# Supporting Exploration Missions by Enabling Exploration Mission System Software

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**Future exploration missions will consist of a multitude of data sources, systems, and operators collaborating to complete mission objectives. Presently, NASA is instantiating the contractual mechanisms, such as the Exploration Extravehicular Activity Services (xEVAS) and Human Landing System (HLS) contracts, to produce these mission assets. Architectural planning is also underway to establish the networking protocols and infrastructure to digitally create and connect mission elements, such as LunaNET. However, without new horizontally integrated data systems, these advancements will be limited in their ability to get mission data appropriately integrated into the plan, train, fly, explore workflow of the flight operations workforce. Here we describe several mission system software development efforts underway that are designed to support human spaceflight missions. This paper describes the current iterations of a suite of tools to support EVA procedure authoring and execution, and mission context creation for both International Space Station (ISS) and Artemis missions. These tools have been developed iteratively and continue to be used in present-day ISS operations on orbit and in several NASA facilities such as the Neutral Buoyancy Lab (NBL) and Artemis field testing. These solutions demonstrate how software development can be aligned with ongoing operations development activities to discover the features that best support both current and future human spaceflight missions.**

## Nomenclature

| | | |
|---|---|---|
| *AEGIS* | = | Artemis EVA Geographic Information System |
| *AiRT* | = | Apollo in Real Time |
| *CLPS* | = | Commercial Lunar Payload Services |
| *CODA* | = | Collaborative Operations Data Activation |
| *EHP* | = | EVA and Human Surface Mobility Program |
| *EMSS* | = | EVA Mission Systems Software |
| *EVA* | = | Extravehicular Activity |
| *FOD* | = | Flight Operations Directorate |
| *ISS* | = | International Space Station |
| *IV* | = | Intravehicular |
| *LunaNET* | = | Lunar Network |
| *NASA* | = | National Aeronautics and Space Administration |
| *NBL* | = | Neutral Buoyancy Laboratory |
| *NSTGRO* | = | NASA Space Technology Graduate Research Opportunities |
| *NSTRF* | = | NASA Space Technology Research Fellowship |

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*PET* = Phased Elapsed Time
*SMD* = Science Mission Directorate
*xEVAS* = Exploration Extravehicular Activity Services

# I. Introduction

NASA is embarking on 21st century space exploration via Artemis to establish a sustained lunar presence using innovative technologies to explore the lunar surface.[1] Artemis will involve the construction of lunar surface and orbital assets as well as a multitude of mission assets and capabilities (e.g. lander, rovers, payloads, etc.) which are being incrementally realized via contractual mechanisms solicited by NASA to industry vendors such as: Human Landing System (HLS) services development[2], Exploration Extravehicular Activity Services (xEVAS)[3], Commercial Lunar Payload Services (CLPS)[4], Lunar Network (LunaNET).[5,6] These systems will produce a wealth of data which will need to be manipulated, interrogated, and analyzed by mission support and crew to make informed decisions to cope with the demands of future missions. At present, there is a noticeable absence of contractual mechanisms in place to ensure seamless interoperability of data sets from a myriad of mission assets with the purpose of supporting mission operations personnel. Therefore, we assert in this paper that mission data are at risk for becoming siloed, being in inconsistent and incompatible formats, and requiring custom tooling to manipulate. These risks will result in limiting mission data utility and delaying the acquisition of actionable information within mission operations workforce unless there is a deliberate effort to create temporally and spatially integrated data management systems.

Mission operation personnel for human spaceflight have historically divided their work scope into plan, train, and fly mission phases.[7] Each phase involves an integrated choreography of multiple specialized teams and their flight products all dedicated to preparation and execution of specific mission aspects.[8,9] Artemis, and its envisioned innovative technologies, offers the opportunity to expand this work scope to support a fourth phase, *explore*, which we define here as the repeated, continual, and incremental learning and expansion of mission knowledge that lasts well beyond the duration of any particular moment of a mission. The most relevant example of *explore* is exhibited in the continued scientific discoveries spurred by the exploration and sample collection during Apollo.[10,11] Another example that currently occurs during International Space Station (ISS) operations is the creation of anomaly reports (see ISS EVA Suit Water Intrusion Mishap Report[12] as an example) that serve to rectify unanticipated events that may occur throughout the mission. Both examples necessitate operations personnel to interrogate a multi-dimensional array of mission data at specific moments (e.g. photography, video, crew reports, samples, system telemetry) in unique and unpredictable ways to reconstruct mission moments to both interpretate what happened and derive insights to inform future discussions and decisions.

This paper describes a specific set of tools, known collectively as the Extravehicular Activity (EVA) Mission System Software (EMSS), to transform the EVA plan, train, fly, explore work processes. This transformation is taking place by helping real users perform real mission operations job duties within ISS and Artemis. These tools and concepts could one day be extended into other facets of the future missions; however, a central tenant of the current EMSS effort is to align specific software capabilities with a specific set of users and their needs within the mission team that adds mission value right now. EMSS supports EVA-specific flight controllers who work together among the broader flight team to achieve EVA success, from EVA planning to post-execution analysis.[8,13] The remainder of this paper first provides a brief overview of the EMSS initiative. Second, a summary of each core EMSS tool is provided that describes the interface and capabilities. Finally, these tools are described within on-going ISS and Artemis EVA operations to ensure system capabilities align with users' needs and the demands of their work.

# II. EVA Mission System Software

## A. EMSS Initiative Overview

The origins of EMSS span a once diverse set of individual efforts led by a number of the co-authors of this paper who were tackling orthogonal mission operations data creation, capture, manipulation, and curation challenges associated with advancing EVA operations using modern software tools. In 2015, the https://apolloinrealtime.org/ (AiRT) website was launched by co-author Feist which horizontally integrated thousands of disparate data products across the entire Apollo 17 mission.[14] In doing so, these once isolated and disjointed moments in history were aligned in time and thereby brought back to life in a seamless experience that allowed the general public to re-live any moment of the mission in a never before experienced integrated mission context. Co-author Charney joined the development efforts for *Apollo 11* and *13 in Real Time* which have also been horizontally aligned. AiRT provides a glimpse of what might be possible if mission data and systems were intentionally designed to be coalesced and interacted with in temporal synchronicity, while minimizing the burden placed on the user to be aware of, access, and retrieve the data.

In 2013, the NASA Space Technology Research Fellowship (NSTRF), known today as NASA Space Technology Graduate Research Opportunities (NSTGRO) funded co-author Miller to apply cognitive systems engineering methods to the spaceflight work domain to design and develop novel decision support systems for EVA operations.[15] Throughout this research, the ISS EVA and planetary analog work domains were studied and modelled to discover underlying cognitive and information relationship requirements that were then used to prototype, design, and test hypothesized future EVA operations with new support systems. In collaboration with co-author Pittman, novel decision support systems that integrated timeline and system constraints were designed and tested in simulated future Mars surface EVA operation contexts.[9,16–18] This effort provided evidence that the construction of new technologies to support future work domains by studying existing work domains can be realized, as long as there was a dedicated alignment with the work domain development process itself.

In 2013, co-author Montalvo, who is a certified ISS EVA flight controller, began to reimagine the existing ISS EVA procedure authoring and execution process, via the creation of the tool: Maestro. ISS EVA procedure authoring and execution involves creating and maintaining a detailed choregraphed sequence of events for crew who work in parallel.[8,13] During EVA plan authoring, a detailed procedure serves as the centerpoint of collaboration between a multitude of flight operations personnel. During EVA execution, the procedure keeps the broader flight team aligned on overall progress of the EVA during execution and provides contingency procedure on-demand to cope with difficulties as they arise. However, this coordination and detailed tracking has been largely a labor-intensive effort using commercial tools such as Microsoft Office products which lack many domain-specific functionalities to support flight controller job duties. Initial Maestro efforts focused on preliminary user research, specifications definition, and design efforts that produced early prototypes. The concept continued to gain momentum, briefly involved university student capstone involvement, and then in 2019, dedicated development started on the Maestro software package. This effort demonstrated that the existing ISS EVA work domain could be improved with modern software capabilities and that the mission risks incurred by introducing new ISS workflows were outweighed by the benefits.

In 2018, these individual efforts united under one common effort, first known as EVA Operations System, and then formalized as EMSS in 2019. Concurrently, human health and performance personnel joined the initiative with a specific interest in aligning mission activity data with crew health and performance related data.[19] Each of these individual efforts brought necessary components together into what today is known the EVA Mission System Software (EMSS) initiative. In summary, co-authors Feist and Charney showed what could be possible with having a multi-dimensional array of mission data horizontally aligned in time to create mission context; co-author's Miller and Pittman demonstrated how work domain construction could be aligned with support system development and co-author Montalvo proved there was an appetite for mission system software changes within the existing ISS EVA work domain.

Since 2019, the EMSS initiative has been incrementally building three core software solutions as shown in Figure 1. Collaborative Operations Data Activation (CODA) exists for the purpose of putting mission data into horizontally integrated mission context to enable current and future NASA missions, as inspired by AiRT capabilities. Maestro aims to digitize EVA procedure authoring and execution. In doing so, coordinated EVA activity can be associated, recorded, and shared in never before ways among the flight team. Artemis EVA Geographic Information System

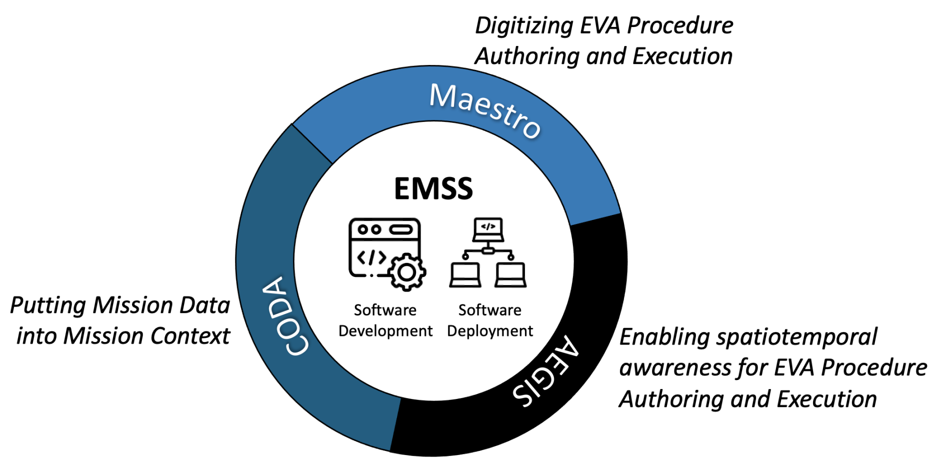


**Figure 1. EMSS core software products: CODA, Maestro, AEGIS.**

(AEGIS) strives to enable spatiotemporal awareness for EVA procedure authoring and execution. The EMSS suite of applications leverage a common architecture. React.js is used as the front-end framework for creating dynamic user interfaces. The back-end consists of Node applications that communicate with data sources and provide data to the front-end. The applications are deployed into the Flight Operations Directorate's secure server environment using Docker containers, which are like lightweight and portable virtual machines that isolate the application from the host environment. The suite also leverages continuous integration and continuous delivery (CI/CD) tools to automate the testing, building, and deployment of code changes. This enables ongoing rapid development and deployment of new features and ensures that the systems are always up-to-date. Collectively, these software development and deployment efforts bring modern software capabilities to EVA plan, train, fly, explore for both ISS and future Artemis missions.

### B. Collaborative Operations Data Activation (CODA)

CODA consolidates all data temporally from mission, training, and testing data into an exploratory web-based platform that enables users to re-live and analyze each moment. Mission context is created by introducing a new way to navigate large amounts of cross-disciplinary data which are traditionally siloed by abstracting away the concept of the individual data file and allows users to move fluidly through an event. In doing so, users are enabled to pick the moments and data (if available) that might matter to them which enables users to more fully understand what happened and what was learned. Figure 2 shows a view of this abstraction process so that the user can spend less time searching for individual files and more time on viewing a unified experience. Important to note here is CODA does not serve as the data repository, but rather seamlessly connects to wherever the source data might exist so that data can be viewed in context with other data. As discussed in the introduction, if data formatting consistency and availability is not established, then the ability to coalesce disparate data sets becomes challenging. CODA also introduces a new way to index post-event content by linking it back to key moments during the event of interest. This new ability to play back moments in history with everything in sync, including media that was not yet available during real-time operations, saves time, reduces costs, and improves the quality of research inquiries and outcomes. Until CODA, flight controllers manually had to sift through disjointed and separated data sources related to EVA or other mission activity, making data exploration costly and burdensome.

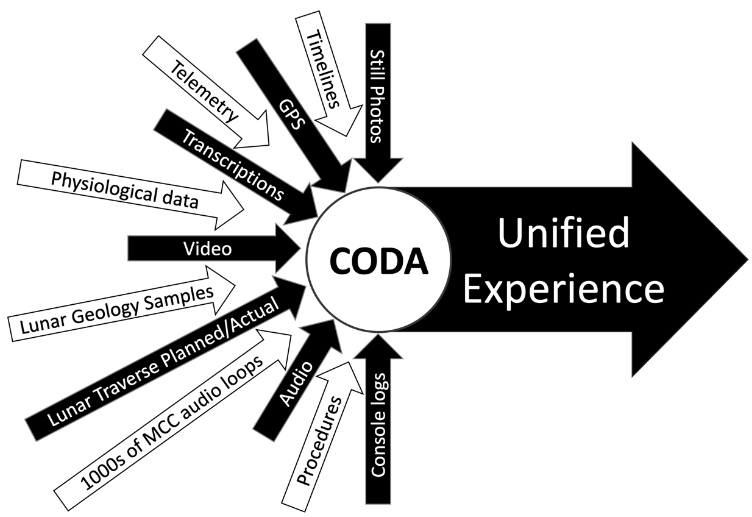


**Figure 2. Simplified diagram of CODA consolidating a multi-dimentional array of disperate data sources and creating a unified experience in time for the user to explore the mission context.**

Figure 3 shows the CODA interface for a particular moment during US EVA 76.[20] The bottom banner shows a 24-hour period of time on a moveable timeline. Each horizontal feature on the timeline indicates the availability of a particular data stream and the Play/Pause button allows a user to seamlessly scan throughout the timeline at their own pace. All data is temporally synchronized so each moment and corresponding data in the timeline can be immediately accessed. By clicking and viewing one individual data product, the system pulls all other available data available at that moment in time forward thereby establishing mission context. Each data type is contained within a dedicated frame that the user can control. Each frame is specifically designed to accommodate that data stream, thereby streamlining user needs to accommodate disparate data types (e.g. ISS orbital telemetry is automatically placed on a map with ground track in the 'ISS Position' frame, instead of simply providing source telemetry ephemeris). The overall layout of the web browser is also customizable and can be saved so that each user can tailor their experience with CODA to meet their particular data exploration needs. At present, CODA can display various data sources that span: 13+ years of ISS mission data, recent NBL training data, and Artemis field testing data, and Artemis I mission data.

Three additional features currently demonstrated by CODA is the integration of as-performed EVA timeline content, the addition of handheld photography, and audio loop transcription. The "EVA INFO" frame displays an interactive sequence of as-performed EVA activities placed correctly in time so users can quickly access segments of the EVA they might be interested in reviewing. CODA also offers two different photography frames (CURRENT or ALL) that pulls data based on time from a NASA internal imagery archival system which substantially streamlines imagery access. If users want the full resolution photography or to learn more detailed metadata information, CODA offers direct links to the underlying archival system for additional data interrogation. Finally, automated transcription services are now being applied to space to ground audio communication. CODA can ingest these timestamped audio transcripts and display that information in a dedicated "COMMUNICATION" frame so that users can search and review exact phrases or conversations that may pertain to their inquiry. The transcript is also hyperlinked in time so that the user can select the phrase of interest and the rest of the data snaps to that moment in time.

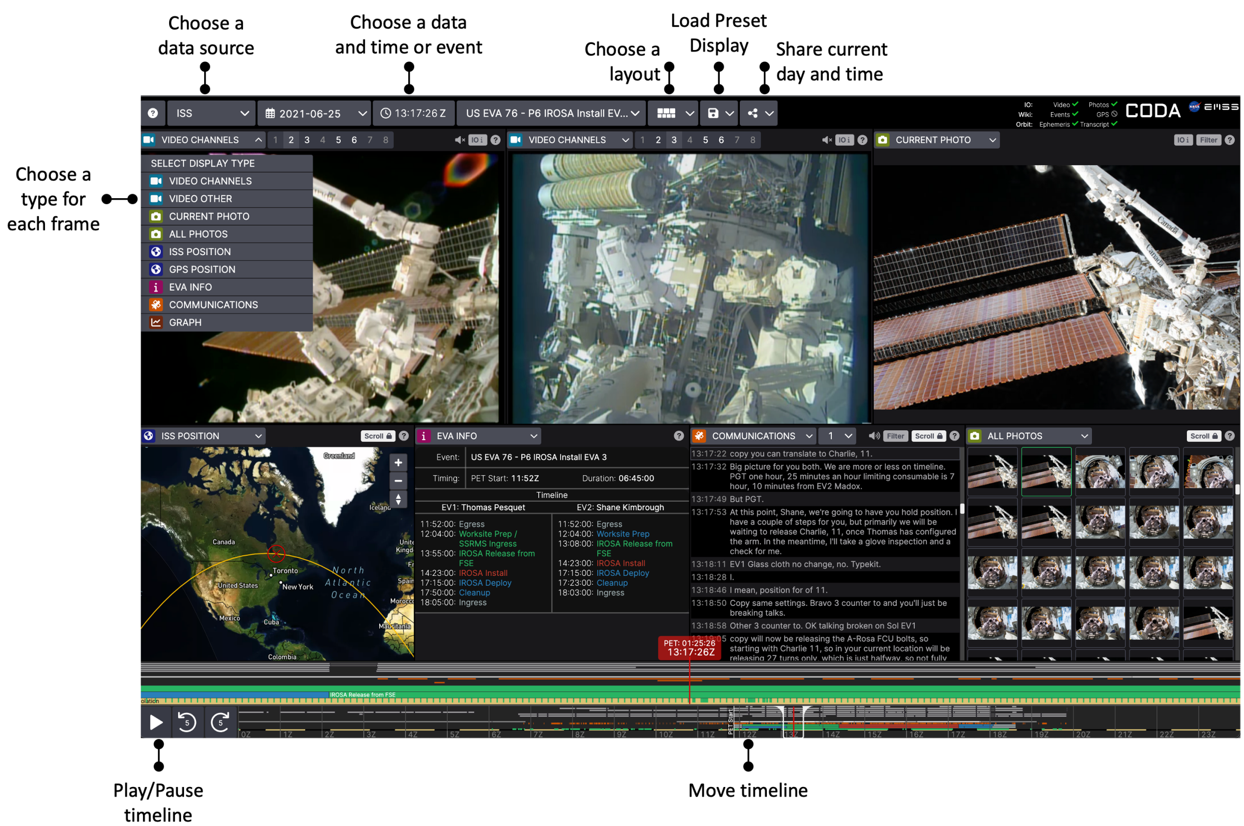


**Figure 3. CODA annotated interface that highlights the disparate data sources arranged in frames optimized for that particular data source.**

## C. Maestro

Maestro consolidates the authoring and execution process within a dedicated tool that can handle the interconnected and unique constraints of EVA procedures. Maestro enables custom capabilities that are different from existing ISS planning and execution tools such as Optimis[21,22] and PRIDE.[23,24] EVA requires the choreography of at least two EVA crew members and support personnel, therefore necessitating the need to handle in parallel the sequence of events for two or more agents at a granular level of detail. Crew work both in tandem and independently, depending on the needs of the EVA tasks. In either case, their respective procedures must be inherently associated and tracked to ensure overall EVA objectives are effectively managed and achieved. In addition to simultaneously handling the planning of at least two agents, EVA procedures for ISS are highly proceduralized, demarcating minute details that must be accomplished at specific moments. Therefore, Maestro enables users to coordinate activities with minute precision while also fully describing the necessary actions with dependencies to be accomplished for two crew members who need to perform hours of work.

Figure 4 shows a moment of time during the execution of an example EVA that has progressed approximately 3:25 phased elapsed time (PET) into a 6:30 hour planned EVA. PET is a reference time in hours:minutes:seconds with zero indicating the start of the EVA. Across the top of the interface is the procedure tab which allows users to handle multiple procedures all at once thereby reducing the data sprawl of EVA products living in separate, static files. At the far right of the Maestro interface exists an overall summary timeline that is interactive to allow viewers to quickly navigate hours worth of procedure content instantly by simply clicking on the portion of the EVA they might be interested in reviewing. The procedure columns to the left of the overall timeline provide the detailed procedures for each crew member, as well as the intravehicular (IV) and other mission control users. These portions of the application allow the user to either independently scroll/interrogate each column of procedure steps or lock them together in time to review their choreographed sequence of events. Because all moments of the EVA are aligned in time, the progress of the EVA can easily be reviewed by seeing what has been accomplished (tan), what tasks might currently be in progress (green) and what still remains to be performed (white). The red dotted line across the summary timeline provides that current position in time overlaid on the actual progress of each crew member. Given the highly customized nature of the tasks on ISS, Maestro enables users to template and streamline the application of discrete steps throughout the timeline. For example, pistol-grip tool (PGT) operations can occur many times throughout the installation of a device on ISS, and follows a standard procedure format with data input fields. PGT operations, for example, requires crew to report turn count of the drill which the flight controller then records. Maestro offers the opportunity for users to directly input expected values provided by the crew in-line with the procedure itself. As a result, Maestro enables the direct association of data at each moment during the procedure execution, thereby improving the accurate record keeping of the as-performed procedure for archiving and post-hoc analysis.

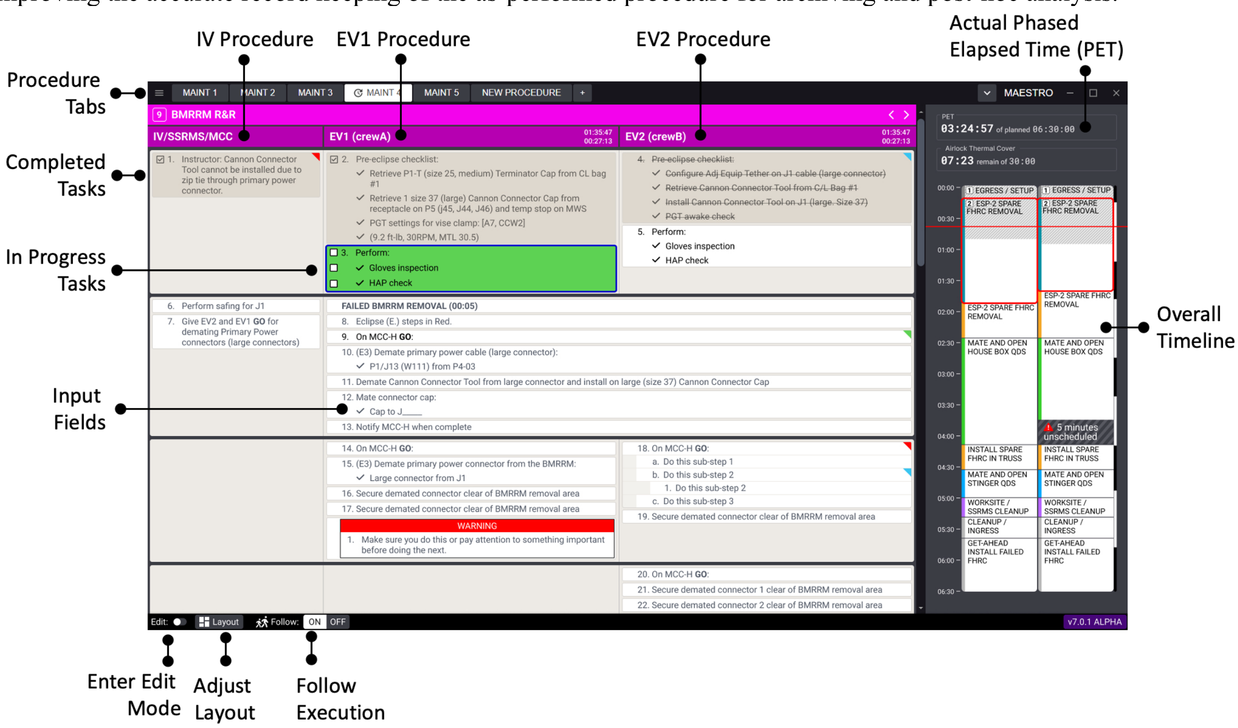


**Figure 4. Maestro execution interface for two crew members.**

EVA execution rarely follows the plan exactly, so therefore there is a need to accommodate changes to the plan in a quick and efficient manner. Maestro enables functionality that has previously never been accomplished during EVA:

the instant rearrangement of EVA tasks and the production of a new integrated timeline. Prior to Maestro, the rearrangement of EVA procedures to cope with as-executed demands was performed in isolation and in static formats such as paper documents. The individual procedure elements shown in Figure 4 can be edited during execution. The time math, the associated numbering and formatting of steps, and the verification of step sequences are all handled by Maestro so the user can spend more time reconciling whether the proposed changes are correct and necessary versus worrying about formatting or performing basic time-math calculations. In effect, making a change to the procedure in Maestro relieves the user of manually tracking and calculating tedious details and streamlines the production of a change. Furthermore, once a change is made, the procedure is published so that any viewing user can see the new plan instantly, thereby reducing coordination costs among hundreds of flight controllers who need to be appraised of EVA progress and understanding the current plan.

### D. Artemis EVA Geographic Information System (AEGIS)

NASA mission operations has not dealt with the spatiotemporal demands of surface mission operations since Apollo. In recent decades, there have been a number of planetary analog efforts that have attempted to understand how modern technologies might enable scientific planetary exploration, particularly in Mars-forward concept of operations.[25,26] For a more complete historical account of these previous analog efforts, see Table 1 of Ref [27]. However, these efforts have had limited impact in activating modern capabilities within the Flight Operations Directorate (FOD), particularly as it relates to effecting work practices and data handling expectations of the flight controllers who will ultimately be responsible for Artemis mission success. The opportunity now exists to support the actual flight controllers who will be charged with supporting Artemis planetary surface exploration.[28]

Figure 5 shows an abstracted view of what the AEGIS tool aims to unite. Lunar surface exploration will be scientifically motivated and one primary mechanism that will drive that prioritization will be in the form of a science traceability matrix (STM) (See an example in the Artemis III Science Definition Report[29]). AEGIS unites STM details to spatial map data to establish locations where planed EVA tasks will contribute to scientific objectives defined in the STM. Furthermore, AEGIS enables the opportunity to build task expectations at those locations and support the sequential arrangement of those locations and tasks to support building spatiotemporal EVA plans that inextricably link scientific value within the context of mission and safety rules. In a similar manner to CODA and Maestro, AEGIS aims to reduce the overall burden of the user to manually track and connect disparate data sources to maintain an integrated understanding of EVA plan, train, fly activities.

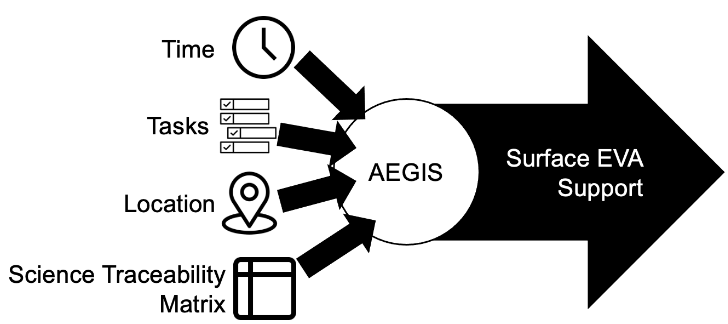


**Figure 5. Simplified diagram of AEGIS consolidating science traceability matrix details, spatial locations, tasks, and timing information to support EVA plan, train, fly activities.**

AEGIS accommodates the import and/or creation of Points of Interest (POI) that are of scientific or operational interest. POI elements also allow for the initial proposition of tasks, such as collecting samples, observations, or measurements to be accomplished at that location that might satisfy particular scientific questions identified in the STM. As a result, the science teams supporting Artemis missions can be comprehensive in their coverage of potential landing sites with specific points that potentially yield scientific value. As the flight teams begin to synthesize scientific rational for reaching specific targets, AEGIS supports the creation of EVA stations in the Station Composition. This portion of the tool enables the deliberate discussion and synthesis of POI's into proposed stations. Stations represent consolidated, detailed tasks at a particular location to support the drafting of EVA plans and includes contingency details such as get-ahead tasks and safety-related walkback constraints. Details created in the POI such as tasks and STM relationships can be seamlessly promoted to Station definition details which maintains underlying traceability to the scientific details. Station composition also enables strategic consolidation of POIs pending their spatial or STM similarities.

As shown in Figure 6, the EVA Composition enables the connection of proposed stations with traverse to and from stations. Traverses take into consideration detail associated with spatial map products such as slope and terrain roughness in addition to estimated crew walking speeds. Together, stations and traverses allow users to immediately see the integrated EVA plan. AEGIS provides estimated EVA times, total STM coverage and the ability to create alterative plans so users can objectively compare similar and contingency EVA plans. Additionally, EVA sequence diagrams, first pioneered during Apollo, provide an instant spatiotemporal view of the planned EVA. The y-axis is the linear distance from lander and the x-axis is the PET of the EVA. The user can also plot underlying pertinent map data along the EVA traverse such as elevation, surface roughness or any other raster data affiliated with the map products as data profiles. These capabilities result in users not burdened by performing any local calculations such as traverse times or cumulative time spent at a series of stations.

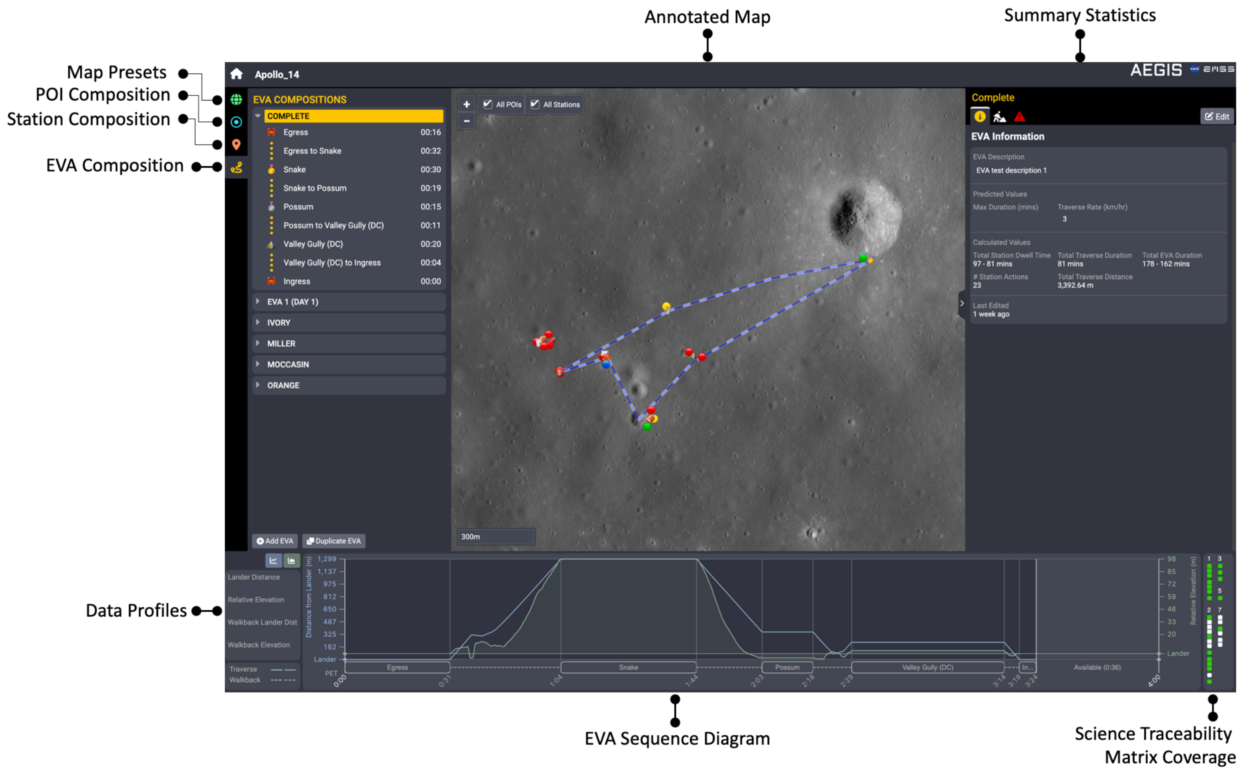


**Figure 6. AEGIS EVA Composition interface with annotations.**

## III. Integrating EMSS into Current and Future Human Spaceflight Operations

The EMSS team is actively supporting ISS operations, NBL training, and Artemis related testing events. Maestro has successfully been deployed in 6 ISS EVAs to-date and is now actively used in the support of planning and training activities at the NBL. CODA is routinely used in support of anomaly reporting for on-going ISS operations and there is active development underway to align NBL data streams to bring similar CODA capabilities to review all NBL EVA training activities. These on-going activities provide a wealth of user feedback and discussions that inform subsequent software tool capabilities. CODA was awarded the JSC Software Excellence Award and subsequently received the NASA agency-wide Major Space Act award in 2022. Maestro has received numerous acknowledgements within the FOD for helping pave a modern way of enabling the flight team to conduct EVAs.

In addition to supporting current mission operations, the EMSS team is integrated into Artemis development. Co-author Miller has been named the NASA Science Mission Directorate - Artemis Internal Science Team Software Systems Lead; the EMSS team is also an integrated component of the NASA EVA and Human Surface Mobility Program (EHP)[30] and leverages NASA Joint EVA Test Team (JETT) events to inform Artemis functionality across the EMSS tools. Most recently, the EMSS team supported the JETT3 field test in October 2022, that included the most complete Artemis flight team surface EVA planning and execution activities performed to-date.[28,31] These activities serve to help distill and design functionality for EMSS tools that meet the needs of the various work groups as those work groups define their anticipated work needs. This iterative alignment of work discovery and corresponding software capability will be vital to yielding meaningful work support. One additional alignment of capabilities is engaging with the Artemis Geospatial Data Team[32] so that EMSS tools can leverage the most relevant lunar surface map data for EVA FOD utilization. Together the EMSS toolsets will evolve as more and more data streams and sources become available as Artemis build capacity to perform more ambitious mission objectives.

## IV. Conclusion

Artemis missions will involve a wealth of mission data that must be handled and shaped to support mission operators make mission decisions. Figure 7 shows how the Apollo EVA support team manually managed the real-time execution of spatial and temporal details during Apollo 17 to track and inform EVA execution progress. These discrete work functions will still exist for Artemis; however, the means by which this work can be performed today can be designed into modern mission support system capabilities. EMSS tools aim to seamlessly integrate spatiotemporal details to support the creation of EVA flight products and support EVA decision-making to incorporate exploration and scientific priorities into flight team decisions during execution of Artemis missions on the lunar surface.

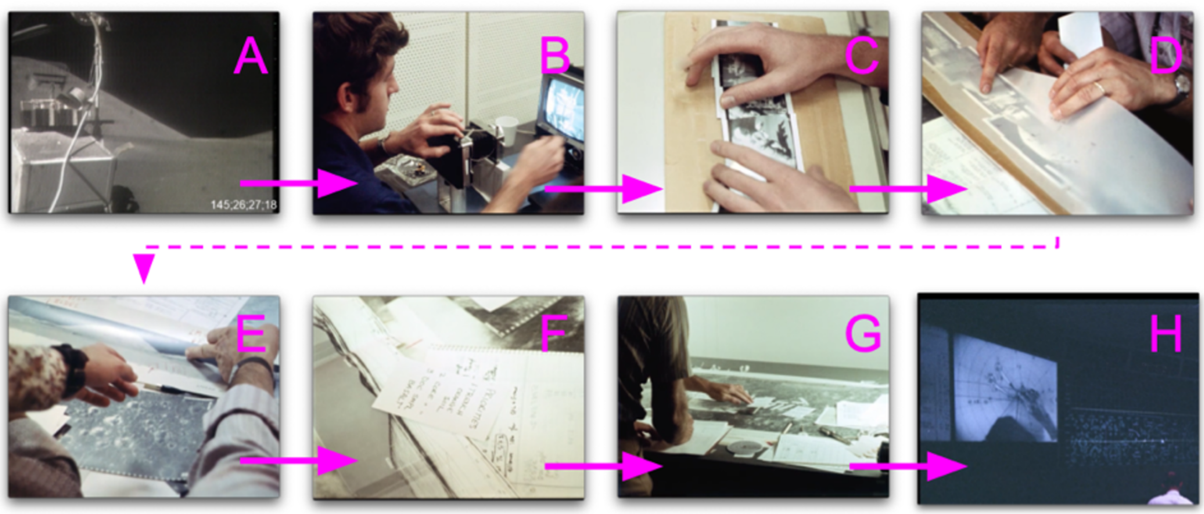


**Figure 7. Snapshots taken from 16mm film shot during Apollo 17 EVA. Video feed from the lunar surface (A) was transferred to Polaroid still photography (B) and collated into panoramas (C) that were overlaid with precursor imagery to estimate crew location and facilitate scientific interpretation (D). These images were compared with other map products (E) to synthesize and articulate real-time science priorities that were passed along the chain of command to impact crew behavior (F). Additionally, estimates of crew location were indicated using icons moved manually on a map alongside operations relevant data such as clock time and event markers (G), which were all shared among the flight team via overhead projector (H).**

EVA operations is a prime mission phase where every moment matters and offers an opportunity to demonstrate the transformation of ISS EVA operations towards Artemis lunar surface EVA operations. EMSS is dedicated to building software tools that enable the EVA flight team to successfully perform their job duties. EMSS consists of three core software systems: Maestro supports the digital creation and execution of EVA procedures, AEGIS supports the EVA composition and execution of lunar surface operations by aligning temporal and spatial data with EVA flight products, and CODA pulls together disparate datasets to create mission context that lasts well beyond the execution phase of the mission. Artemis intends to apply novel technologies to the exploration of the Moon and eventually Mars. With this ambitious goal comes the dedicated need to think deliberately about the software systems required to support mission operators successfully conduct the mission.

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