility to respond to the team's evolving understanding of the lunar surface while keeping the astronaut crew safe. Thus, the Artemis missions require a paradigm shift in planning and execution of EVAs, from engineering-based, directed tasks to discovery-based scientific exploration. The human spaceflight community has been challenged to build on lessons learned from Apollo, merging 50 years of EVA experience with the planetary science community's expertise, to prepare Artemis crews for success on the lunar surface.

NASA's EVA Development Process must therefore evolve to incorporate, and facilitate, principles of scientific exploration. The current version of this process for Artemis has evolved through testing in field and virtual reality. In these tests, NASA Flight Operations Directorate (FOD) flight controllers integrate with Science Mission Directorate (SMD) science teams to develop and execute simulated lunar surface EVAs (e.g., JETT3, as in [1,2]). The tests span several months and encompass mapping, traverse planning, and traverse execution.

The Artemis EVA Development Process encompasses three primary phases: Science Preparation, Flight Operations Iteration, and Creation of Final Products (Fig. 1). Science Preparation and Flight Operations Iteration develops key information that will be needed by astronauts on the surface, including plans for the EVAs. In the last phase, Creation of Final Products, this information is formatted and approved for presentation to EVA astronauts and Flight Control Team members supporting the mission.

II. Flight Control Context

A. Artemis EVA Flight Control Team

Numerous personnel on Earth support the astronaut crew during an EVA. These personnel fill engineering, science, and management roles. Key roles associated with EVA planning and execution are encompassed with the Flight Control Team, including both operations experts and science experts, who physically reside in Mission Control during EVA operations and are actively engaged in facilitating the EVA while it is in progress. The Flight Control Team is supported by teams of engineering and science experts versed in detailed knowledge of the mission's operations, hardware and objectives.

The style, medium, and pace of decision-making varies throughout the process of planning and executing Artemis EVAs. During planning, decision-making may be asynchronous and democratic, with numerous stakeholders engaged in iterative discussions. During mission execution, when astronauts are conducting the EVA on the lunar surface, decision-making shifts to a hierarchical/authoritative structure. This structure channels information from a broader set of technical experts, to systems-specific flight controllers, to decision-making authorities, to the astronauts on the lunar surface (Fig. 2). During realtime operations, specificity in roles and responsibilities promotes effective decision-making through efficient information sharing. Roles and responsibilities in the realtime operations phase generally translate directly to roles and responsibilities in the traverse planning phase.

The key roles considered in this work include the Artemis Science Team, engineering experts (suits, vehicles, and tools) in the Mission Evaluation Room (MER), and several roles in the NASA Flight Operations Directorate: the EVA Officer, Flight Director, Ground IV, EVA Task, EVA Systems, and Science Officer. These roles collaborate pre-flight to plan the EVAs that they then execute during the mission.

1. Flight Control Room (FCR) Personnel

The Flight Control Room (FCR) is the apex of Earth-bound decision-making during realtime mission execution. Information supporting this mission is channeled to specific personnel in the FCR known as Flight Controllers, who integrate that information and generate recommendations for vehicle operations or crew actions. For NASA missions, the Flight Control Room is located in the Mission Control Center (MCC) at Johnson Space Center in Houston, TX.

Within the FCR, the Flight Director is the overall authority for mission execution. The Flight Director integrates information from each flight controller, input from the astronaut crew, and programmatic priorities to determine the path forward that supports astronaut safety, vehicle safety, and mission success. They are the ultimate decision-making authority in the FCR chain of command.

Numerous flight controllers support vehicle systems and astronaut health. This manuscript focuses on a single flight controller: the EVA Officer, or simply “EVA.” To designate their presence in the FCR during mission execution, the acronym “FCR” is appended to their console name. The EVA FCR is the technical and operational authority for EVA activities, suits, and equipment. They integrate EVA priorities (both technical and scientific), operational constraints, equipment health, and suit health to determine the EVA plan that maintains astronaut safety while maximizing achievement of mission objectives. The EVA FCR receives input on EVA activities, equipment, and suits from supporting personnel in the Multi-Purpose Support Room (MPSR), described below.

The “Ground IV” is the communicator in the FCR who verbalizes input from MCC to the astronauts conducting the EVA. They are generally an astronaut as well, with equivalent training to the EVA crew. They represent the EVA crew’s interests during the decision-making process.

In the EVA planning phase, these roles collaborate to approve EVA plans before they are executed. The EVA FCR works with their team to develop proposed EVA traverses that are consistent with mission priorities, objectives, and operational constraints. The Ground IV may participate in this process. Finally, the Flight Director is consulted to approve plans before they are executed in realtime.

2. Multi-Purpose Support Room (MPSR) Personnel

As alluded to above, each flight controller in the FCR is supported by a team of subsystem experts. These personnel do not reside in the FCR, but instead in “Multi-Purpose Support Rooms.” Thus, their console names are appended with the acronym MPSR.

Each MPSR position provides detailed operational and technical expertise for their subsystem to their associated FCR. Personnel in the MPSR may also precoordinate on plans in order to ease decision-making at the FCR level.

MPSR positions supporting the EVA console include Science, EVA Task, and EVA Systems. In the International Space Station EVA flight control team, EVA is also supported by an Airlock MPSR; the requirements for a similar position in Artemis are still being refined.

The flight control position of “Science” is a hybrid FCR/MPSR. Outside of realtime EVA execution, Science is a FCR console supporting planning and execution of geological science activities conducted by the astronauts before, between, and after EVAs. In the fast-paced decision-making environment of EVA execution, however, Science serves as a MPSR reporting to EVA FCR. This flight control team structure enables cohesive EVA plan development and promotes faster decision-making during EVAs. In either context, Science is the authority on mission lunar science and geology goals and objectives, the proper collection and curation of geologic samples, and, outside of EVA activities, orbital observations of the Moon and Earth. During realtime execution, they serve as the interface between the flight control team and the Science Evaluation Room (SER), described below. During EVA traverse development, they serve as the interface between the flight control team and the Artemis Science Team.

The EVA Task MPSR is responsible for the EVA timeline and traverse plan. This includes development of the EVA procedure, including the activities that enable the EVA crew to meet mission goals while safely navigating the lunar surface within time, distance, and other applicable mission constraints. Task serves as the technical expert on EVA tools, including troubleshooting of tools in the event of failures. Finally, they are the operational authority on navigation, responsible for generating the map products used by the EVA crew on the lunar surface. During realtime execution, Task monitors progress of the EVA and recommends updated timelines and/or traverse routes to maximize astronaut safety and mission success. During traverse development, Task and Science work together to optimize traverse routes.

The EVA Systems MPSR is the technical authority on operation of the spacesuit used during the EVA. In realtime, they monitor consumables (such as oxygen, CO₂ removal, and temperature control) and work with Science and Task to modify the EVA plan if required by consumables limits. In the traverse development process, they communicate any operational constraints on the suit that may impact a traverse plan and ensure that those constraints are correctly implemented.

3. Support Personnel

For exploration-driven EVAs where geological scientific discovery is a primary goal, the support of the scientific community is crucial to facilitating mission success. Scientific support to Artemis missions is provided by the experts present in the Science Evaluation Room (SER) and Science Mission operations Room (SMOR)

As alluded to above, the Science FCR/MPSR console relies on lunar science and geology expertise from the Science Evaluation Room (SER) as well as the Science Mission Operations Room (SMOR), which serves as a backroom to the SER. Both rooms are located onsite at the NASA Johnson Space Center, the SER in the Mission Control Center and the SMOR (developed and led by the Astromaterials Research and Exploration Science group at JSC) in Building 36. The SER functions as the real-time brain trust for the lunar science and geology objectives in the mission, funneling strategic and tactical science information and recommendations through the Science console. Designed specifically with exploration science operations in mind, the SER is a unique flight control support room in MCC that allows for air wave science conversations in addition to more traditional consoles for communication with other operations teams. The SER and SMOR will be populated by a mix of lunar science and geology experts, team leadership and communicators, and specialists in geographic information systems (GIS), software tools, scientific visualization, sample & image analysis, curation, and more. Each mission’s Science Team will staff these rooms, pulling from NASA internal scientists and specialists, geology teams competed from the external science community, and more.

Additional engineering support is present during realtime execution. The Mission Evaluation Room (MER) is staffed by engineers from vehicle and equipment vendors. These personnel are technical experts in specific components of subsystems, available to provide detailed information in the event of failures or realtime analysis needs. Personnel in the MER have two reporting chains during realtime: to the MPSRs of subsystems they support, or through an internal chain to the MER Manager, who speaks directly to the Flight Director. Generally, MER Manager and Flight Director correspond only if a potential discrepancy

arises between operational priorities and hardware constraints. In that case, the Flight Director and MER Manager consult to examine and acknowledge the risk to hardware.

Though this manuscript focuses on lunar science and geology EVA tasks, it should be noted that NASA Marshall Space Flight Center's Payload Mission Operations Division also plays a critical role in Artemis science and utilization operations, as do the individual payload teams that support mission operations. PMOD is the lead operations authority for intravehicular (IVA) payload operations (except IVA lunar observations and imaging), IVA science preparation of EVA deployed payloads, and operations of EVA payloads post crew departure. Each payload manifested on an Artemis mission will also support the deployment and operations of their payload from individual operations centers. Where these centers will be will be payload-dependent, but may include NASA facilities and/or offsite academic, research, or international partner facilities.

III. Phases of EVA Development

During EVA planning, the EVA MPSR positions work as primary integrators to develop the plans used by the astronaut crew to deploy scientific instruments, locate geologic points of interest, and collect geologic samples. The final product includes detailed procedure steps where required, navigational information, and reference material used by the astronauts. The process of creating this material requires identifying the goals for geologic exploration and the key constraints on the EVAs, then iterating between the two until a workable combination of activities, timing, and route are developed.

A. Mission Definition

In the Mission Definition phase, operational and scientific considerations that impact the EVA plan are gathered. This initial data gathering identifies the driving goals and constraints that form the bones, and boundaries, of the EVA plan.

1. Operational Considerations

Operationally, Mission Definition consists of identifying the key constraints that impact the EVA plan, including specific activities that must occur during the mission to meet programmatic goals, as well as limitations imposed on the EVAs by hardware, crew capabilities, or risks.

Programmatic direction can be generated at multiple levels within NASA's Moon to Mars Program, which integrates multiple stakeholders to effect Artemis missions. Moon to Mars provides integrated mission architecture, including landing site, mission priorities, time on the surface, number of EVAs, number of crew, etc. Moon to Mars stakeholders particularly relevant to lunar EVA include the Flight Operations Directorate (FOD), the Science Mission Directorate (SMD), the EVA and Human Surface Mobility Program (EHP), and the Human Landing System (HLS). SMD carries out the scientific community's objectives for lunar exploration, EHP oversees development of the suits and tools used for EVA, as well as rovers and other surface mobility assets, and HLS manages development of the lander used to deliver crew to the lunar surface.

FOD, which is responsible for the Flight Control Team, ultimately integrates the constraints from all stakeholders into the products used to execute the mission. However, the operations team can also identify constraints that are imposed by operational risk mitigations – that is, elements of the EVA traverse which are designed to reduce risk to the astronauts but may not be otherwise imposed by hardware or program limitations. For example, the operations team may set limitations on the length of EVA traverse that occurs in shadow to reduce the risk of the astronauts from unseen slopes or obstacles.

Table 1 summarizes example constraints defined by various operational stakeholders in this phase.

2. *Scientific Considerations*

The Artemis Science Plan formulates overarching Artemis Science Objectives from the decades of lunar research conducted since the Apollo landings, consolidating the perspectives of the global lunar science community. Those Objectives flow down to Goals, which in turn flow down to Investigations. Goals denote areas of research, while Investigations delineate activities that address the associated goals [A3 SDT Report]. “Specific actions” are then the literal tasks undertaken by the astronauts on the lunar surface to complete the activities associated with science objectives [Achilles et al 2024].

The relationships between Goals, Objectives, Investigations, and specific actions are represented by a Science Traceability Matrix (Fig. 3) developed by the Artemis Science Team. This framework “operationalizes” the science of Artemis, enabling trades between specific actions (and, hence, science priorities) and other mission constraints [Achilles et al 2024]. The requirements-like framework of an STM functions well as it is familiar to scientists, engineers, and decision-makers.

Specific actions are additionally associated with physical locations on the lunar surface, identified through geologic mapping. Mapping is already underway for candidate Artemis landing sites. Leveraging geologic maps and other derived data products, each mission’s Artemis Science Team (consisting of NASA scientists and external competed geology and payload teams) identifies areas of scientific interest, designated as Points of Interest (POI). Within POIs, specific actions associated with investigations can be identified. A single POI may have one or more specific actions associated with it. Leveraging the framework of the STM, POIs can then be prioritized based on their relative contribution to mission science goals.

The prioritized POIs, including their locations and specific actions, are shared with the Flight Control Team as the starting point for the next phase: integrating scientific and operational considerations into an EVA plan. However, the priorities and constraints identified in the Mission Definition phase are not set in stone, particularly for early Artemis missions when capabilities are still being developed and understood. The iterative nature of the EVA planning process enables appropriate evolution of constraints and priorities.

B. Flight Operations Integration

The goal of the Integration phase is to generate an EVA plan that maximizes scientific return while keeping the astronauts safe and productive. Points of Interest are grouped into Stations for exploration, the specific actions to be performed at those stations are finalized, and the recommended navigation routes between those Stations and the Lander (referred to as “traverses”) are developed. The associated map of Stations and navigation routes constitutes the initial Traverse Map, which is generated using the Artemis EVA Geographic Information System (AEGIS) platform.

Task and Science collaborate closely in this phase. Combining terrain information, the initial map of POIs, and operational constraints, Task proposes an initial traverse route. It is likely that conflicts arise between science priorities and the achievable route, given operational constraints. Task and Science generate proposed solutions to those conflicts, and Science brings the proposals back to the Artemis Science Team for concurrence. Science may also reach out to the Science Team to seek proposed solutions if a high-priority science trade must be made to keep the traverse within mission constraints. Because the Science Goals span all of the mission’s EVAs, updating any given EVA can produce a waterfall of changes throughout the entire mission—for example, removing an action from EVA 4 may require it be added to EVA 3, thereby requiring removing an action from EVA 3, and so on. Thus, the process demands sufficient time to thoroughly review all EVAs as an integrated whole, not just each individual EVA.

This phase is iterative between the Flight Operations team and the broader community of EVA stakeholders. Once Task and Science develop proposed plans, they release each revision to the stakeholder community for informal review. Initially, this review is heavily science-focused, often addressing questions associated with Station actions and priorities, but may include engineering or payload team reviews of specific actions. Intuitively, multiple iterations between Science and Task further optimization of the traverse path.

At the end of this phase, Task and Science have generated close-to-final maps of the EVA traverses and descriptions of the tasks to be performed at each station, including informal review by key stakeholders.

C. Creation of Final Products

In the final step before conducting the EVA, the Flight Control Team generates products that convey the EVA plan to the astronauts and the stakeholder community. These products include traverse maps, EVA procedures, crew Cuff Checklists, Crew Map Book, and other realtime references. Once created by Task, Science, and Systems, these products are formally reviewed by the stakeholder community. Only after formal review can the products be officially released for flight.

1. Traverse Maps & Crew Map Book

Map products for EVA traverses come in two “flavors”: a GIS tool known as Artemis EVA Geographic Information System (AEGIS), which enables traverse planning and mission execution through a GUI, and hardcopy maps used by the astronauts on the lunar surface. AEGIS enables multiple users to simultaneously access georeferenced map data, including selectable map layers for satellite data sets that inform traverse planning (Fig. 4, left). During the Integration phase, Task and Science utilize AEGIS to identify POIs, determine Stations, and map traverse routes. The tool also enables placing pins to indicate navigational references or hazards. AEGIS is also leveraged during EVA execution, and for replanning between EVAs based on lessons learned.

On early Artemis missions, the crew on the surface will not have access to electronic map products such as AEGIS and will instead utilize a hardcopy Map Book. The Map Book will consist of printouts of the content viewable in AEGIS, depicting details of the lunar traverses as well as operational information such as comm coverage, slopes, and anticipated lighting. The Map Book also includes information to help the crew maintain scientific context, including geologic maps, geologic unit descriptions, and details on POIs.

2. EVA Procedures

EVA Procedures are detailed, written instructions used by the Flight Control Team to define the sequence of events that will occur during the EVA. EVA procedures are often tens of pages long (if printed), and are therefore not practical for the EVA crewmembers to carry—thus, the Ground IV uses the written procedures as a reference and provides specific words to the EVA crew when appropriate.

For Artemis EVAs, the level of detail in the EVA procedure varies according to usefulness for the FCT and EVA crew. While the crew are navigating between stations, for example, specific written instructions are not useful, as the crew’s path depends upon terrain and may evolve based on their ground truth observations. However, the details of assembling and deploying a payload are likely to remain constant, and thus are well-served by the checklist-style format of an EVA procedure.

3. Cuff Checklist

Cuff Checklists are small (~10x10 cm) booklets worn on the EVA crew’s arm (Fig. 5). Primarily these booklets contain emergency suit procedures, but do include a small section of traverse-specific instructions. These pages are formatted to reference Map Book content. They provide the crew with summaries of specific actions and timing at a given Station, as well as checklist-style instructions for recurring, complex procedures (such as Drive Tube sampling).

4. *Flight Rules*

Flight Rules are a set of guidelines that are decided upon prior to flight, in order to shorten the time and reduce thinking required during real-time operations. Flight Rules are agreed upon by all stakeholders prior to flight. They can be modified or waived with good rationale, but any waiving must be approved by the Flight Director.

IV. Conclusion

Planning and executing lunar EVAs requires a different set of skills than those required for planning and executing ISS EVAs. These EVAs require flexibility and a degree of crew autonomy that hasn’t previously been used in EVA operations. Developing the Work Instruction for lunar EVA Development has required a new way of thinking and coordination among a large group of stakeholders. This new way of thinking has developed over a series of field and Virtual Reality tests that engaged the spectrum of these stakeholders in months-long events, leading to an efficient process that will allow for effective planning and execution of flexible EVA plans.

V. Supporting Materials

A. Images, Figures, and Tables

Table 1: Mission Definition Contribution Examples by Stakeholder

Stakeholder	Operational Contribution to Mission Definition
Moon to Mars	Mission priorities, landing site, duration of stay, number of EVAs, available surface assets, etc.
SMD	Scientific/geologic priorities, sample mass priorities, payloads to be deployed, deployment specifications, terrain hazards, geologic maps
EHP	EVA suit capabilities, tool capabilities, operational controls for risk mitigation
HLS	Suit/airlock interfaces, communications capabilities/range, etc.
FOD	Operational risk mitigations; maximum traverse distance, maximum distance from lander, traverse lighting requirements, maximum safe slope for walking, maximum time without line of sight to lander, consumables redlines, etc.

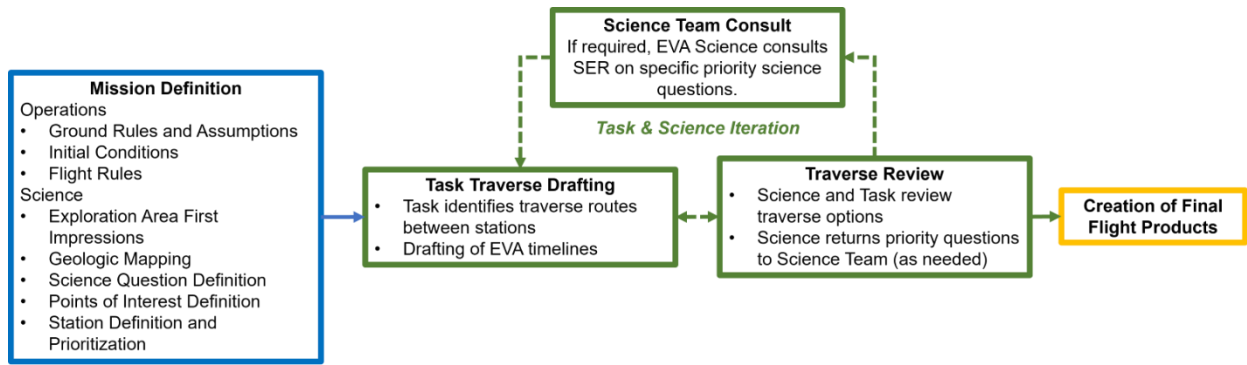


Fig. 1 Artemis EVA Development phases. Adapted from [3].

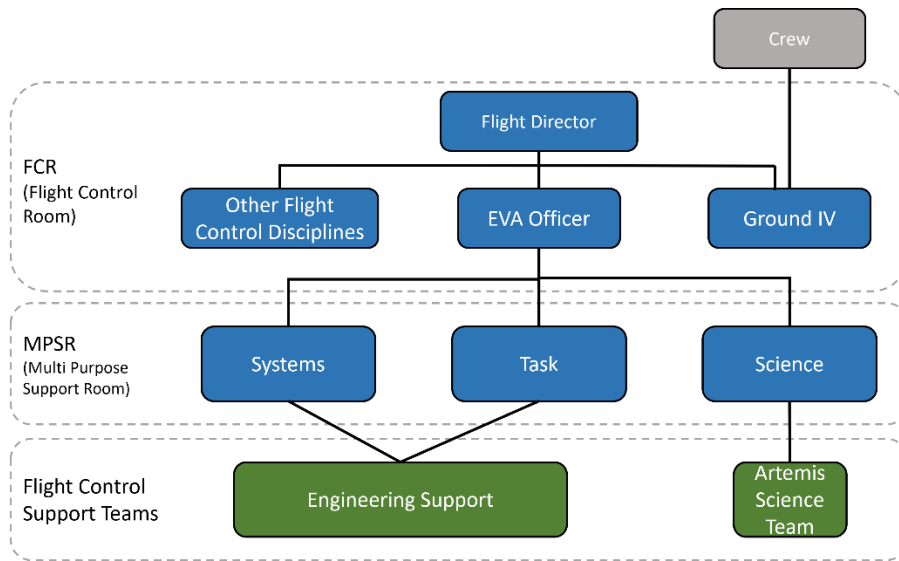


Fig. 2: Communications structure during EVA operations. Adapted from [3]

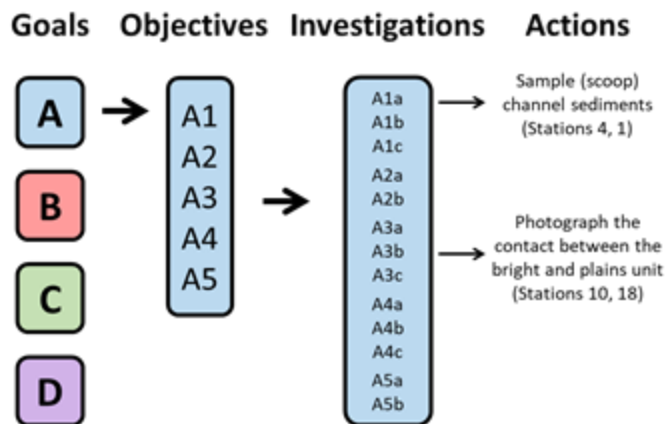


Fig. 3: Depiction of the Science Traceability Matrix framework.

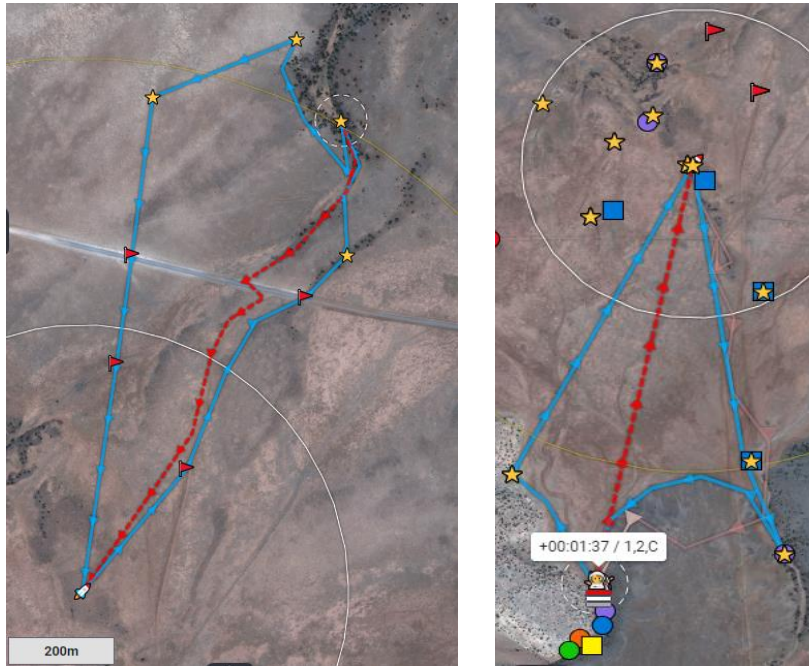


Fig. 4: Representative AEGIS traverse plans. [Left] EVA traverse plan showing Stations (stars), navigational references (flags), and traverse route (blue line). A notional return path to the lander from the highlighted Station is shown as a dashed red line. [Right] EVA traverse in “Execution Mode,” showing Stations, POIs (blue squares), and at-station specific actions (colored circles, squares). Estimated EVA crew position is shown as an astronaut icon.

EVA 4: Station 27 Map Book Page 30		Distance to Lander: 850 m (25 min) Lander Visible
Time at Station	EV1	EV2
	A. Station Characterization Station Description	A. Station Characterization Pano Photos
00:10	● B. Chip, Ridge Outcrop	● E. Describe, Photo plains contacts
00:15	● C. Desc, Photo transition, ridge to plains Looking North from ridge	■ F. Scoop, Light Plains Unit 3x Sample Markers Check MCC
00:20	● D. Scoop, Mottled Plains ~20 m north of ridge	● G. Scoop, Intermed. Plains
00:25	H. Tool Audit EV1 Tool Belt EV2 Tool Belt	H. Tool Audit EV1 Tool Belt EV2 Tool Belt
00:30	Cart – No empty spots	Cart – No empty spots

Fig. 5: Example EVA crew Cuff Checklist page.

B. References

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