Review of Advanced Informatics and Display Systems for Extravehicular Activity Operations

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Abstract— **New operational challenges exist for coordination and collaboration amongst spatially and temporally distributed teams as NASA prepares to return to the Lunar surface and beyond to execute ambitious Extravehicular Activities (EVAs). Novel strategies will be required to effectively execute human surface exploration activities where communication and bandwidth latencies disrupt coordination. Additionally, testing novel strategies for EVAs can be challenging, requiring an approximation of distant planetary bodies, specific concepts of operations (ConOps), and prototype information management/decision support technologies. This paper compiles existing literature on EVA analog environments and associated decision support software systems (DSS), providing an overview of the state of the art for simulated EVA mission environments and supporting technologies. Prototype software explicitly supporting EVA planning, execution, and post-hoc analysis was the primary focus, as these capabilities are most aligned with anticipated shifts in crew responsibility and future needs.**

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1. INTRODUCTION

Extravehicular activity (EVA) refers to any suited activity performed by an astronaut outside of a spacecraft and is generally considered one of the most complex and risky activities in human spaceflight. EVAs have enabled historic events such as the exploration of the lunar surface during the Apollo missions and the construction of the International Space Station (ISS) in Low Earth Orbit (LEO). These complex, safety-critical operations have historically relied on tightly coupled coordination between extravehicular (EV) operators (i.e., suited astronauts) and ground support teams located in Mission Control Center (MCC) to help achieve EVA objectives [1].

ISS EVA operations are heavily reliant on ground support teams in MCC, with near-instant communications enabled by Earth-LEO infrastructure. NASA's upcoming Artemis missions will travel far beyond LEO to the lunar surface, where notable communication delays and bandwidth restrictions are anticipated. One-way light time (OWLT) delays for the Apollo lunar missions were ~1.25 seconds on average, allowing astronauts to communicate in near real-time with ground-based support during EVAs [2]. While Apollo EVAs occurred near the Lunar equator, Artemis will explore the Lunar South Pole, a communication environment characterized by 5-14 second one-way latency [3] and intermittent blackout periods. Intermittent communications between suited crew and ground-based support operators introduces challenges for coordination, as ground support will have a reduced ability to actively monitor, track, and assist real-time EVA execution, potentially contributing to decremented team performance [4].

These operational constraints will require astronauts to perform EVAs in a more Earth-independent manner, placing greater responsibilities on crew to manage and execute EVA operations. Achieving this elevated degree of crew Earth-independence will require the development of support tools for crews to make prompt, informed decisions in the time- and safety-critical EVA operational environment. Therefore, there is a need to better understand the landscape of EVA support tools to help inform the development and application of novel support systems for future missions.

The methodology applied in this paper involved an identification and synthesis of publicly available scientific and technical literature compiled over the past four decades. The sources include peer-reviewed journals, proceedings from prominent aerospace and human factors conferences, technical reports issued by international space agencies, and relevant industry publications. The applied analytical approach centers upon tracing the progression of key technological advancements, delineating recurring human factors challenges, and identifying pivotal milestones in the development of sophisticated human-machine interfaces tailored for extreme environments.

2. BACKGROUND

Earth-based analogs replicate space mission environments in order to test novel mission technologies such as Augmented Reality (AR), explore team configurations, validate concepts of operations (ConOps), and/or investigate effects on human health. For this paper, we focused on EVA analogs, i.e., analogs that include EVA simulations.

OVERVIEW OF EVA ANALOGS

Analog tests approximating EVA surface operations predate the Mercury missions [5]. While early efforts up to and throughout the Apollo program were essential for safe and efficient mission planning [6], the scope of these analogs was limited to training personnel and testing systems to prepare for upcoming missions, rather than evaluating future operational concepts. In recent decades, EVA analog environments have placed greater emphasis on understanding the capabilities needed to enable future crewed missions. The desire to replicate operational and environmental aspects of EVA operations has driven the use of both terrestrial and aquatic analogs. These analogs provide researchers with the ability to implement and evaluate technologies at various stages of development in a semi-representative operational environment that is more conducive to rapid deployment and iteration without the associated degree of budgetary and mission stressors experienced in actual human spaceflight [7]. Existing analogs vary in the mission objectives and degree of operational fidelity – simulating anticipated future elements of spaceflight destinations such as the reduced gravity, isolation, or regional geography [8, 88] – but have formed a foundation of Earth-based analysis for various technologies and operational configurations for future EVA concepts.

Early surface analogs focused on the incremental testing and development of spaceflight technologies, such as advanced spacesuit designs in early Desert Research and Technology Studies (Desert RATS) field tests. This annual series of field evaluations began in 1997, initially focusing on suit technology and gradually incorporating other technologies enabling surface exploration. Capabilities such as on-suit information systems, along with planning and replanning tools, were first introduced in 2005 and 2006, respectively, marking a shift towards supporting future anticipated operational concepts [9]. The integration of science operations into these field analog studies was introduced in 2008, which used a science team based on the Apollo backroom model to enable human-in-the-loop remote field geology [10]. The Desert RATS campaign in 2009 emphasized the importance of pre-mission planning and training processes for facilitating productive scientific missions [11]. The 2010 campaign continued to conduct technological evaluations, specifically aligned to support surface operations objectives such as exploration [12] and geology [13]; however, these evaluations were situated within a large-scale multi-team integrated operational mission scenario, where assessments of different team composition (see [14] for 2010-2011 analysis) and operational approaches [10, 15, 16] were being performed to provide a more informed, holistic understanding of future EVA operational environments. Insights into future crew compositions were gleaned from the 2011 Desert RATS and 2012 RATS deployments, which demonstrated the benefit of having four (versus three) crewmembers [8]. The presence of at least one intravehicular (IV) crewmember was found to be important for maintaining situational awareness and providing scientific context, while co-location of multiple IV crewmembers was desired [17]. This extensive series of analog field tests has served as a foundational resource for the development of subsequent analog tests, as described below.

Earth analogs are particularly well-suited as dress rehearsals to train and practice EVA science objectives, where geologically relevant terrains can enable comparable surface exploration. For example, the European Space Agency (ESA) Cooperative Adventure for Valuing and Exercising human behavior and performance Skills (CAVES) conducts their analog exploration in caves [86]. However, a practical limitation in these environments is the absence of integrated life support systems. Aquatic analogs typically approximate microgravity or partial gravity by placing analog astronauts (sometimes referred to as 'aquanauts') underwater. Examples include the Pavilion Lake Research Project (PLRP) and NASA Extreme Environment Mission Operations (NEEMO), which performed science-driven simulated microgravity EVAs [18], investigating the effect of communication latency on EVA operations, timelines, and tasks in a mission-like operational environment [2].

The culmination of lessons learned from Desert RATS, PLRP, and NEEMO formed the preliminary concept of operations for a subsequent Mars-focused field test known as the Biologic Analog Science Associated with Lava Terrains (BASALT) project. This project was the first NASA analog to incorporate Mars-relevant field science into the testing and evaluation of planetary EVA operations [19]. Specifically, the analog executed a science-driven mission under Martian operational conditions [20], with the explicit goal of understanding how to best structure and support ground-based Science Team (ST) operations, including the necessary telecommunication capabilities [7], to actively influence EVA execution across long communication latencies [21]. This included requiring active ST participation during surface operations to minimize crew idle time [22]. BASALT simulated science operations under Mars-like latency, utilizing relevant technologies and science support tools for mission planning, scheduling, navigation, task execution, and communication [23, 24].

Recent field tests have provided valuable insights into the anticipated work environment for near-future lunar surface exploration missions. These analogs informed the development of the Joint Extravehicular Activity and Human Surface Mobility Test Team (JETT), which is the most complete Artemis flight team surface EVA planning and execution activities performed to-date [25]. These field tests aim to directly support the Artemis missions through the development and evaluation of the ConOps proposed for the upcoming lunar missions [26], though major shifts in team roles and operational strategies relating to latent communications have not been a focus for JETT thus far.

SHIFTING CREW ROLES

Under communication latencies anticipated for future surface EVAs, traditional ground-centered operations will be less desirable due to the potential scientific value of every minute spent exploring planetary surfaces. Previous analog work assessed the challenges associated with communication delays greater than ISS norms, finding that science discussions during the simulated EVAs became cumbersome under intermittent communications [11]. Apollo EVAs indicated that the majority of EV-support communication revolves around question-and-response dialogue [27], which could further strain team cohesion under even minor latency.

To mitigate these effects, the Artemis missions plan to reintroduce dedicated onboard IV crewmember(s) to provide temporally co-located support to EV astronaut teammates [28], taking on some of the operational taskwork previously assigned to support personnel in MCC. This contrasts with ISS and prior Shuttle missions under near real-time communication, where this support role has been located at Mission Control. Figure 1 illustrates the anticipated shift in crew locations between ISS and Artemis EVA operations.

Analog missions provide evidence that IV crewmembers serve an important role as communication mediators between ground-based support and EV crew [2, 8, 31], reducing EV crew workload and enabling efficient decision-making. Researchers have suggested that more dedicated roles be split between two IV crewmembers [22], with one of these positions dedicated to supporting science operations [2]. Shifting crew roles raise the challenge of effective functional allocation, as distributed team members must be correctly assigned responsibility and authority to competently execute mission functions [32]. Role definition and task allocation is additionally made more complex by increasing use of automated systems, requiring deep understanding of trade-offs, assumptions, and failure modes of the employed technologies [33, 102].

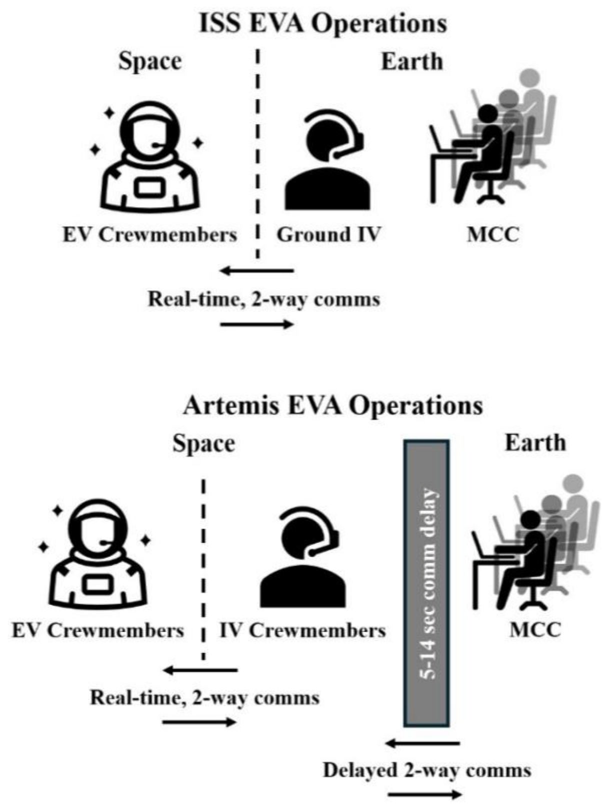

Figure 1. Shifting crew roles for upcoming lunar EVA operations (adapted from [29])

With future surface exploration activities anticipated to operate under varying degrees of communication latency, a fundamental shift towards ground-based personnel adopting the role of mission 'support' as opposed to mission 'control' has been recommended [34]. Future Earth-independent work also must cope with the open-ended and dynamic nature of planetary surface exploration. Compared to Space Shuttle and ISS EVAs, planetary surface EVAs introduce significant uncertainty [22] through variables such as limited data fidelity of lunar terrain [90], varied and dynamic scientific sampling goals, and limited operational data on how novel EVA hardware impacts surface traverse speeds and consumable drain over time (among others). These complexities coupled with transferring other responsibilities traditionally held by ground support personnel to astronaut crews indicate a clear need for decision support tools enabling informed EVA decision-making in increasingly Earth-independent operational environments.

DISTRIBUTED MULTITEAM SYSTEMS

Spaceflight involves multiteam systems (MTS) [94]. MTSs, particularly those with high team distance (e.g., geographic, cultural), may require more shared mental models than those with relatively low team distance (e.g., those that are co-located [95]). Shared mental models are similar (or common) mental representations held by team members about constructs such as taskwork, team roles, and relationships of variables within work (such as key environmental variables or hazards) [96, 97]. Teams operating with highly consistent ("shared") mental models have been associated with superior performance [98]. The MTS including EV, IV, and mission control teams are highly spatially and temporally distributed [94], increasing the likelihood of breakdowns developing and maintaining shared mental models.

Teams that operate remotely (considered distributed and/or virtual in the literature) face additional challenges to perform effectively. These potential challenges include fewer opportunities for informal and unplanned communication, difficulty in team cohesion, and increased conflict [e.g., 99]. Technology is a key theme in research on virtual teams, as different technological tools are generally used to facilitate communication and coordination (e.g., email, text [100]). Researchers advise choosing technology that matches their specific tasks and needs, for instance choosing a communication technology that supports rich, nuanced interactions for group problem solving [101].

One key psychological construct underlying the increasing need to shift EV crew support responsibilities from MCC to IV is collective attention, or the synchronous focus of multiple individuals on a shared target [91]. Collective attention drives shared mental model formation, supporting common ground and team coordination [103]. Communication delays disrupt collective attention between the crew in cislunar space versus the Earth-based MCC, but performance of the EVs may be maintained with enhanced real-time support from the IVs. Enactment of teamwork skills (e.g., timely and clear communication, backup behaviors, and other collective risk assessment and decision-making) influences task performance such as the completion of EVA objectives and scientific sample quality. Analog studies examining the effects of communication delays of 30 seconds or more found that collective attention mediates the negative relationship between communication delay and team performance [92]. Additionally, high task experience, clear communication, and distribution of subtask leadership responsibilities work to buffer the deterioration of collective attention to support performance. System design should accommodate the need for information sharing and division of responsibility in communication delayed environments [48].

HUMAN-CENTERED DESIGN APPROACH FOR EVAS

With EVA recognized as a system design driver [35], efforts to impart a human-facing emphasis from the initial stages of system development should be pursued. While some dimensions related to human-system performance are notoriously difficult to capture during the early stages of system design [36], a proactive approach will be vital to developing systems that are functional upon deployment and avoid the need for subsequent modification. Previous literature has identified a lack of methodologies which use operator needs to drive requirements being applied early in the systems engineering phase [37]. Influencing early system development offers the best opportunity for human system integration issues to be resolved (such as ensuring system compatibility across different digital mediums [38]), as later rectification could have structural, temporal, and/or budget implications [39].

To incorporate human-centered design in the development of information display systems, the use of human factors techniques such as Cognitive Work Analysis (CWA) and Ecological Interface Design has been explored. The application of these techniques to military mission planning [40] and petrochemical production processes [41] demonstrate viability in similar information-dense, time-critical environments. Analysis techniques including both work domain [42] and task-based approaches [43] have been used to guide interface design for support tools [44], with an emphasis on designing to reflect the work of the end practitioner in the context of their decision-making environment and mental trade space. Other approaches, such as Cognitive Task Analysis techniques of elicitation by critique, have been suggested for use in identifying information requirements in fast-paced domains, where insights into the information that operators would look for to support decision making can be obtained [45]. While efforts from analogous industries (e.g., commercial aviation, naval operations, industrial engineering, nuclear power plants, and robotics and automation) can inform the basis of human factors requirements for support tool development, the applicability of specific lessons learned to the EVA work domain is limited [37].

To begin mitigating concerns of applying design principles from related domains to support planetary surface operators, recent efforts leveraging cognitive systems engineering (CSE) theory and practices have been applied to display design in the EVA domain [46]. From a set of constraints generated using CWA techniques, support tool models were developed and applied within PLRP, NEEMO, and BASALT analog environments, providing a high-fidelity evaluation case for these support systems. It is important to note that the focus of these initial efforts was to develop a set of requirements applicable to the EVA work domain rather than to evaluate the specific designs developed and deployed from them. Efforts expanding on this initial work have sought to apply CSE requirements derivation, verification, and validation processes to support IV operators in the EVA work domain in adopting work functions traditionally held by ground controllers [1]. The designed tools sought to enable IV operators to perform timeline tracking and alteration along with life support system management throughout the execution of an EVA timeline, two specific work functions that these operators may be expected to adopt in new distributed team architectures. This work found that not all constraints elicited using CWA methods have equal impact on the work domain, reinforcing the need for additional investment into understanding and classifying the EVA work domain, recognizing it as a uniquely individual environment, even amongst those sharing similar time and safety pressures under high information density.

The efforts described above form a foundation for future designers to approach the development of support tools for specific operators, with recent efforts seeking to directly apply CSE methods to the EVA work domain. However, the CSE community often struggles to disseminate research findings to system designers and developers such that a shared understanding of the work domain problem and a possible solution is formed [45]. Bridging the gap between researchers identifying the needs to support domain operators and the developers who ultimately implement recommendations into support tools will be essential to assisting operators within the EVA work domain. In concert with the methods captured here, alternative approaches should be investigated to inform future tool development. Approaches leveraging decision-making theory, such as naturalistic or distributed decision making, have been recommended as expansions of existing efforts to develop tools for the EVA work domain [1]. Applying principles aimed at intentionally accommodating the needs of operators in this novel team structure, particularly during the early phases of design, is vital to ensuring that support tools can be readily applied in time- and/or resource-critical scenarios. With EV/IV crews assuming increased authority and responsibility during EVA execution, tools must enable crew members to make informed, rational decisions to achieve mission goals.

3. EVA Decision Support Software

The following subsections describe the development of software tools to support decision-making processes within different aspects of EVA operations. Decision support systems (DSS) are a class of work tools enabling all mission phases of human spaceflight operations [47]. DSS are developed to support shared understanding and mental models amongst MTS. especially important in environments facing communication latency [50]. It is essential to avoid the pitfalls identified in similar domains such as aviation [49], where mutual understanding and collaboration are hampered due to conflicting shared mental models maintained by individuals within distributed teams [48, 49]. These support tools are not solely designed to assist EV crew members in executing EVA operations but encompass tools that help members of a broader distributed team to plan, support, monitor, and execute surface EVA.

Initial focus is given to tools which support crew self-scheduling, an important capability to enable more Earth-autonomous operations in the absence of real-time support from ground operators. These tools are intimately related to those which assist in EVA planning and execution, as they will empower astronauts to prepare for and conduct surface operations in an informed manner, with greater knowledge of timeline and consumable implications leading to more natural and fluid exploration activities. Beyond the immediate execution of real-time EVA activities, it is critical that future support tools can integrate varied data sources to provide robust contextual information for ongoing operations. Capabilities to record, process, integrate, and disseminate contextualized mission data are critical to both enabling informed real-time support from external (i.e., MCC and IV) operators and expediting mission analysis or science processing on the ground, either in-mission or post-flight. A review of such *post hoc* analysis tools is the tertiary point of discussion. The section concludes with an overview of advanced display efforts, future tools which will directly augment EV operator capabilities while conducting surface operations. Table 1 (found in the Appendix) lists and summarizes all the software tools identified in this paper.

Activity Scheduling and Procedures

Decades of sustained human presence in space on the ISS have established strong precedent for prolonged resource management and planning across intravehicular and extravehicular activities. ISS scheduling is performed by a team of highly trained Operations Planner (OPSPLAN) flight controllers in Mission Control Center – Houston (MCC-H) [53, 66]. OPSPLAN personnel manage competing mission objectives (e.g., science, maintenance, crew health) to provide a feasible schedule for the crew to follow. Activities added to crewmember timelines are planned to the minute, providing each crewmember with a highly precise schedule they should be following at the start of each mission day. However, increasingly Earth-independent astronaut crews will need the ability to effectively interpret and manage their daily activities. For sustained human presence on a distant planetary surface, crew self-scheduling of activities has been highlighted as a key function enabling independence from ground.

Crew self-scheduling will require robust decision-support capabilities to manage the resource-limited, interdependent nature of prolonged space habitation. Lab studies with novice schedulers (which astronauts are considered) have shown that while spaceflight-like crew self-scheduling is feasible, it is increasingly difficult with the addition of more constraints [67]. Dynamic mission phases such as Artemis surface EVAs will introduce additional complexity for mission timelines, as EVA outcomes, resource expenditure, and equipment states could have cascading effects for broader scheduling efforts. Despite Apollo EVA operations having been heavily scripted [68], the occurrence of unanticipated setbacks frequently resulted in timelines being adjusted during surface operations [69]. Crew feedback following the Apollo missions also emphasized the need for “a far more active role for the crew in planning and executing their activities...than has previously been required” [70]. This input from crews functioning under near real-time communication with ground support emphasizes the fundamentally unique challenges experienced while conducting surface operations. Thus, empowering crews to conduct timeline replanning is as important, if not more so, than planning for future surface operations under latency with ground support.

Decision support tools provided to future astronaut crews must allow them to evaluate the impacts of evolving mission plans and make informed decisions to adjust timelines such that relevant constraints, emergent priorities, and a diverse set of mission objectives are satisfied. Allowing distributed teams to quickly evaluate replanning options through this lens will help to enable thorough, insightful surface operations while balancing competing mission objectives. To explore the concept of greater crew self-scheduling for both planning and replanning of timeline activities, several tools have been developed and evaluated.

Early development of decision support tools for crew self-scheduling focused on supporting timeline planning prior to activity execution. These efforts leveraged the concept of automated planning assistants [51] (similar to those used in MCC for ISS planning) to manage schedule conflicts and ensure acceptable resource allocation. At NASA Ames, scheduling tools such as Scheduling and Planning Interface For Exploration (SPIFe) [38] have seen extensive flight and analog implementation in support of planning and scheduling operations. However, efforts to transform the tool to support real-time operations – as would be required for crewed surface activities – encountered limitations of the existing tool's capabilities. SPIFe was designed for mission planner needs, not crew; thus, it attempts to provide the same platform to both user types were unsuccessful. Users needed a collaborative, mobile platform to maintain shared situation awareness. This case highlights the importance of considering the needs of end users in tool design to ensure that similar limitations are not encountered.

To resolve the need to push updated schedules to missions planners, a new planning and scheduling tool named Playbook was developed [38]. The Playbook tool is a mobile schedule viewer and real-time execution software aid, which provides timeline viewing, an integrated communication interface between ground support and crews (known as Mission Log), and a procedure repository. Playbook significantly increases crew autonomy over their schedule by enabling astronauts to directly edit timeline plans without the need for intervention from ground personnel [53]. While future concepts of operation will likely still have ground personnel develop initial crew schedules, astronauts will have the capability to reschedule some assigned tasks and add new ones.

Initial capabilities for the Playbook tool were evaluated in the NEEMO analog, where the self-scheduling features of the tool, such as constraint visualization to avoid conflicts between activities, were assessed. Subsequent iteration across diverse analog environments (including PLRP and BASALT) [54] and experimentation on the ISS [55] served to enhance the tool's supportive capabilities and demonstrate the feasibility of crew self-scheduling in operationally relevant environments. The tool can be accessed by all crewmembers in a distributed team architecture, as Mission Log messaging can be presented to EV crewmembers on a portable, wrist-mounted display, as demonstrated within the BASALT analog [21]. Mission support control (MSC) and IV crewmembers can use Mission Log to send time-stamped text, files, images, and videos with one another, enabling condensed ST input and feedback to be shared with the EV crew. Similar design approaches which accommodate the needs of all members within distributed teams are essential to enable future mission operation concepts and will be key in facilitating the paradigm shift towards ground operators assuming a more supportive role within planetary exploration operations [51, 52].

The lack of a self-scheduling approval process can lead to reduced situation awareness within teams [53], but a balance must also be struck so as not to overwhelm operators with excessive detailed logging of all changes which occur. Further investigation is needed to balance task load and delegation strategies between EV/IV crews and ground support personnel, particularly because surface EVA timelines will likely need to be adjusted for various competing reasons, such as shifting scientific priorities and uncertainty around time to execute traverses and/or tasks. Similarly, timeline awareness and management will be crucial for temporally distributed teams, as ground support personnel and IV crew members must understand how much time they have to provide input into future EV actions [24].

At NASA, the step-by-step operational instructions for EVA are considered procedures. Recently, the Maestro software tool has been adopted to create, modify, and track ISS EVA procedures, modernizing EVA procedure authoring and execution for EVA flight controllers. Maestro is one of multiple EVA Mission Systems Software (EMSS) tools anticipated for Artemis. This tool provides the distributed team the ability to track the EVA elapsed time, comparing expected versus actual timeline progression. The most powerful component of this tool is the capability to dynamically alter digital procedures to accommodate real-time changes. This allows detailed procedure items to be instantly rearranged to produce a new integrated timeline for EVA teams [50]. Since November 2022, Maestro actively supports ISS EVA operations [56]. It is also the primary procedure management system utilized during EVA training activities at NASA's Neutral Buoyancy Lab (NBL).

EVA ROUTE/TRAVERSE PLANNING AND EXECUTION

A fundamental goal of the Artemis missions is to conduct scientific exploration and sampling on the Lunar South Pole. Pre-mission path (or traverse) planning will be a critical component of these surface operations. Traverse planning serves as the mission's scientific backbone, defining priorities for EVA operations such as sites of geological interest and helping to keep surface exploration on-track even if crews encounter off-nominal situations [15, 68]. The development of traverse plans is iterative and complex, with Apollo traverse plans formed in a collaborative effort between astronauts, operational personnel, and scientists. However, the plans generated cannot fully account for the dynamic, uncertain nature of exploring a distant planetary body. Deviations from preplanned Apollo activities were typical practice when discoveries were made during exploration which would better satisfy mission objectives [71].

Unanticipated challenges while traversing can impact EVA paths and timelines. This occurred during Apollo 14 EVA 2, where EV crew became disorientated during an unexpectedly strenuous traverse. This resulted in an impromptu decision to forego the planned objective to reach the rim of Cone Crater [85]. Additionally, the generation of initial traverse plans is reliant on the quality of available planetary spatial data to anticipate terrain challenges or potential high-value geologic sample targets [23].

Multiple path planning tools have been developed in the past two decades, often in tandem with ongoing analog experiments. Planetary Aid for Traversing Humans (PATH) focused on assisting in pre-EVA traverse planning (as opposed to intra-EVA), with path optimization considering various environmental conditions including low sun angles experienced at the Lunar South Pole [57]. PATH provided traverse planners with data on environmental conditions, a terrain map visualization, path manipulation functionalities, and path information. The work also explored utilizing various automated technologies to support path generation during EVA traverse replanning activities [58]. It was found that while operator performance improved with more autonomous control of traverse planning, this was offset by a decrease in operator situation awareness, suggesting user complacency in the capabilities of the provided automation [59]. Subsequent studies highlighted how operators planning a traverse path required specific information from the system to enable strategy adaptation and path comparisons via sensitivity analysis [60]. These preliminary efforts provided a strong foundation for the development of tools to support traverse planning and execution activities.

Subsequent tools to support path planning have seen extensive testing and iteration in analog environments. The xGDS tool, most recently deployed in BASALT as part of the suite of tools known as Minerva, supported both EV and IV/ground capabilities during traverse. xGDS contained a traverse plan editor to plan field activities in a geospatial context, with mapping capabilities allowing crews to share, author, and visualize map layers [21]. Within the BASALT deployment, the ground-based ST used xGDS for the majority of EVA planning during the strategic planning phase prior to EVA execution [24]; however, MSC and IV crewmembers also utilized the tool to track EV progress, enabling shared awareness amongst the team of EVA progress. EV crew members also had the ability to utilize GPS tracking, accessed via the same wrist-mounted display used for the Playbook Mission Log, to help maintain location awareness. While xGDS was critical for initial traverse planning, a lack of integration with the Playbook tool meant that traverse and activity plans were not jointly modifiable during real-time execution. Thus, intentionally integrating support tools whose capabilities have direct implications on one another has been strongly recommended for subsequent tool development.

Minerva included Surface Exploration Traverse Analysis and Navigation Tool (SEXTANT, a follow-on tool of PATH), which provided resource-based path planning support to optimize human traverses. SEXTANT includes capabilities for IV crewmembers to monitor EV crew traverses, estimating path traversal times, and determining the feasibility of reaching proposed sample locations. Path optimization expands to individually consider traverse length, traverse time, or metabolic rates when determining ideal EV traverses [21]. Future tools should look to incorporate multiple criteria in path optimization efforts to ensure that relevant traverse parameters are considered during path determination. Multiple terrain features, such as friability and surface temperature [19], may be integrated with terrain slope and projected EV crew metabolic cost constraints to enable future path planning and replanning operations.

Similar EVA software efforts have been assessed in CAVES and Planetary Analogue Geology and Astrobiology Exercise for Astronauts (PANGAEA), ESA analogs that have developed and used the Electronic FieldBook (EFB) information system [87, 88]. Through EFB, EVA teams can delineate a traverse path through waypoints on a digital map. EV position is tracked and overlayed against the map. Science data (e.g., instrument measurements or images) collected in the field is aggregated and collected within this information system. EFB distinguishes itself from Minerva by including an external interface with machine learning algorithms to support real-time data analysis [87].

Recent advances in EVA traverse planning tools have aimed at supporting Artemis lunar traverses, particularly the Artemis EVA Geographic Information System (AEGIS). Developed at NASA Johnson Space Center (JSC), AEGIS explicitly seeks to support the flight controllers tasked with supporting Artemis planetary surface exploration [56]. AEGIS visualizes planetary geospatial data for EVA planning and execution purposes, relating lunar map data to temporal mission data for EVA planning and execution [50]. AEGIS calculates estimated EVA activity times and total coverage of scientific objectives outlined in a science traceability matrix (STM), providing the ability to create and meaningfully compare EVA plans. This planning and execution tool seeks to facilitate more informed surface operations by providing flight control teams with greater awareness of where EVA activities are to be executed. AEGIS presents relevant geospatial data for operators to plan traverse paths, relying on human expertise to interpret data rather than path optimization models, though future validated models may be incorporated.

The evolution of path planning tools has seen the incorporation of a greater set of operational constraints and optimization criteria, along with visual representations of expected traverses to better visualize and prepare for EVA exploration. Few efforts related to integrating traverse planning and real-time EV data, such as suit consumables and physiological performance have been explored and published. Ensuring that EV crews remain informed of EVA timelines and traverse plans as they evolve during surface exploration will give crews greater confidence to perform more fluid operations. Simultaneously, providing support team members (whether IV crew or ground support) with the ability to understand the implications of traverse augmentation and relay critical information – such as anticipated consumables usage – to EV crewmembers will ensure that informed decisions are made to uphold crew safety during exploration EVAs.

POST HOC MISSION ANALYSIS

In addition to providing relevant information during EVA execution, tools are necessary to interpret data gathered once EVA is complete. Post hoc tools contextualize disparate data sources and streamline access to data from surface operations (or mission analogs). A primary goal of these capabilities is to enable replanning under time pressure [10], as notional EVA plans are subject to change based on opportunistic science, variable traverse times, and shuffling priorities based on consumables and timeline. Integrated and accessible data from prior EVAs have been identified as a key need in recent literature [24, 32], enabling richer characterization events than what could be gleamed in real-time. Publications following the Desert Research and Technology Studies (DRATS) 2011 field analog described that when crews lack real-time mechanisms to verify the quality of collected data, the level of science return and crew independence during exploration missions is severely hampered [71]. Other analog environments have indicated a desire for greater contextual information and data synthesis tools to enable meaningful input from ground support who would otherwise spend much of their time gathering meaningful contextual imagery rather than assimilating data [2, 23].

Requests for tools supporting the capture of contextual data were first implemented within the xGDS tool suite, demonstrated in both PLRP and BASALT. In addition to the mapping capabilities mentioned above, all data that passed through the xGDS tool was time-stamped and geolocated [24]. With this data stored within xGDS, the tool contained an integrated data archive which could be used for *post hoc* analysis, browsing, and searching [21]. This capability meant that all pertinent data could be correlated, enabling analog ST personnel to associate geospatial data with sample imagery or video when searching for specific samples. This expedited search process allowed operators to better associate scientific data products, enabling active ST participation in EVA execution, even under time delay. The data archive retrieval capability was a major use case of the xGDS tool during the first BASALT deployment [24], reinforcing the importance of providing teams with tools to integrate importance context into surface EVA operations. Similarly, EFB also supported post-mission data analysis, integrating scientific data collection, images, and audio transmissions [87].

An additional motivator for improved contextual embedding within science-driven EVAs has been the prolonged data analysis efforts seen on Apollo EVA data, which has been investigated for over 50 years due to the lack of a unified data contextual framework [62]. Extensive efforts to compile and evaluate EVA timeline execution cite data collection as the most demanding aspect of such analyses [72], underscoring the obstructive effect of non-contextualized mission data on insightful scientific analysis. While these lingering inefficiencies still exist, efforts to horizontally integrate the disparate data products from the Apollo missions was achieved in 2015 with the creation of the Apollo in Real Time (AiRT) website, which consolidated and contextualized data from the Apollo 17 mission [56, 61]. Subsequent efforts aligned data from the Apollo 11 and 13 missions and served as inspiration for the development of context-driven tools for future EVA operations.

There has been a concerted emphasis within software development for the Artemis missions (i.e., EMSS) to provide a suite of tools that record geospatial and temporal mission context data for subsequent analysis [62]. To accomplish this, the Collaborative Operations Data Activation (CODA) tool was developed, which horizontally integrates mission context [56] — consolidating Maestro's EVA timeline data with AEGIS map products and ground audio, video, and telemetry feeds — to enable current and future NASA missions. CODA seamlessly connects to source data locations such that different data can be viewed in context with one another. The tool contains data spanning across over a decade of ISS mission operations, NBL training data, Artemis field testing data, and Artemis I mission data. The tool is presently used to support anomaly reporting on the ISS and is poised for implementation in NBL training activities to provide integrated review capabilities to support personnel.

ADVANCED INFORMATICS DISPLAYS

While software support tools described so far have been focused on assisting ground teams and/or IV crewmembers, advanced technologies include hardware envisioned to support EV crew during future EVA. Wearable, suit-mounted heads-up displays have been recognized as a key component of future exploration EVA systems [9], boasting the potential to provide EV crew with useful capabilities and data visualization for real-time, local procedure management, map annotation, and consumable tracking. Helmet-mounted displays have been under development at NASA since the mid-to-late 1980s, where preliminary experiments indicated that in-helmet displays decreased time to accomplish tasks and resulted in a measurable decrease in the need for verbal support [64, 73].

Wrist-mounted displays have been another area of significant development and testing, with field deployments occurring in an Arctic spaceflight analog environment [64], volcanic terrain [21], or underwater [89]. In the 1980s, an EVA electronic cuff checklist was developed for spaceflight [104]. It was flown and evaluated in space four times as part of Space Shuttle EVA flight experiments [73, 102]. Further enhancements stalled and this digital technology was never integrated into EVA spaceflight operations, likely due to the marginal benefits the technology provided at that time.

Virtual reality (VR) has been used at NASA since the early 1990s to train astronauts conducting EVAs [63]. While there are clear applications for VR in EVA training, other operational uses are still being explored. Additionally, augmented reality (AR) displays to support crew decision-making during EVAs have been studied. Systems such as the Joint Augmented Reality Visual Informatics Systems (Joint AR) project at NASA JSC recently leveraged physical hardware prototyping and VR environments for iterative development and testing of capabilities such as registered information (heads-up-display overlays which are spatially anchored to a physical location in an operator's field of view) have been assessed to provide mission-relevant data to astronauts during future lunar EVAs [65]. Information that may be relevant to include in these AR displays includes life-support consumable monitoring, dynamic procedure updates, and navigation support during exploration EVAs (xEVA). Some of this information may be repackaged from the support tools mentioned above to facilitate presentation in an AR display, but other pieces of mission-relevant data expose additional areas for further maturation of existing technologies and methods. For instance, modeling challenges were experienced with crew metabolic rate expenditures and consumables usage during the Apollo EVAs, with astronauts frequently exceeding the rates predicted prior to mission execution [74].

Specific strategies to address these challenges directly are beyond the scope of this review; however, developing methods to accurately monitor and subsequently present physiological data will be an enabling factor for informed surface EVAs to extract maximum scientific value. Furthermore, if EV crewmembers are to have the ability to communicate with IV and ground support, the communication medium will need to be reflected in these displays. Under time delay, extensive analog findings have evidenced that text-based communication formats are preferred over voice communications, the latter of which have been found to be unacceptable over latency [2, 8, 29, 31, 75]. Thus, advanced displays must incorporate text-based communication architectures to facilitate more fluid interactions amongst EVA team personnel.

Previous research on heads-up information displays for EVA has shown that astronauts may struggle to interpret or resolve information presented against the expected lighting conditions of the Moon; low Sun angles at the lunar south pole introduce shadows and highlights that may impact display legibility. One potential design consideration for EV suit-mounted displays is visual redundancy [65], where information is interlinked and accessible at different locations within the user interface (UI) to mitigate high contrast lighting conditions. A possible solution to this issue could be developing different display 'templates' that strategically position mission-relevant data at certain locations on the UI relative to anticipated lighting conditions. While reducing the need for visual redundancy, such an approach could quickly encounter scope issues depending on the number of display changes deemed necessary to account for different anticipated lighting conditions. Depending on the severity of display impairment, it is also possible that a diverse set of display configurations would not place all pieces of important information in a legible location for certain lighting conditions.

Various implementation challenges still exist for on- or in-suit visual aids, such as enabling registered HUD displays, particularly surrounding optical projection, radiation tolerance, and bandwidth limitations [76]. Advanced displays in EVA contexts offers potential to offload physical information artefacts in a digital medium. Future efforts may also extend the support capabilities of such tools to incorporate in-flight training [77], which will be critical for providing crews on extended missions with refresher and proficiency training in the absence of real-time ground-based instruction.

4. Gaps and Future Needs

Applying Theory to Tool Development

Prior tool development efforts have focused on evaluating the functionality and information provided by developed designs, with an explicit lack of emphasis placed on evaluating the usability of the proposed tools [24]. This challenge can partially be attributed to the reality of designing tools to support an emerging work domain, as identifying what capabilities are (or are not) required to safely and effectively perform mission operations at a given location is a first-order priority [8]. This emphasis on evaluating the features and functions which will be most critical for future spaceflight mission similarly detracts from the ability to rigorously assess the acceptability of specific decision support tool implementations within a given analog environment [19]. This reflects a key discrepancy between theory and practice in the realm of interface design. It is critical that future design efforts seek to directly support the cognitive work required within the EVA domain [1], which may include developing tools that reflect the mental models developed by domain operators for task execution [59]. To proactively design to accommodate the needs of users within this novel work domain, future tool design efforts should incorporate the suggested human-centered design processes to support novel team designs for EVA.

Additionally, a key distinction exists between the information content of a display and its visual presentation (e.g., visual hierarchy, contrast, salience, scale) to users to ensure that critical information is presented and understood for informed decision-making. While prior analogs have sought to leverage subjective assessments of capability acceptability, suggestions provided by operators often address higher-level improvements and do not delve into more granular constructs like information presentation and context [19]. A broader commentary on the challenges of deriving meaningful, tool-specific insights relevant to the anticipated future EVA work domain is addressed in the following subsections. From a team-oriented standpoint, maintaining common ground and shared mental models of task and mission objectives, which are updated and need to be accurate over time, will enable team performance and communication. Maintaining these shared mental models is important to ensure that distributed teams can function in a cohesive manner. The Apollo surface EVAs stressed the importance of team cohesion, with a journal entry from Apollo 17 astronaut Gene Cernan highlighting that the "key is that you train for knowledge of each other, and you train for teamwork" [78]. Ensuring that all team members are operating from a shared base of information surrounding the EVA environment is critical to mission success.

DEFINING SUCCESS DURING SURFACE EVA

Future research should iterate on existing approaches to assess EVA performance across multiple objectives and priorities. For example, there is a gap in evaluating and understanding EVA team performance and shared mental models. While analogs such as DRATS and JETT3 captured EVA metrics such as "boots on surface" suit time and distance walked for each EVA [26, 79, 80], test data was not used to evaluate overall team performance but was primarily focused on human factors concerns regarding the effects of suit wear.

A key element to identify adequate EVA performance measures is specifying which part of the system an analog testing environment is aiming to approximate. Analysis of the BASALT field tests highlighted that a limited number of standard evaluation methods exist to examine the EVA work domain [21], specifically isolating which metrics are analog specific vs flight-like. Evaluations of decision support tools for EVA have encountered similar issues, with performance metrics pertaining to final location accuracy and traverse time not capturing similarly important traverse aspects such as path efficiency, which has implications for metabolic expenditure and consumables usage [65].

The identification of viable performance metrics will be equally important to maintaining crew safety during operations. Previous efforts have suggested that fatigue should be measured, particularly towards the end of long EVAs [23]. Prior analog evaluations of fatigue have been conducted at the beginning and end of traverses [80], highlighting the need for intra-EVA monitoring to inform timeline and operational decisions.

One notable challenge when developing performance measures for surface EVA is that many quantitative metrics (such as distance traveled, time spent exploring, or number of samples collected) are not aligned with the nature of scientific exploration activities that are often subjective and qualitative. Further characterization of the tradeoffs associated with operational limitations (such as hardware, consumables, and resources) to perceived scientific output or efficiency are needed [71, 81]. These assessments do not present a quantitative measure of productivity or success, nor do they provide explanations for the specific reasons for deviations from planned timelines [69, 74, 93].

To obtain insights into why specific timeline deviations were encountered requires a more granular analysis. In the case of Apollo 14 EVA 1, voice transcripts assessment in conjunction with timeline deviations allowed gleaning into the actual challenges the EVA team encountered [72]. The insights gained from incorporating multiple data streams to rationalize observed timeline deviations on Apollo 14 EVA 1 emphasize the need to develop support tools which can integrate varied sources of information to contextualize operations as executed, similar to AiRT and CODA. It is proposed that such tools may serve as a mechanism through which representative performance metrics can be naturally revealed during operations. Early investment in context-integrated support tools warrants future investigation, as these tools ultimately facilitate the definition of more precise performance metrics. Early investment in support tools which integrate mission context can allow domain operators in support roles to observe and define more precise metrics by which both tool and operator performance can be assessed in this operational environment. Future work should further investigate this gap.

While Apollo EVA assessments may be the most representative data for future EVA work, they do not consider the effects of modern, technological advancements. The trends observed from Apollo analyses may suggest specific tasks which require greater timeline consideration in the event of challenges experienced during execution, it cannot be said that similar tasks will be completed with comparable efficiency for future missions. Future tools and capabilities with which lunar EV crews will conduct these operations along with the specific regions which crews are tasked to explore may impose different operational challenges to those experienced on the Apollo missions. Thus, we also need measures that incorporate assessment of novel EVA information software and tools. While NASA has adapted widely used tool evaluation methods to meet the needs of spaceflight operators [82], usability scores derived from these approaches may not directly map to team performance *in-situ* [83]. Direct comparison to EVA norms for the ISS is also insufficient due to major differences associated with planetary surface exploration and geology-driven EVAs, compared to EVAs on engineered structures [23].

Future efforts should continue to investigate measures to characterize performance across multiple facets of surface EVAs, leading to more standardized assessments of tool, individual, and team performance.

5. CONCLUSION

Despite over five decades of EVA experience, operational focus has remained almost exclusively on microgravity rather than planetary surface operations. Integration with new digital technology for EVA operations have only recently emerged with EMSS tools focusing on ground support. Crew-centric digital support was limited to isolated, failed attempts with electronic cuff checklists. Planetary exploration has unique demands that are best supported by digital systems. As shown in Table 1 (see Appendix), terrestrial analogs have already begun to embrace these advancements, providing a comprehensive performance dataset that validates the net benefits of digital integration for future surface missions. As mission profiles shift toward the lunar 'proving ground' and the heavily communication-latent environment of Mars, a prevailing takeaway is that we cannot simply rely on the presence of advanced tooling and displays to ensure effective EVA. Instead, future development must rigorously align technology with the specific *jobs to be done*—a process that entails defining and maturing operational roles and responsibilities in tandem with the tools designed to support them.

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ACKNOWLEDGEMENTS

This work was sponsored by NASA Human Research Program under the Human Factors and Behavioral Performance Element in response to NASA solicitation 80JSC024NA001-FLAGSHIP (Award Number: 80NSSC25K7248).

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APPENDIX

EVA Support Domain	EVA Execution Phase	Tool	Tool Capabilities	Maturity Level	Intended End User
Activity Scheduling and Procedures	Pre-mission	SPIFe [38, 52]	Planning and scheduling of crew activities	Actively Supporting ISS Operational Scheduling	Flight control team
	Pre-mission + real-time execution	†Playbook [21, 53-55]	Schedule viewer for crew activities	Flown on ISS, Actively Supporting Variety of Analogs	Flight control team & crew
	Pre-mission + real-time execution + post mission	‡Maestro [50, 56]	Digital EVA procedure authoring; real-time procedure tracking	Actively Supporting ISS EVA, Ongoing Artemis EVA development	IV crew, MCC personnel
EVA Traverse Planning and Execution	Pre-mission + real-time execution + post mission	†xGDS [21, 24]	Traverse plan editor; map sharing, authoring, and visualization; EV location tracking	Supported Analog Testing Only	MCC personnel, IV crews, EV astronauts
	Pre-mission	PATH [57-60]	Pre- and intra-EVA traverse planning optimization with lighting conditions, precursor to SEXTANT	Research Platform	MCC personnel
	Pre-mission + real-time execution	†SEXTANT [21, 84]	Path planning optimization considering traverse length/time or metabolic rate; EV crew traverse monitoring; estimated traverse time; path feasibility	Supported Analog Testing Only	MCC personnel, IV crews
	Pre-mission + real-time execution	Electronic Field Book [87]	Traverse planning; EV traverse monitoring overlayed on aggregate maps	Supported Analog Testing Only	IV crew, MCC personnel
	Pre-mission + real-time execution + post mission	‡AEGIS [50, 56]	Estimated EVA times; traverse coverage of scientific goals; comparing path plans	Supports Ongoing Artemis EVA Development	Flight control team
	Pre-mission + real-time execution + post mission	†xGDS [21, 24]	Data archive for analysis, browsing, and searching	Supported Analog Testing Only	IV crew, MCC personnel
Post-Hoc Data Analysis	N/A	AiRT [61]	Horizontally consolidating data products from Apollo 17 EVAs	Available for Public Use	General public
	Execution + post mission	Electronic Field Book [87]	Data aggregation, embedded machine learning, and archiving	Supported Analog Testing Only	MCC personnel
	Real-time execution + post mission	‡CODA [56, 62]	Tagging/association of geospatial data to imagery/video and audio	Actively Supporting ISS EVA, Artemis EVA Development	MCC personnel
	Pre-mission + real-time execution	VR Training [63]	Simulate EVAs for training procedures	Supported Shuttle and ISS EVA Operations	EV astronauts
Advanced Display Informatics	Real-time execution	Wrist-mounted displays [21, 64, 89, 102, 104]	Display crewmember vitals or condensed information from other support tools	Flown for Shuttle EVA and Supported Analog Testing	EV astronauts
	Real-time execution	Tablet display [89]	Display cuff checklist procedures	Supported Analog Testing Only	EV astronauts
	Real-time execution	EVA Information System [89]	Digital tablet display for cuff checklist	Supported Analog Testing Only	EV astronauts

† Tool deployed as part of Minerva suite during BASALT field tests
‡ Tool deployed as part of EVA Mission System Software (EMSS) suite during JETT field tests

	Pre-mission + real-time execution	Joint AR [36, 65]	Heads-up display containing information from local onboard data sources, local lunar data sources, and remote data assets	Supported Analog Testing Only	EV astronauts
	Real-time execution	Electronic Field Book [87]	Display providing scientific and operational guidance to the astronauts, integrating data from ground teams and instruments	Supported Analog Testing Only	IV crews, EV astronauts

Table 1. Overview of EVA Decision Support Tools

BIOGRAPHY

Joshua Elston *received his B.S. in Aerospace Engineering Sciences from the University of Colorado Boulder in 2024. He is currently pursuing an M.S. in Aerospace Engineering at Texas A&M University. During his undergraduate degree, he conducted research in the CU Bioastronautics Lab, exploring the viability of cognitive state modeling using wearable sensors to measure operator performance in human-autonomy teaming environments. His master's research in the Systems Engineering, Autonomy, and Knowledge Lab focuses on advancing the capabilities of autonomous agents to assist operators with anomaly response in Earth-independent environments.*

Jacob Keller *received his B.S. in Human Systems Integration and M.S. in Industrial and Systems Engineering, both from Ohio State University. He is currently an Exploration Engineer at NASA Johnson Space Center, and a member of the Artemis Internal Science Team (AIST) Data and Software sub-team. His work spans creation and maturation of decision support software and cartographic products for both Artemis astronaut crew training and Artemis EVA Flight Control Team operations.*

Matthew Miller *received his B.S., M.S., and Ph.D. in Aerospace Engineering from the Georgia Institute of Technology in 2012, 2014, and 2017, respectively. He is the Artemis Internal Science Team Data and Software Lead for the Science Mission Directorate at the NASA Johnson Space Center. His work is focused on Extravehicular Activity (EVA) work domain development and the integration of science interests within Artemis missions. Dr. Miller is also embedded withing the Artemis EVA operations flight control team where he supports the design and execution of mission simulations to support crew and flight team training development for Artemis. He is also a Technical Authority for the Amentum/NASA JSC task order within JSC-XI4 to provide science mission support services.*

Susannah B. F. Paletz *(Ph.D., Social/Personality Psychology) is an Associate Professor at the University of Maryland, College Park College of Information. Her research focuses on teams, creativity, culture, technology, and applied psychology such as AI in teams. She has held positions at NASA Ames Research Center, the University of Pittsburgh, and the University of Maryland Center for Advanced Study of Language. Her work has been funded by the NSF, Army Research Office, Office of Naval Research, Minerva Research Initiative, NASA, and others.*

Dr. Lauren Blackwell Landon *is the Team Risk Discipline Scientist in the Human Factors and Behavioral Performance (HFBP) Element in NASA's Human Research Program, and a scientist in the Behavioral Health & Performance (BHP) Laboratory at Johnson Space Center. Her research is focused on teams living and working in extreme environments, examining team composition and teamwork processes as they influence team performance and functioning over time. Dr. Landon also trains team skills to astronauts and flight controllers and is a member of the NASA Astronaut Selection Team.*

Paromita Mitra *received her B.S. and M.S. degrees in Aerospace Engineering from Mississippi State University. Currently, she serves as the Data Systems Lead for NASA's Lunar Architecture Team — helping develop system-of-systems products connecting computer architectures across Artemis. Previously, she served as principal investigator for a team of engineers building a heads-up display system for spacesuits and has held positions working working on display systems for Lunar vehicles, engine testing for the F-35 Lightning II, designing satellites, and analyzing human psycho-physiology for software development. Her current technical focus is at the cross-section of human needs and ensuring data protocol and architectures support the end user.*

John Karasinski *received his B.S. in Physics from UCSC and his M.S. and PhD in Mechanical and Aerospace Engineering from UCD. He is currently a Human Factors Researcher and Engineer in the Human-Computer Interaction Group at NASA Ames Research Center. His research promotes crew autonomy and Earth-independent operations for increasingly distant crews beyond low-Earth orbit.*

Jessica J. Marquez *received a B.S.E. in Mechanical Engineering from Princeton University, followed by a S.M. from the Department of Aeronautics and Astronautics at MIT. She received her Ph.D. in Human Systems Engineering from MIT. Since 2007, she has been working at the NASA Ames Research Center within the Human Systems Integration Division. As part of the Human Computer Interaction Group, she has supported the development and deployment of various planning, scheduling, and execution software tools for space missions, such as Playbook and SPIFe (Scheduling & Planning Interface For exploration) for the International Space Station, Mars surface missions, and various Earth-analogs. She is currently the SPIFe team lead.*