An Operational Feasibility Assessment for Extravehicular Activity in Human Spaceflight Under Communication Delay Using an Underwater Research Analogue

By

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ABSTRACT

As manned space exploration advances beyond low-Earth orbit, new challenges in the planning and execution of mission tasks such as extravehicular activity (EVA) will emerge. One such challenge will be the mitigation of risks associated with communication delay between Earth and remote exploration crews. This paper provides an introduction to the problem of EVA operations under Mars-like communication delay, and evaluates the feasibility of a relay-based communication protocol through a research investigation conducted at an underwater space flight analogue facility.

Three underwater dive expeditions were completed to investigate the impact of communication time delay on the execution of a model geological survey EVA. To simulate communication with an exploration team on Mars or a near-Mars asteroid, a 5-minute transmission delay was instituted each way between divers and mission controllers. Performance measures tracked included task completion times, number of sampling activities completed, and incidence of task interruptions which delayed sampling activities.

Findings indicate that, even under communication delay, aquanauts were able to complete a high number of the prescribed mission tasks, with only minimal interruptive events occurring. Task complexity was a major determining factor for completion duration, and the occurrence of interruptive events did not significantly increase completion times.

Overall, the findings from this study support the operational feasibility of a relay-based strategy for mitigating risks related to communication delay. While further work remains to be done, this study represents an initial step in the elucidation of an important operational consideration for the success of future manned missions beyond Earth orbit.

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Author's Note

The work presented in this dissertation represents original research completed in collaboration with NASA and the NEEMO program. While completing this work, the author was supported by funding from NSBRI.

All literature review, statistical analysis, data interpretation, and conclusions presented here are the sole work of the author. In addition, the author contributed to the planning of the project by taking part in research group meetings and study design discussions. Although not on-site during the NEEMO 19 expedition nor directly involved in the execution of the analogue mission, the author also contributed to data collection remotely by providing science support through real-time video link-up, monitoring tasks during EVA-simulation dives and contributing observation notes. The author independently performed all data analysis presented here-in.

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List of Abbreviations

CSA	Canadian Space Agency
D-RATS	Desert Research and Technology Studies
ESA	European Space Agency
EVA	Extravehicular Activity
FIU	Florida International University
FMARS	Flashline Mars Arctic Research Station
ft	feet
HI-SEAS	Hawaii Space Exploration Analog and Simulation
hr	hours
in	inches
ISS	International Space Station
JSC	Johnson Space Center
km	kilometers
LSB	Life Support Buoy
M	mean
m	meters
MCC	Mission Control Center
min	minutes
NASA	National Air and Space Administration
NBL	Neutral Buoyancy Laboratory
NEA	near-Earth Asteroid
NEEMO	NASA Extreme Environment Mission Operations
RATS	Research and Technology Studies
ROVs	Remotely Operated Vehicles
s	seconds
SCUBA	Self-Contained Underwater Breathing Apparatus
SD	standard deviation
SRMS	Shuttle Remote Manipulator System
SST	Surface Support Team
SVMF	Space Vehicles Mockup Facility

Introduction

The capabilities necessary to ensure the safety and success of future manned space exploration are not limited to those attained through technological progress alone. Overcoming future operational obstacles will require the consideration of human factors and distributed team performance as well. As exploration targets beyond low-Earth orbit are identified, new challenges in the planning and execution of mission tasks such as extravehicular activity (EVA) will emerge. One such challenge will be the mitigation of risks associated with extended latency in transmissions between Earth and remote exploration crews. This paper aims to provide an introduction to the problem of EVA operations under Mars-like communication delay, and to evaluate the feasibility of a relay-based communication protocol through a research investigation conducted at an underwater space flight analogue facility.

A Brief EVA History

The first extravehicular activity, or EVA, was conducted March 18, 1965 by the Soviet cosmonaut Alexey Leonov. The spacewalk lasted approximately 12 minutes. The first American EVA was performed in June of that same year by astronaut Edward White. White's EVA was almost twice as long as Leonov's, clocking in at 21 minutes.

NASA defines an EVA as "any operation conducted by an astronaut while in a pressurized suit in a vacuum environment," further stipulating that an EVA is "activity performed in space or on a celestial body by an astronaut external to the space vehicle" (Brown, Dashner,

& Hayes, 1973). An EVA may be orbital, lunar, or interplanetary, and can be a planned, unscheduled, or contingency operation. The two operational modes of EVA are defined as "umbilical" or "free": in an umbilical EVA, the astronaut is connected to the vehicle by a tether which provides life support, although a self-contained emergency pack containing enough oxygen to feed a leak, as well as a supply of temporary coolant in the event of a thermal control loop failure, is generally also worn; in a free EVA, the astronaut carries all needed life support (either integrated with or in addition to the spacesuit) and is fully independent of the vehicle in terms of power and functioning (Brown et al., 1973).

Throughout the Gemini program, NASA continued to build its EVA competency, and during the Apollo program, a new milestone in EVA history was reached with the first moon landing on July 20, 1969. Between 1969 and 1972, a total of 15 EVAs were conducted on the lunar surface. To date, these are the only non-Earth surface exploration EVAs to have been executed, however NASA is currently looking ahead towards future deep-space expeditions which will carry astronauts to asteroids and, one day, to Mars.

Such remote target destinations, however, present newfound operational challenges beyond the existing engineering and biomedical obstacles faced thus far in low Earth orbit (e.g. radiation, bone and muscle atrophy, power, life support, etc.). The distance separating the Earth and Mars varies between 55 and 378 million km; such a vast separation introduces a delay in the relay of radio signals—and therefore information and communication—by roughly 5-20 minutes each way.

Given that the average distance between the Earth and the Moon is roughly 384,400 km, only a very minimal transmission delay of approximately 1.3 s between astronauts on the lunar surface and mission controllers on Earth has been previously experienced in the orchestration of extravehicular activities. This latency period proved essentially inconsequential for the geological surveying conducted during Apollo. However, with the present NASA objectives of visiting a near-Earth Asteroid (NEA) and eventually Mars (or one of its moons), the impact of increased communication delay becomes a serious component of operational planning for future EVAs that must be considered.

Present and Future EVA Operations

Before exploring the future of deep-space EVAs, an introduction to current EVA operational and training procedures is useful. Currently, NASA astronauts are trained in EVA operations at a number of facilities located at the Johnson Space Center (JSC), including the Sonny Carter Training Facility (also called the Neutral Buoyancy Laboratory (NBL)) and the Space Vehicles Mockup Facility (SVMF). The SVMF houses full-scale mockups of International Space Station (ISS) and other pertinent trainers, such as a precision air-bearing floor which simulates zero gravity (Moore & Gast, 2010).

The NBL is primarily employed for crew training, as well as for the development of hardware and EVA procedures. The facility contains an enormous immersion pool (202 ft in length, 102 ft in width, 40 ft in depth, holding 6.2 million gallons of water), which is large enough to hold full-sized mockups of the ISS so that crews may rehearse EVAs to scale and in real-time. The facility also has multiple control rooms, a communication system, a water treatment system, closed circuit television, cranes, and a specialized diving medical treatment facility (Moore & Gast, 2010). Additional EVA training for astronauts may include time in virtual reality simulators and the DC-9 reduced gravity aircraft.

Decades of EVA experience have contributed to the creation of extensive protocols, guidelines, and limitations in EVA operations (Brown, Dashner, & Hayes, 1973). However as Moore & Gast (2010) point out, both protocols and astronaut training procedures would need to change as focus shifts from orbital to surface activities, and the development of new types of EVA skills become necessary.

For instance, the development of competency in robotic interactions will most likely be an essential component of future EVA training. While many EVAs since 1981 were conducted with the aid of the robotic Shuttle Remote Manipulator System (SRMS), or Canadarm, successful future space exploration missions will probably be an even more integrated effort conducted jointly by humans and automated systems; cooperation with autonomous and remotely controlled robotic assistants, therefore, will be critical to the success of future EVAs (Jacobs & Akin, 2010; Hoffman, Leonard, & Lee, 2011).

Much research has already investigated the application of various software-based support systems for the planning and execution of EVA operations (Anderson, 1999; Marquez & Cummings, 2008; Marquez, Ludowise, McCurdy, & Li, 2010), as well as the potential applications of wearable devices and enhanced information interfaces for EVA astronauts (Carr, Schwartz, & Rosenberg, 2002; Hodgson, Sidgreaves, Braham, Hoffman, Carr, Lee, Marmolejo, Miller, Rosenberg, & Schwartz, 2003).

Furthermore, operational strategies are currently in development to promote effective human-robot collaboration in order to improve mission performance and safety. As a recent study points out, telerobots are ideal for implementation in monotonous, highly-repetitive, low-complexity, long-duration, or high-risk tasks, including surveying, site preparation, and routine repair or simple construction (Fong, Zumbado, Currie, Mishkin, & Akin, 2013). In this regard, such robotic technology is well poised to assist in the directed preparation of exploration sites before the arrival of a human crew. For example, future space missions may begin with a robotic exploration phase in which early scouting and sampling is conducted autonomously or semi-autonomously in preparation for crew arrival; these robots could then transition to the role of assistants to aid the crew, and later act as caretakers for the exploration site once the crew has departed (Hambuchen, Burridge, Ambrose, Bluethmann, Diftler, & Radford, 2012). Such a mission design, however, will require a great deal of robustness on the part of the robotic technology employed, as it will be require to shift not only in the role plays within the mission, but also in its level of automation and amount of time delay tolerated for receiving instructions (Steel, 2013).

Spaceflight Analogue Research Environments

In parallel with these technological investigations into the capabilities of robotic and automated software assistants for future manned EVAs, scientists have also been conducting human-behavioral and performance-based research in simulated space exploration environments to develop new procedures for dealing with the operational challenges which lie ahead for future crewed missions to Mars.

Since 2000, the Flashline Mars Arctic Research Station (FMARS) on remote Devon Island in the Canadian Arctic has hosted a series of simulated Mars missions ranging in duration from one to four months. FMARS is administered by the Mars Society, a non-profit organization which seeks to promote the human exploration of Mars. The National Aeronautics and Space Administration (NASA) has largely funded another Mars research outpost on Devon Island known as the Haughton–Mars Project, in cooperation with the Canadian Space Agency, The Mars Institute, and the Search for Extraterrestrial Life Institute. NASA has also conducted a series of simulated space missions as part of the NASA Extreme Environment Mission Operations (NEEMO) program, in which crewmembers spend the duration of the simulation in an underwater habitat facility off the coast of Florida (a more detailed description of the NEEMO analogue research program will follow in the *Methods* section).

The analogue expeditions conducted at these facilities attempt to replicate the operational conditions that would face human surface exploration teams on Mars, including isolation and confinement. Additionally, the often extreme environment settings of these analogue facilities allows for the testing of robotic equipment, navigation and communication devises, and spacesuit prototypes (Battler, Auclair, Osinski, Bamsey, Binsted, Bywaters, Kobrick, Harris, & Barry, 2008).

One of the primary advantages of such Earth-bound analogue research facilities is that they provide high-fidelity simulations for the investigation of human factors and team dynamics (for a review on teamwork and team selection for crewed space exploration, see Paris, Salas, & Cannon-Bower, 2000). For example, a four-month simulated Mars mission conducted on Devon Island in 2007 included a spectrum of spaceflight human factors studies investigating stress and isolation countermeasures, group dynamics, sleep and cognitive performance, and food choice and preparation (Binsted, Kobrick, O'Griof, Bishop, & Lapierre, 2010). Similarly, another analogue campaign, the Hawaii Space Exploration Analog and Simulation (HI-SEAS), which is run jointly by Cornell University and the University of Hawaii, is currently undertaking a series of research missions examining dietary regimes and food preparation protocols for use in future space exploration.

The longest-duration analogue staged to date is the Mars500 mission, concluded in November 2011. Sponsored by the European Space Agency in conjunction with the Russian Academy of Science at the Institute of Biomedical Problems in Moscow, this project saw a six member international crew undertake a 520-day Mars simulation to test the physiological and psychological effects of long-term isolation.

In addition to these psychological and human-factors based investigations, other analogue research studies have a more operational focus, providing researchers with a test environment for assessing new EVA procedures in conditions simulating Mars or an asteroid surface. For instance, the Desert Research and Technology Studies (D-RATS) field test completed in 2011 conducted a series of simulated surface EVAs on a near-Earth asteroid (NEA). Since the focus of this investigation was to better understand the impact of communications latency and limited data bandwidth on the planning and execution of surface exploration, a 50 s one-way latency was imposed on transmissions between crewmmembers and mission controllers, and operationally feasibility was then assessed (Abercromby, Chappell, & Gernhardt, 2013). In a follow-up 2012 study, NASA conducted a similarly structured 2-week Research and Technology Studies (RATS) NEA exploration simulation to evaluate hardware prototypes and to develop operational definitions for the safe and effective coordination of human and robotic efforts (Abercromby, Chappell, Litaker, Reagan, & Gernhardt, 2012).

NEEMO missions 15 and 16 have also incorporated short time delays in their research investigating NEA scenarios. NEEMO 15, which was conducted over 13 days to test operational methods for human asteroid exploration, included a robotic precursor mapping expedition of the coral reefs surrounding the underwater habitat, which was followed by humans conducting sampling and observation via remotely piloted submersibles; finally submersibles participated on simulated EVAS with diver crewmembers to evaluate tools and protocols for sample collection (Chappell, Abercromby, & Gernhardt, 2013). This research was expanded upon by the NEEMO 16 follow-up study, which investigated crew factors such as team size and strategies for optimizing human-robotic cooperation (Chappell, Abercromby, Reagan, & Gernhardt, 2013)

While investigations such as D-RATS (2011), RATS (2012), and NEEMO missions 15 and 16 have yielded insights into the planning and execution of EVA on near-Earth asteroids, the findings they offer may not adequately extrapolate to Martian surface exploration, as the expected Earth-Mars communication delay far exceeds the 50 s latency assessed in these near-Earth asteroid studies. The following section will explore previous research in the fields of operational planning under communication delay, with particular focus on research relevant to the 5-20 min latency period anticipated for Mars missions.

Previous Research

Previous research investigating the impact of communication delay on team performance has been largely concentrated in the cognitive psychology and human factors domains. This work includes studies exploring topics such as group consensus formation via chat and teleconferencing (Graetz, Kimble, Thompson, & Garloch, 1997), distributed decision-making under delay (Billard & Pasquale, 1995), and the affects of geographic distance on collaboration using computer-based communication (Bradner & Mark, 2002).

In Mars-exploration scenarios, coordination between crew and MCC will be particularly challenging in the event of unexpected events or problems which require extensive collaboration and discussion. Several studies have investigated these issues through simulations involving communication delay conditions. In their work, Love & Reagan (2013) identified several key challenges arising from communication delay, including sequence confusion, inefficient time use, impaired ability to adequately relay relevant information, losing track of message order, and reduced situational awareness. However, the authors argue that these challenges can be addressed in part through appropriate additional training, detailed recordkeeping in message transmission, and greater efficiency in the presentation of communicated information.

Findings from an investigation examining the impact of communication delay, and the medium of communication available (text vs. voice), on distributed team performance in a simulated systems repair task indicated that teams required significantly more time to complete repairs under asynchronous communication conditions, although communication medium was not found to significantly impact task efficiency under the delay condition (Fischer & Mosier, 2014). These results suggest that successful teams under time-delayed conditions are able to adapt to the communication constraints and establish shared task understanding. These findings also point to the necessity for future crew and Mission Control Center (MCC) teams to develop effective strategies for managing time delay in communication through adequate use of available technologies.

Furthermore, previous investigations have highlighted the need for increased crew autonomy in future exploration missions as communication delays with MCC increase (Bobskill & Lupisella, 2014). Currently, anomaly response in MCC is distributed across functionally distinct teams, which are able to communicate in real-time with each other and the astronaut crew, thereby increasing robustness in the face of uncertainty (Watts-Perotti & Woods, 2007). Increased communications delay will require crews to plan and perform many science tasks without direct instruction from Earth-bound ground support, and will necessitate in-situ science analysis capabilities. Not only will crews need to be able to assess surface samples independently in order to achieve mission science objectives, they will also need to make real-time operational decisions from a safety perspective and replan mission parameters as necessary.

A recent study directly investigated the impact of high versus low crew autonomy on the interaction between crewmembers and mission control (Kanas, Saylor, Harris, Meylan, Boyd, Weiss, Baskin, Cook, & Marmar, 2010). High autonomy periods, as defined by the study, were those in which crewmembers controlled much of their own schedule planning; during low autonomy periods, schedules were dictated by MCC. Data was examined across three groups of space simulations: NEEMO, the Haughton-Mars Project, and the pilot phase of the Mars 500 Program. High work autonomy was associated with positive mood reports by crewmembers and the successful accomplishment of mission goals; it did not result in any observed adverse effects. Mission control personnel, however, reported some confusion about their work role during high crew autonomy periods. Achieving a balance between crew autonomy and Earth-based support will, therefore, be a key challenge for Mars and deep-space missions, particularly as relates to the clear definition of roles and responsibilities for all teammembers.

The shift towards more autonomous crew operation was directly investigated in the NEEMO 13 mission, which incorporated an 'autonomy implementation' and a 20 min one-way communication delay (Chappell, Abercromby, Todd, & Gernhardt, 2011). The investigation revealed that, as crews begin to behave more autonomously, the role of MCC shifts from supervisory (providing clear directives regarding plans, procedures, and schedules) to advisory (offering recommendations on mission objectives, constraints, and priorities). As the study suggests, team interaction becomes more critical under communication delay, as crewmmembers must rely more heavily on one another to accomplish tasks, mitigate uncertainty, and address emergencies.

A similar study was conducted during the 105 day Mars simulation conducted as part of the Mars 500 project at the Institute for Biomedical Problems in Moscow. For the first 10 weeks, the 6 member crew interacted with the 18 member MCC team in real-time under a low crew autonomy condition. During the remaining 5 weeks, a high autonomy condition was imposed in which crewmembers planned their own work schedule and communicated with MCC under a Mars-like time delay. Weekly measures of mood, group interaction, perceived work freedom, and performance were collected for both crew and MCC. Findings suggest that while the crew responded positively to high work autonomy (in terms of mood ratings, report self-direction, and performance measures), mission control personnel reported increased anxiety and greater work role confusion under the high crew autonomy manipulation (Kanas, Harris, Neylan, Boyd, Weiss, Cook, & Saylor, 2011).

Crew autonomy, however, will need to extend beyond scheduling planning and operations, and into medical care as well: as immediate assessment, evaluation, and recommendation by Earth-bound medical officers will not be possible, onsite care and the autonomous management of acute medical emergencies will be critical on Mars and near-Mars expeditions. As Kuypers (2013) points out, the inaccessibility of real-time telemedicine consultations with MCC highlights the need for wilderness and emergency medical training for future Mars-bound astronauts.

An Investigation of EVA Operations Under Mars-Like Communication Delay

As demonstrated, previous investigations of spaceflight operations under communication delay have either been limited to short-delay conditions simulating NEA scenarios (e.g. D-RATS, RATS, NEEMOs 15 and 16), or have focused on the interpersonal crew dynamics stemming from Mars-like communication delay with Earth (Kanas et al., 2010; Kanas et al., 2011); existing studies have not adequately addressed how this delay period impacts EVA operations specifically, neither in terms of logistical execution nor crew performance.

Methods

The objective of this investigation was to operationally validate a research approach for risk mitigation strategies in extravehicular activity (EVA) under communication delay. In particular, this research focused on evaluating the frequency of interruptive events related to communication errors in the execution of a model geological survey EVA expedition. This research was conducted as part of the 19th underwater expedition of the *NASA Extreme Environment Mission Operations* (NEEMO) program.

Participants

The 4-member aquanaut crew of the NEEMO 19 mission was composed of an international team representing the National Aeronautics and Space Administration (NASA) of the United States, the European Space Agency (ESA), and the Canadian Space Agency (CSA). The all-male crew ranged in age from 38 to 52 years old (M = 44 years old); 3 participants were astronauts, 1 having flown in space and the other 2 having completed Astronaut Candidate Training, while the fourth team member was a highly experienced astronaut trainer and ESA spacewalk instructor. Having completed comparable programs of operational training, all participants were assumed to be of equal proficiency in the EVA-related procedures relevant to this investigation; only one member of the group was actually experienced conducting EVA on orbit, having logged 11 hr and 50 min extravehicular time while aboard the International Space Station. In terms of previous operational experience, 2 participants were of a military background, and all participants had a minimum of a private pilot's license.

Facility

NEEMO 19 took place in the *Aquarius Reef Base* underwater research facility, located 62 ft (19 m) below sea level, 5.4 mi (9 km) off the coast of Key Largo, Florida. *Aquarius* is situated on the ocean floor, near a large outcropping of coral, in the Florida Keys National Marine Sanctuary.

Since 2001, NASA has used the facility for research and training purposes through a series of simulated space exploration missions under the NEEMO program. The underwater location of the *Aquarius Base* provides conditions similar to those of space travel—including confinement, isolation, and a high-risk operational environment—and therefore offers a suitable Earth-bound research analogue. At the same time, the underwater environment provides additional benefits for the testing of EVA procedures, as it allows for the differential weighting of aquanauts to simulate various gravitational environments including the moon and Mars. Saturation diving, in which divers do not return to the surface following a day's dive but instead maintain working atmospheric pressure while in the habitat facility, allows for extend duration stays underwater, with typical missions ranging in from 7 to 14 days.

While not in use by the NEEMO program, the *Aquarius Reef Base*—which has been managed since 2013 by the Florida International University's (FIU) *Marine Education and Research Initiative*—is employed through the Medina Aquarius Program for the study of underwater ecosystems, educational outreach, technological development, and professional training.

Habitat Structure

The *Aquarius* facility is an 80–ton cylindrical chamber measuring 43 ft (13 m) in length by 9 ft (2.7 m) in diameter, and is anchored to the ocean floor via a 116–ton baseplate. The facility is comprised of 3 compartments: the main lock, the entry lock, and the wet porch (*Figure 1-4*). Locking doors separate the compartments and maintain the differential pressure between the various sections.

The main lock provides living and working area, including a six-bunk sleeping room and a small kitchen facility. The main lock also houses communications and video equipment, as well as life support and medical supplies.

The wet porch provides sea access, as well as storage space for SCUBA equipment.
The air pressure inside the wet porch is maintained at a level equivalent to ambient pressure at depth (approximately 2.6 atmospheres).

The entry lock, the smallest compartment in the facility, connects the wet porch and main lock, and serves as an airlock for pressure adjustments as personnel move between the two areas, as well as between the habitat and surface. The entry lock also houses a bathroom, communications equipment, gas and electrical panels, and life support equipment.

The Life Support Buoy (LSB)—33 ft (10 m) in diameter and stationed at the surface above the habitat—provides air, power, and data and communication links to the facility. The LSB is connected to the *Aquarius* by a 138 ft (42 m) long umbilical cord.

Figure 1. Overhead view of the Aquarius facility floorplan.

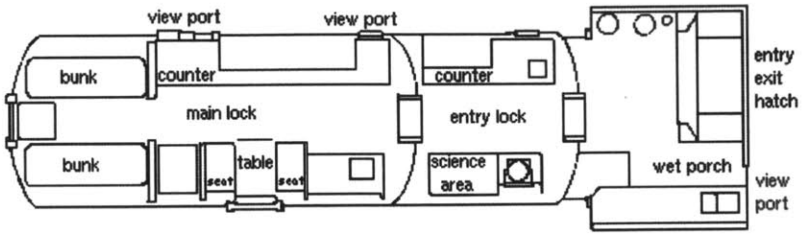


Figure 2. Port elevation view of the Aquarius facility.

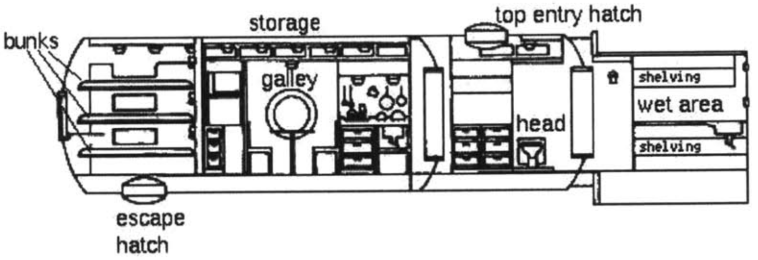
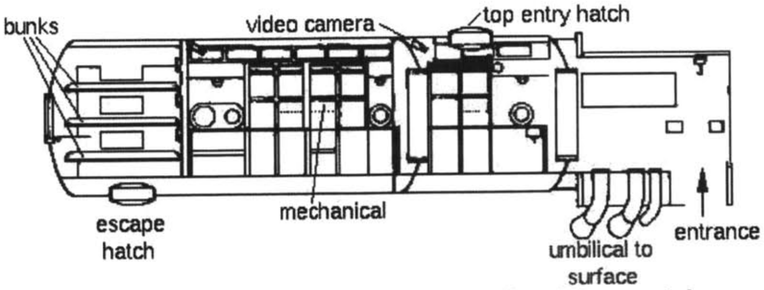


Figure 3. Starboard elevation view of the Aquarius facility.



Images from the FIU Aquarius Facility briefing materials

Figure 4. External image of the Aquarius research facility on the ocean floor.

Image courtesy of NASA

Additional Staff and Facilities

As standard practice for safety, and to ensure the proper operation of the *Aquarius* facility's on-board systems, two FIU employees accompany all NEEMO crews into saturation. Additional safety monitoring is provided by the Surface Support Team (SST), based on-shore in Key Largo at the FIU *Reef Base*. The SST includes NEEMO research team members, divers, and medical personnel.

To model the Earth-based command center employed during space exploration, NEEMO missions are monitored by a Mission Control Center (MCC) located on-shore. The NEEMO MCC is staffed 24 hours a day during all missions. MCC personnel monitor the telemetry of the facility, approve all dive plans, and are responsible for the overall safety of the mission.

Mission Overview

NEEMO 18 (July 21-29, 2014) and NEEMO 19 (September 7-14, 2014) were conducted jointly by the international space agency partners NASA, ESA, and CSA. The objective of this complimentary pair of underwater missions was to provide a training and testing bed for Mars and near-Mars surface exploration techniques, in preparation for upcoming ventures such as the Asteroid Redirect Missions currently slated for the early 2020s.

The NEEMO 19 mission, in particular, provided the opportunity for hardware evaluation, including new technologies such as the ESA telemonitoring devices which were designed to integrate with wearable technologies to provide mission controllers real-time feedback on crewmember activities. NEEMO 19 also allowed for the testing of new operational procedures and tools, such as drilling equipment for the extraction of core samples from the surface, as well as strategies for mapping of exploration sites using Remotely Operated Vehicles (ROVs).

Simulation of EVAs Under Communication Delay

Future exploration-class crewed space missions to Mars or near-Mars asteroids will almost certainly involve a delay in communication between astronauts and mission controllers on Earth, given the time needed for radio-based signals to traverse the distance between them. In order to prepare mitigation strategies for dealing with contingencies that may arise from communication delay, researchers are presently investigating ways to operationally validate the study of EVA procedures in analogue environments, including the *Aquarius Reef Base.*

To this end, a research program involving a set of 3 underwater dive expeditions was conducted during the NEEMO 19 mission. The focus of these dives was to investigate the impact of time delay in communication on EVA performance, and to test operational concepts for dealing with communication delay. The structure of the dives was designed to simulate geological sampling EVA expeditions conducted on a moon of Mars or a nearby asteroid. The evaluation of performance measures related to these 3 dives will be the primary focus of the remainder of this dissertation.

The dives were conducted across 3 separate days of the NEEMO 19 mission, with one simulated EVA taking place each day. Each expedition was conducted by a pair of aquanauts, with the aquanauts alternating at each expedition so that all 4 NEEMO 19 crewmembers had the opportunity to complete at least one of the simulated EVAs. Of the 4 aquanauts, only 1 completed two EVAs during the NEEMO 19 mission.

To simulate communication with an exploration team on Mars or a near-Mars asteroid, a 5-minute communication delay was instituted each way between MCC and the habitat facility. During each expedition, instructions from MCC were relayed to the EVA team by the remaining 2 aquanauts in the habitat, effectively creating a relay-based communication loop. All audio, video, and data transmitted between the EVA team and the habitat was communicated in real-time; this information was then piped from the habitat to the surface via the umbilical, where it was downlinked following a 5-minute delay to MCC on shore. Reciprocally, MCC communicated directly with the habitat facility under time delay, after which instructions were relayed in real-time to the EVA team.

The aquanauts in the habitat also participated in the execution of EVAs, with 1 team member controlling the remote rover and monitoring the real-time video feed, while the other in-habitat aquanaut monitored progress of the EVA protocol. Safety support divers were also in the water for all EVA expeditions.

Exploration Traverse Procedures

Each EVA expedition traversed the same exploration course, comprised of 4 unique locations on the reef bed, each with 8 flagged subfeatures around the primary sampling site (exploration course shown in *Figure 5*). This 4-site course was repeated in sequence up to 3 times per expedition, with a separate set of geological survey tasks assigned to each round of the course traverse (survey tasks explained in more detail below).

The tasks completed during the first 2 circuits were designated "high complexity," with the 3rd round circuit being comprised of "low complexity" tasks (a sample list of tasks in each category is provided in *Figure 6*). The landmark locations, as well as the task activities and their order of assignment, remained consistent across the 3 EVAs. The time limit for completion of each EVA expedition was 2.5 hrs (due to the operational constraints of the safety diver support team), after which the EVA aquanauts rejoined their teammembers in the habitat facility.

Figure 5. Site map of landmarks surveyed. The "Landing Site" where each EVA began is here labeled "Manta," with the yellow quadrilateral structure representing the Aquarius habitat.

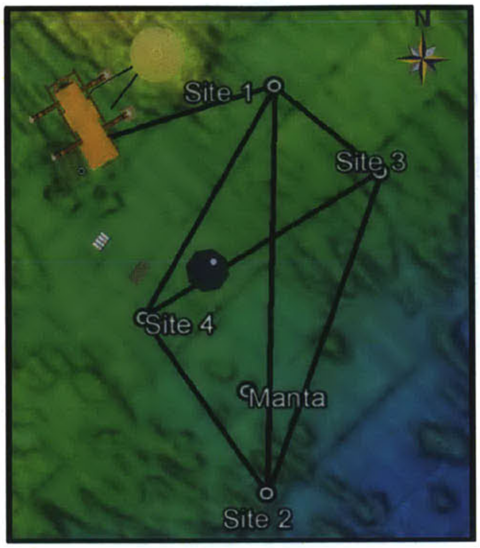
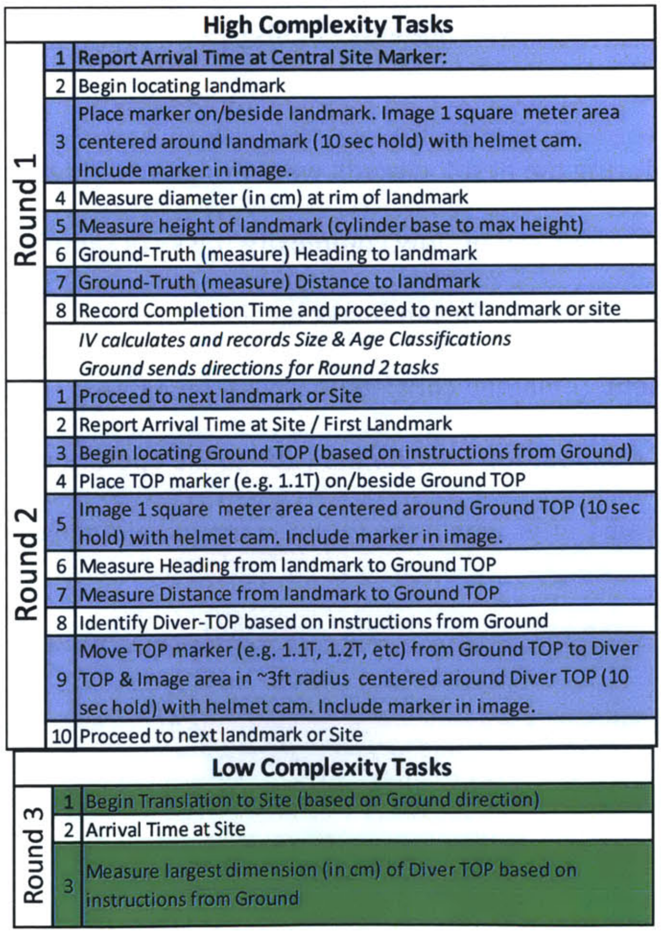


Figure 6. List of potential EVA sampling tasks, by complexity and circuit pass.



		High Complexity Tasks
Round 1	1	Report Arrival Time at Central Site Marker:
	2	Begin locating landmark
	3	Place marker on/beside landmark. Image 1 square meter area centered around landmark (10 sec hold) with helmet cam. Include marker in image.
	4	Measure diameter (in cm) at rim of landmark
	5	Measure height of landmark (cylinder base to max height)
	6	Ground-Truth (measure) Heading to landmark
	7	Ground-Truth (measure) Distance to landmark
	8	Record Completion Time and proceed to next landmark or site
		IV calculates and records Size & Age Classifications *Ground sends directions for Round 2 tasks*
Round 2	1	Proceed to next landmark or Site
	2	Report Arrival Time at Site / First Landmark
	3	Begin locating Ground TOP (based on instructions from Ground)
	4	Place TOP marker (e.g. 1.1T) on/beside Ground TOP
	5	Image 1 square meter area centered around Ground TOP (10 sec hold) with helmet cam. Include marker in image.
	6	Measure Heading from landmark to Ground TOP
	7	Measure Distance from landmark to Ground TOP
	8	Identify Diver-TOP based on instructions from Ground
	9	Move TOP marker (e.g. 1.1T, 1.2T, etc) from Ground TOP to Diver TOP & Image area in ~3ft radius centered around Diver TOP (10 sec hold) with helmet cam. Include marker in image.
	10	Proceed to next landmark or Site
		Low Complexity Tasks
Round 3	1	Begin Translation to Site (based on Ground direction)
	2	Arrival Time at Site
	3	Measure largest dimension (in cm) of Diver TOP based on instructions from Ground

Geological Sampling Tasks

The geological sampling tasks were as follows: in the first circuit pass through the 4 sites, aquanauts located the sampling target at each landmark and photographed the site's geological features using helmet-mounted cameras; these images were then sent for 'science evaluation' to MCC via relay through the habitat. After the images were evaluated, MCC then followed up with further instructions regarding tasks to be completed in subsequent circuits, from a list of possible tasks that remained consistent across all 3 EVAs. After receiving MCC instructions via habitat relay, aquanauts completed remaining "high complexity" tasks on the second circuit; these included tasks such as measuring the diameter of the landmark feature, measuring the height of the feature, classifying the age of the formation based on physical characteristics, and recording the headings and distances between landmarks for navigation. Finally, "low complexity" tasks were completed on the third circuit, as time permitted (a list of possible tasks in both "high" and "low" complexity categories is included in *Figure 6*). On each expedition, the 2 EVA aquanauts completed their own list of tasks independently, except where tasks required joint cooperation to complete.

Quantitative Performance Measures

As one of the primary objectives of this series of simulated EVA expeditions was to assess the impact of communication delay on mission performance, several quantitative measures were recorded during each EVA; measurements were made by the support team. These included task completion times, number of sampling activities completed, and incidents of task interruptions which delayed the completion of sampling activities.

Data Analysis

The 4 primary dependent measures assessed in this investigation were (1) the quantity of surveying conducted, in terms of both the number of tasks completed and the number of landmarks surveyed; (2) the time needed for task completion; (3) the number of interruptive events experienced; and (4) the time delay experienced due to the occurrence of interruptive events. Interruptive events were used here as a proxy for errors experienced as a result of the communication delay, and were meant to quantify the occurrence of phenomena such as read-back errors or mishearings of instructions that resulted in a temporary suspension of activity while crewmembers waited for instructions to be repeated and relayed. Descriptive statistics and comparison measures for these variables are presented in the following section.

Completion numbers for landmarks at each EVA were evaluated out of a potential total of 24: 4 sites, each completed a possible 3 times (once each circuit), by 2 divers who were assessed independently (since, though they worked as a team, the pair was not constrained to perform the same set of tasks simultaneously). Due to the small sample size of 3 EVAs, and given the fact that each aquanaut independently completed his own task lists, each sampling task was evaluated here as a separate trial event in an effort to maximize statistical power for the assessment of the impact of interruption on task completion time.

Results

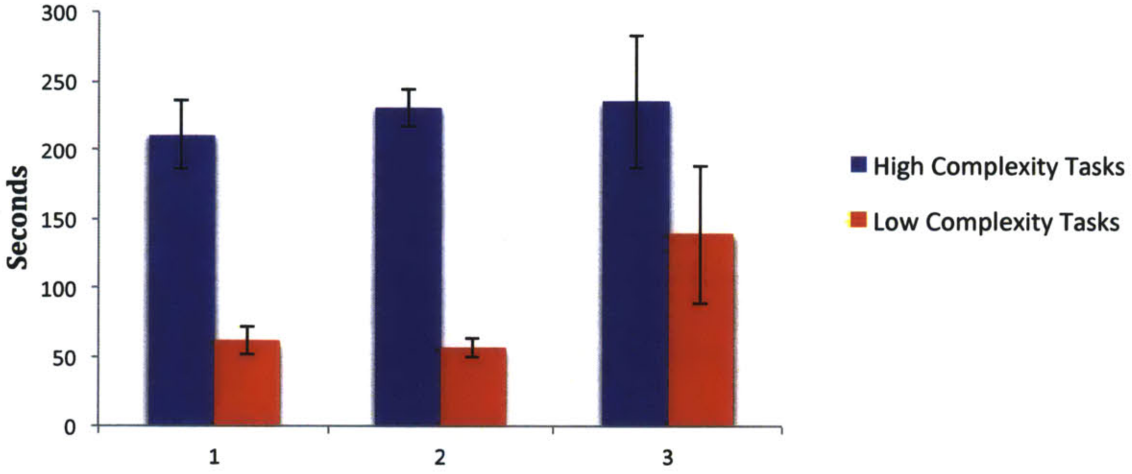
Findings from the quantitative evaluation of the underwater EVAs indicate that, even under communication delay, aquanauts were able to complete a high number of the prescribed mission tasks (*Figure 7*). Across the 3 EVA expeditions, aquanaut pairs surveyed a mean of 19 out of a possible total 24 landmarks, and completed a mean of 25 high complexity tasks and 19 low complexity tasks.

Figure 7. Summary chart of EVA performance metrics by expedition. On average, EVA teams under communication delay completed a high number of tasks and surveyed a majority of the 24 possible landmarks, and experienced few interruptive events.

EVA	Total Number Landmarks Completed	Total Number High Complexity Tasks Completed	Total Number Low Complexity Tasks Completed	Total Number Interruptions During High Complexity Tasks
1	20	26	20	3
2	20	26	20	5
3	16	24	16	2

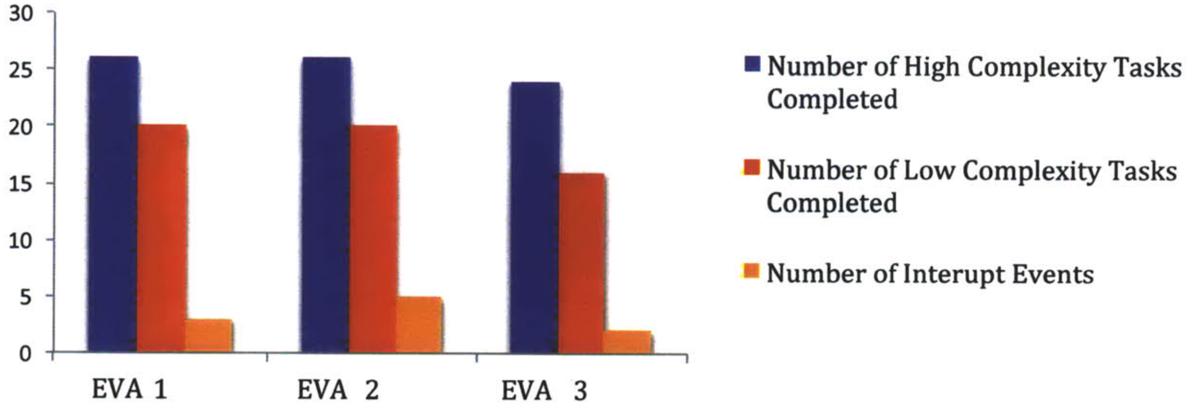
At each landmark, the mean completion time for high complexity tasks (across all participants and EVA expeditions) was 229 seconds (SD = 76 s), while mean completion times for low complexity tasks were, as expected, substantially lower (M = 79 s; SD = 59 s) (*Figure 8*).

Figure 8. For each EVA expedition (numbered 1-3), mean completion times (in seconds) per landmark are shown for high complexity tasks (blue) and low complexity tasks (red). As expected, high complexity tasks required substantially more time to complete than low complexity tasks. This chart also shows that while EVAs 1 and 2 were highly consistent in terms of average time required to complete low and high complexity tasks, EVA 3 required more time for all task types, even though the tasks themselves and the sampling sites remained consistent across EVAs, suggesting that individual variability across aquanauts may be an important factor contributing towards variance in observed performance metrics.



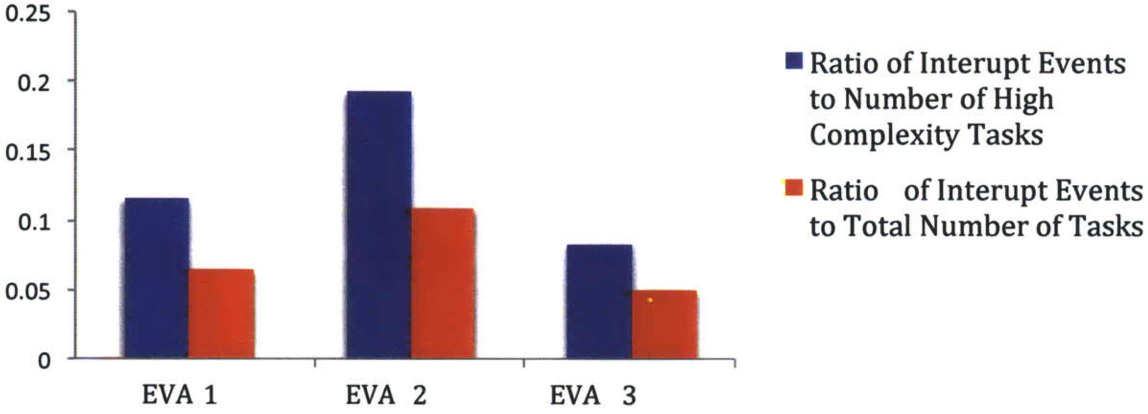
Overall, mission personnel as a whole—including the MCC team, EVA crews, and in-habitat aquanauts—managed the communication delay effectively, with only minimal interruptive events occurring across EVA expeditions (M = 3 interruptions of operational activity per EVA expedition) (*Figures 7* and *9*). Interruptive events were categorized as any disruption of geological surveying tasks, such as a read-back error or a mishearing of MCC instructions, that resulted in a hold or delay of mission activity. All interruptive events experienced during NEEMO 19 EVAs occurred during high-complexity task activities, with no such interruptions taking place during low-complexity task operation.

Figure 9. Number of tasks completed for each EVA expedition (numbered 1-3). High complexity category tasks are represented in blue and low complexity category are shown in red. The total number of interruptive events experienced in each EVA are illustrated in orange. The graphs show a pattern of consistency across the 3 expeditions.



An examination of the frequency of interuptive event occurance during the simulated EVA operations of NEEMO 19 revealed an interuption risk rate of 7% for all sampling tasks, and 13% for high complexity tasks only, suggesting that the risk of interuptive event occurance increases as task complexity—and therefore complexity of communicated instructions—increases (*Figure 10* charts the occurrence of interruptive events across the individual EVA expeditions).

Figure 10. Ratio of interrupt event occurrence to number of tasks completed (high complexity tasks in blue; all tasks in red), for each EVA expedition.



The occurrence of an interruptive event did not have a statistically significant detrimental impact on task performance in terms of time: a one-tailed, independent-samples t-test (heteroscedastic t-test with a two-sample unequal variance) comparing the average time required to complete tasks at each landmark for sites where an interruption was experienced (M = 253 s) versus task time for sites where no interruption occurred (M = 206 s) revealed no significant effect ($p = 0.14$). For this comparison, a one-tailed test was employed as it was hypothesized that interruptive events would have a negative impact on task efficiency, resulting in longer task completion times when an interruption was experienced, though in fact this effect was not demonstrated.

It should be noted, however, that not all events recorded as "interuptions" were a result of communication errors or errors stemming from time delay; a small number of these interuptions were in fact caused by procedural problems including the snag of an umbilical cord which required assistance from support divers to resolve, and a couple of incorrectly placed or missing site markers. These interuptions, therefore, may be more representative of general operational delays that can occur under EVA, rather than those strictly resulting from errors related to the communication delay.

Discussion

As expected, the simulated EVAs conducted during the NEEMO 19 mission revealed that task complexity is a major determining factor of completion duration in geological surveying but that, surprisingly, the occurrence of interruptive events related to communication delay with MCC was not a significant contributor towards increased completion times.

In fact, although it was presumed at mission onset that all participants were of equal skill and proficiency in EVA procedures (having completed comparable programs of EVA training), variance in individual performance seemed to be the highest determining factor of task time and number of tasks completed (for a detailed breakdown of task time, completion rates, and interruptive event frequency by participant, see *Appendix A*). Since the tasks remained consistent across EVA expeditions, the observed differences in performance were not attributable to the tasks themselves, but rather stemmed from unpredictability in events during the expedition, and from individual differences amongst the participants. These findings, therefore, suggest that contingency occurrences may in fact be more relevant in impacting task time and success in mission completion than the attributes of the individual tasks themselves or factors related to the challenges of delayed communication (i.e. interruptive events).

Implications for Operational Planning of EVA Under Communication Delay

While the operational constraints of this particular simulated EVA study did not allow for further statistical analysis of performance metrics, it did serve as a useful proof-of-concept mission for the design planning of EVA expeditions which incorporate a time delay in communication. Overall, the findings from this study support the operational feasibility of the relay-based strategy for mitigating risks related to communication delay.

This study points to the need for planning EVAs with the anticipation of when ground communication will need to occur, in order to minimize the potential disruption incurred through delay-related errors. At the same time, this investigation highlights the need for the standardization of communication protocol to deal effectively with transmission delay. For example, though it was not explicitly stipulated in the communication protocols for this investigation, confirmations of message receipt ('copy on receive') and standardizations in how CAPCOM transmits messages (for instance, in a maximum of 20 word segments transmitted 30 seconds at a time) would be useful in future investigations.

Limitations

There were 3 primary limitations that arose in this project: (1) task complexity; (2) statistical power; and (3) lack of a suitable 'control condition.'

This study relied on task completion numbers and times as operational metrics of performance in order to assess the impact of communication delay-related interruptions. However, little variance was observed in task completion numbers or times, with all EVA pairs completing the 3 possible sampling circuits. These findings point to the need for increasing the complexity of tasks in future investigations in order to more closely approximate the reality of EVA operations.

One possible way simultaneously increase complexity and improve simulation fidelity in future research is through the introduction of conditional tasks: for example, after the initial measurement of a coral sample, a subsequent conditional sampling task, such as further imaging or assessment, would be initiated if the sample met a prescribed minimum size.

The second limitation encountered in this investigation was power. Since only 3 total EVAs were accomplished, each with a limited number of independent sampling tasks, the study was underpowered for statistical examination. While this investigation was primarily intended as a pilot study to operationally validate the communication delay and EVA sampling research protocols, and achieving high statistical power was not a primary objective, future investigations should employ experimental manipulations and strive to increase task number and complexity.

Finally, the logistical limitations of this investigation did not allow for a suitable control condition (i.e. a 'no time delay' condition) against which performance measures such as task times and frequency of interruptive events could be compared. This limitation could be overcome by introducing an experimental manipulation in future investigations which would allow for the direct comparison of EVA performance across different study conditions.

Future Work

In order to address the limitations highlighted in the previous section, and to further interrogate the differential impacts of various kinds of interruptive events, future investigations could structure a set of simulated EVAs in such a way as to allow for the direct assessment of the impact of different 'classes' of interruptive events.

One option would be to identify 4 types of potential interruptive events that would be most likely to occur on an exploration-class mission under communication delay, and to then examine them and their effects independently by imposing one class of interruptive event on each EVA day (for example, a 'read-back error' on EVA 1, a 'request for message repeat' on EVA 2, etc.). Interruptive events can be classified, for example, by whether they (1) cause a need for message repetition; (2) cause a need for message clarification; (3) cause delay in activity; or (4) result in the execution of inaccurate task(s) (*Figure 11*).

For such an investigation, it would also be necessary to define several additional EVA-related operational performance metrics (for both aquanauts and MCC staff) that could be systematically tracked in order to experimentally evaluate the impact of interruptions and any resulting time loss on the mission. Such a study might enable the identification of types of tasks which are most impacted by various kinds of interruptive events, in order to develop mitigation strategies for investigation in future research studies. It could also allow the exploration of resilience strategies within mission planning and allow for the examination of different approaches for dealing with and recovering from interruptive events.

The experimental manipulation of interruption would require the use of one or more confederates in either MCC or the *Aquarius* habitat, as these individuals would need to implement the interruption assigned for that EVA while other crewmembers remain unaware of when in the mission or what type of interruptive events will occur; the use of such a experimental confederate can be counterbalanced across the EVA days by alternating the staging of communication related errors (for instance, imposing a read-back error or requesting the repetition of a set of instructions) for half the missions by MCC and the other half by the habitat crew. This way, strategies for coping with interruption could be independently assessed for both MCC and aquanauts.

Figure 11. Potential classification system for categorizing types of interruptive events for future investigations of EVA operations under communication delay.

	Cause of Interruption	*Result of Interruption*
Type 1	Needed information inaudible or misheard	Results in request for repeat of information
Type 2	Needed information unclear	Results in request for message clarification
Type 3	Needed information unavailable	Results in idle time until information arrives
Type 4	Inaccurate information received	Results in execution of incorrect tasks until corrected information arrives (i.e. continuation of preplanned activity until replanning information transmitted)

Future investigations should also consider the ordering of tasks by complexity categories. That is to say, 'high complexity' and 'low complexity' tasks should be intermixed and equally distributed across sites to minimize the loading of carry-over effects. Sites should also be consistent in terms of number of tasks performed, so that differences attributable to the requirements at the sites themselves do not significantly impact upon performance measurements.

One additional recommendation for follow-up work would be to investigate the effects of communication delays on mission replanning. Such research could also explore the possible interaction effects of task complexity with communication delay to assess which types of activities are more recoverable following the occurrence of communication delay related interruption, and which types of tasks present higher risk of disruption.

This could be accomplished by holding constant the amount of time delay as well as the set of tasks, of which there would be equal numbers across 3 levels of complexity (though the sequence in which tasks are completed would be counterbalanced across the EVAs to account for any potential order or carry-over effects) while imposing a different type of interruptive event on each EVA. Such a study design would also address the need for increased trial numbers to improve statistical power; for instance, incorporating 16 distinct sampling tasks at each of 3 levels of complexity, per EVA crew member per EVA, would yield a total 288 possible trial events (assuming 3 EVAs with 2 aquanauts each) to analyze in terms of performance across complexity levels. Although an initial EVA route through a series of sites would be planned, a re-planning event triggered by MCC feedback following data collection from the initial sample site would be introduced, upon which the EVA crew would need to initiate a new exploration traverse. Recovery rate and delay impacts on replanning or mission timeline would then be tracked.

Concluding Statements

The study presented in this report has many advantages. Unlike several pervious investigations, this project directly examines the impact of a 5 min, Mars-like delay in communication on operational EVA performance in a model geological surveying task. This study was conducted in a high-fidelity spaceflight analogue environment, with astronaut participants. Although the experimental manipulation of research conditions was limited in this investigation, the present study does adequately present a validation of a relay-based communication approach for mitigating risk related to Earth-crew communication delay, and makes progress towards establishing empirical metrics for assessing EVA performance. While further work remains to be done, this study represents an initial step in the elucidation of an important operational consideration for the success of future manned missions beyond low-Earth orbit.

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APPENDIX A.

Breakdown of EVA performance by expedition day and individual aquanaut.

Mission Day	Crewmember	Total Number of Landmarks Surveyed	Number of High Complexity Tasks Completed	Number of Low Complexity Tasks Completed	Total Number of Interruptive Events Experienced	Average Time per Landmark for High Complexity Tasks	Average Time per Landmark for Low Complexity Tasks
3	A	10	13	10	1	190 s	62 s
3	B	10	13	10	2	232 s	62 s
4	A	10	13	10	2	208 s	48 s
4	C	10	13	10	3	231 s	65 s
5	B	12	16	12	0	174 s	100 s
5	D	4	8	4	2	379 s	255 s