

Human-in-the-Loop Operations over Time Delay: NASA Analog Missions Lessons Learned

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Teams at NASA have conducted studies of time-delayed communications as it effects human exploration. In October 2012, the Advanced Exploration Systems (AES) Analog Missions project conducted a Technical Interchange Meeting (TIM) with the primary stakeholders to share information and experiences of studying time delay, to build a coherent picture of how studies are covering the problem domain, and to determine possible forward plans (including how to best communicate study results and lessons learned, how to inform future studies and mission plans, and how to drive potential development efforts). This initial meeting's participants included personnel from multiple NASA centers (HQ, JSC, KSC, ARC, and JPL), academia, and ESA. It included all of the known studies, analog missions, and tests of time delayed communications dating back to the Apollo missions including NASA Extreme Environment Mission Operations (NEEMO), Desert Research and Technology Studies (DRATS/RATS), International Space Station Test-bed for Analog Research (ISTAR), Pavilion Lake Research Project (PLRP), Mars 520, JPL Mars Orbiters/Rovers, Advanced Mission Operations (AMO), Devon Island analog missions, and Apollo experiences. Additionally, the meeting attempted to capture all of the various functional perspectives via presentations by disciplines including mission operations (flight director and mission planning), communications, crew, Capcom, Extra-Vehicular Activity (EVA), Behavioral Health and Performance (BHP), Medical/Surgeon, Science, Education and Public Outreach (EPO), and data management. The paper summarizes the descriptions and results from each of the activities discussed at the TIM and includes several recommendations captured in the meeting for dealing with time delay in human exploration along with recommendations for future development and studies to address this issue.

I. Introduction

THIS is a summary compilation of the materials presented at the TIM. As such, much of the content of this package is directly or indirectly attributed to the presenters. The presentation materials presented are available on the Internet at:

https://oasis.jsc.nasa.gov/projects/advdev/analogs/Delay_TIM/default.aspx

Attendees are listed below with presenters noted. Also, each of the presentation packages (available on the website listed above) is referenced with their authors at the end of this paper.

Andrew Abercromby (Presenter) – JSC – Representing EAMD

Mathias Basner (Presenter) – University of Pennsylvania Perelman School of Medicine -Representing the Mars 520 Analog Mission

David Coan (Presenter) - JSC – Representing the EVA Community

David Dinges (Presenter) – University of Pennsylvania Perelman School of Medicine - Representing the Mars 520 Analog Mission

Benjamin Douglas (Presenter) – ESA – Representing the Medical Community

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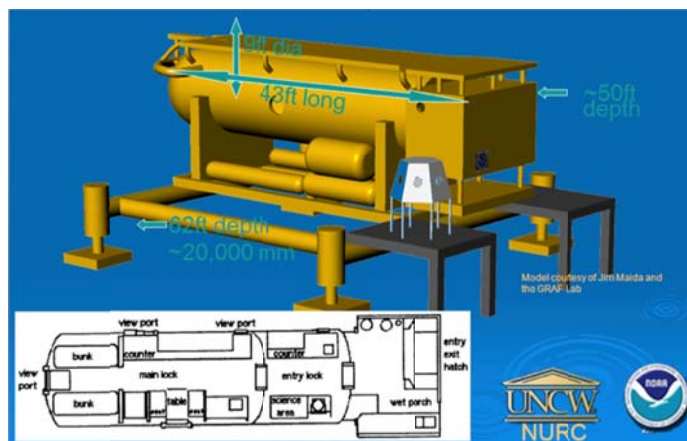
Michael Downs (Presenter) – KSC – Representing the Communications Community
 Dean Eppler (Presenter) – JSC – Representing the Science Community
 Jeremy Frank (Presenter) – ARC – Representing the Advanced Mission Operations (AMO) Project.
 Steve Gibson (Presenter) – JSC – Representing Mission Operations Planning
 Stephen Hoffman (Presenter) – JSC – Representing Antarctic Analog (and historic) Missions
 Barbara Janoiko – JSC – Representing the AES Analogs Office & TIM organizer
 James Johnson (Presenter) – JSC – Representing the Desert RATS Analog Missions & TIM organizer
 Young Lee (Presenter) – JPL – Representing JPL and Mars Rover Missions
 Lauren Leveton (Presenter) – JSC – Representing the Behavioral Health and Performance Community
 Darlene Lim (Presenter) – ARC – Representing Pavilion Lakes Research Project
 Stan Love (Presenter) – JSC – Representing the Astronaut Community & TIM organizer
 Richard McGinnis – NASA HQ – Representing HQ Analog Leadership
 Andrew Mishkin – JPL – Representing JPL and Mars Rover Missions
 Frank Morino (Presenter) – JSC – Representing ISTAR
 Michele Parker – JSC – Representing the AES Analogs Office & TIM organizer
 Steve Rader (Presenter) – JSC – TIM Organizer/Facilitator
 Marc Reagan (Presenter) – JSC – Representing the NEEMO Analog Missions & TIM organizer
 Michael Rodriggs – JSC – Representing ISTAR
 William Todd – JSC – Representing the NEEMO Analog Missions
 Sharada Vitalpur – JSC – Representing JSC Engineering
 Wendy Watkins (Presenter) – JSC – Representing the Education & Public Outreach Community
 Nick Winski (Presenter) – JSC – Representing Mission Operations Planning

II. Summaries of Analog Mission Presentations

The following section provides brief summaries of each of the presentations for analog missions provided. These missions include NASA Extreme Environment Mission Operations (NEEMO), Desert Research and Technology Studies (DRATS/RATS), Exploration Analogs and Mission Development (EAMD), International Space Station Test-bed for Analog Research (ISTAR), Pavilion Lake Research Project (PLRP), JPL Mars Orbiters/Rovers, Mars 520, Autonomous Mission Operations (AMO), Devon Island Analog Missions, and Apollo experiences.

A. NASA Extreme Environment Mission Operations (NEEMO)

Marc Reagan and William Todd from NASA's Johnson Space Center presented an overview of the time delays studies that have been performed as part of the various NEEMO missions. NEEMO missions were performed in an undersea habitat (NOAA's Aquarius facility located off the coast of Key West, Florida). These undersea missions provide an analog extreme environment to space including



reduced gravity simulated EVAs, isolated living in a facility similar in size to space habitats, dependency on life support systems, and realistic missions with timelines, objectives, and science.

To date, NEEMO has executed 16 safe and successful missions. Of those, NEEMO missions 7, 9, 13, 14, and 16 all studied the effects of time delay on the ability to perform the mission. All missions included a crew of 6 (4 NASA and 2 NOAA Undersea Research Center or NURC support crew) and lasted between 10 – 18 days. These missions studied a number of space operations techniques, tools, and scenarios in addition to the effects of time delay.

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NEEMO missions 7 and 9 objectives focused on exploration concepts for tracking, navigation, etc. It's time delay studies focused

on tele-robotic and tele-mentoring operations. A time delay of 0 – 2 seconds (One way light time or OWLT) was used for robotic controls testing, but not for nominal crew operations. High-level results from these missions showed that successful tele-surgery is not possible with a time delay of greater than approximately one second.

NEEMO mission 13 was a 10-day mission designed specifically to address how to operate when the crew is “autonomous.” The crew operated in “crew autonomous” mode for 5 continuous days where operations were designed to minimize ground team resources (vice maximize crew productivity). This mission included real-time voice, email and data communications with crew/ground conferences held in the mornings and evenings. During the “crew autonomous” days (mission days 5 – 9), the operations were modified to include a 20-minute communications delay (OWLT). The team replaced crew/ground conferences with exchanging daily reports and voice communications was not used operationally (limited to use only if autonomy test failed or aborted). The summary findings from NEEMO 13 were:

- 1) Simple information should be transferred via a simple method (e.g. text) so as to require less bandwidth and a reduced chance of a “nuanced interpretation.”
- 2) Voice and video clips can be very powerful (for better or worse) in that they are very effective for transferring technical or schedule information, but they can be distracting and are packed with psychological meaning.
- 3) Caution should be used with psychological messages being sent to the crew and possible effects to crew moral.

NEEMO mission 14 was a 14-day mission designed to address lunar exploration concepts. The time delay studies focused on a mars delay of 20 minutes (OWLT) where communications was limited to twice a day. Half of the mission was executed with no time delay and half of the mission was executed with the time delay. Mission objectives included evaluating advanced space suit designs, lunar exploration activities, life science experiments, and investigation of crew autonomy operations concepts. The results of the time delay studies were:

- 1) Over 340 exploration tasks were performed and measured in both the real-time and delayed environments and there was little detectable difference in the total number of tasks completed, the average time per task to complete, or the total time to complete all tasks.
- 2) Recorded videos between crew and MCC were useful mostly for psych / morale reasons with important information being conveyed by text/email/file transfer.



Figure 2 Aquarius Habitat Actual underwater view of the facility.

NEEMO mission 16 was a 12-day mission designed to address Near-Earth Asteroid (NEA) exploration concepts including evaluations of NEA exploration tools and techniques and a habitability study. This mission included the most comprehensive communications latency investigation for a multi-day human spaceflight mission to date. It included a full spectrum of communications times including voice, video downlink, video conference, text, file transfer, etc. and full scope of purposes including operations, medical, psychological support, and public outreach. The mission time delay studies focused on a NEA mission time delay of 50 seconds (OWLT) with continuous communications coverage. The emulator accurately delayed voice, text messaging, and video streams (however file transfer was not modeled and assumed not relevant at 50 seconds). This mission also conducted two simulated emergency events with 5 and 10 minutes OWLT delays. Summary findings from the time delay studies were:

- 1) Both voice and text messaging were useful and complimentary (with texting the preferred method for non-time critical communications).
- 2) Communications tools need significant enhancements to be operational robust in a delayed environment (i.e. voice recording/playback, visual audio alerts of incoming texts, etc.)
- 3) While it sometimes degraded capabilities, all nominal activities were able to be accomplished with a 50 second latency
- 4) During simulated emergency events, communications between the ground and crew significantly broke down (both for 5 and 10 minute latencies). This illustrated the need for better tools to help cope

operationally and the boundary condition (tools and techniques that allow good communications in emergency situations will also be robust enough to facilitate normal operations).

Based on the time delay studies to date using NEEMO missions, there are a couple of overarching observations:

- 1) Both texting and voice tools have significant enough ops limitations that it is premature to draw concrete conclusions on the utility of voice vs. text with this time delay. This seems that operators naturally move to the tool that's less limiting for the situation, instead of the capability that's more enabling.
- 2) Emergency cases proved the need for off-nominal simulations to really understand the best methods for human space flight communications delays. This emphasized that emulators are required (and need to be upgraded) and that some kind of operational mitigation tool needs to be developed to keep track of all the myriad, disconnected inputs associated with a complicated case.



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B. Desert Research and Technology Studies (DRATS/RATS)

James Johnson from NASA's Johnson Space Center presented an overview of the time delays studies that have been performed as part of the various DRATS/RATS missions. Desert RATS analogs were initiated in 1997 with a 4-member team travelling to Death Valley, California to assess shirtsleeve mobility and field-geology tasks. DRATS has since grown to a team of over 100 individuals involved in assessing technologies, mission architectures, and operational concepts in an integrated setting. The team most recently completed its 15th year of testing. Most testing through Fall 2011 has been completed in the high desert outside Flagstaff, Arizona, with the final year of testing occurring solely at JSC. Aspects of communications delay were investigated in DRATS 2009, 2010, 2011 and during the RATS 2012 test.



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DRATS 2009 focused primarily on assessing the habitability and human factors of the Lunar Electric Rover (LER) in support of a 14-day mission and the effects of varying communications coverage on crew productivity. This test was performed at Black Point Lava Flow in Arizona in late August through early September of 2009 with a crew of two (one astronaut and one geologist) supporting a 14-day traverse. The mission was supported by a Mobile Mission Control Center (MMCC), which provided simulated ground support through emulated space communications including voice and video.

This mission evaluated crew productivity during EVA and IVA science operations and LER operations for continuous real-time communications coverage and intermittent communications coverage. Intermittent communications was based on modeling a single highly elliptical lunar South Pole coverage relay satellite (assumed 66% coverage). However, for this test light-time delay was not emulated and unintended communications dropouts precluded meaningful comparison of modes. The communications test plan consisted of:

- 1) 1st 6 days utilized continuous communications
- 2) Next 4 days utilized intermittent communications where initial 8 hours of communications followed with 4 hours of loss-of-communications
- 3) Remaining 4 days was unspecified to allow for additional testing



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as deemed necessary by the crew (this included opportunity for the evaluation of a 20 minute one-way communications latency).

Results from these DRATS 2009 investigations were documented in the following publications:

- 1) *A Human Factors Assessment of the Lunar Electric Rover (LER) During a 14-Day Desert Trial*. H. Litaker, R. Howard, et. al.
- 2) *Desert Research and Technology Studies (DRATS) 2009: A 14-Day Evaluation of the Space Exploration Vehicle Prototype in a Lunar Analog Environment*. A. Abercromby, M. Gernhardt, H. Litaker
- 3) *Science Support Room Operations During Desert RATS 2009*. G. Lofgren, F. Horz, et. al.
- 4) *Desert RATS 2009 At-A-Glance*

DRATS 2010 primarily focused on understanding dual Space Exploration Vehicle (SEV) and Portable Utility Pallet (PUP) operations within an early lunar architecture framework. This test was again performed at Black Point Lava Flow in Arizona in late August through early September of 2010. This mission incorporated features of a Malapert-style (lunar South pole) traverse. There was a total crew of eight distributed as two 2-person crews for one week of operations each. Each 2-person crew consisted of 1 geologist & 1 astronaut/crew representative. The simulated ground operations supported on-location through the Mobile Mission Control Center (MMCC) with approximately 8 operators supporting rover operations, Capcom, communications, etc. and a full science support team of ~25-30 individuals spanning the test period.



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Communications consisted of voice (status/informational and two-way), video and data/file transfer. The key tests evaluated both a continuous communications and twice-a-day communications architecture. The architecture assumed no lunar relay satellites were available, no light-time delay (emulation), and high bandwidth for Earth-lunar communications was achieved through practiced deployment of a Portable Communications Terminal (PCT). The main drivers for evaluating the communications architecture were 1) a potentially significant cost and/or operational implications in maintaining continuous Mission Control Center (MCC) to SEV communications, and 2) a need to learn how to operate without real-time MCC support for exploration beyond the Moon.

Results from these DRATS 2010 investigations were documented in the following publications:

- 1) *Acta Astronautica: Evaluation of dual multi-mission space exploration vehicle operations during simulated planetary surface exploration*. A. Abercromby, M. Gernhardt, J. Jadwick
- 2) *Human Factors Assessment of a Dual Rover Field Study*. H. Litaker, R. Howard
- 3) *Desert Research and Technology Studies (DRATS) Field Test Report 2010. CA/Director Flight Crew Operations*



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D-RATS 2011 focused on the evaluation of multiple near-Earth asteroid (NEA) operations concepts to evaluate exploration productivity in relation to 0, 1, and 2 multi-mission SEV's (MMSEV) and to identify crew roles and distribution among exploration elements. For this test, roving traverses were replaced with more localized traverses at NEA-like translation speeds. This test was also performed at Black Point Lava Flow, Arizona in late August through early September of 2011. This nine-day test included a total crew of eight distributed as two 4-person crews rotated throughout the test. Each 4-person crew consisted of both geologists and astronauts. The simulated ground operations supported remotely at Johnson Space Center (JSC) using the Remote Mission Control Center (RMCC) with approximately 19 operators supporting rover operations, Capcom, communications, science, etc.

Communications consisted of voice (status/informational and two-way), text, video and data/file transfer. The test was the first thorough exercise of a NEA-like communications latency (50 second one-way light time) in an operational environment. It assumed constant communications coverage through models of relay satellites/use of Deep Space Habitat (DSH) resources and there was a single-day comparative evaluation conducted of a high-bandwidth vs. low-bandwidth data transmission. The mission utilized extensive use of a texting client (Pidgin/Monl) as a communications tool and also assessed robotic tele-operations over a 50 second one-way latency in comparison to tele-operations in real-time (assuming robotic control from the NEA exploration elements). For this test, operations were re-set during each test day (i.e., no strategic re-planning between crew days).



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Results from these DRATS 2011 investigations were documented in the following publications:

- 1) *GLEX Conference Desert RATS 2011: Human Exploration of Near-Earth Asteroids A. Abercromby, M. Gernhardt, S. Chappell Desert RATS 2011 At-A-Glance 7*

The mission in 2012 was renamed as simply RATS since it was performed at JSC and not in the desert. This was a two-phase test with the 1st phase assessing NEA simulation capabilities and the Gen 2A MMSEV cabin

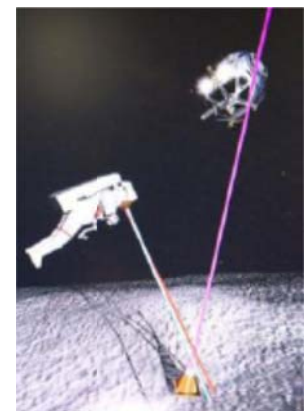


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human factors/habitability and the 2nd phase assessing the distribution of a 4-person crew among deep space exploration assets (simulated DSH workstation, MMSEV(s)) for both anchored and free flying NEA operations utilizing a high-fidelity physics based simulation. The 2nd phase also continued human factors and habitability assessment of the Gen 2A MMSEV cabin. The first phase was conducted in January of 2012 and the second phase in August 2012 for a total of 10 test days. All tests were conducted in the JSC, Building 9 High-Bay utilizing the Gen 2A MMSEV mockup with a video wall projecting the simulated NEA environment for the cockpit, the Virtual

Reality lab for EVA crew members (utilizing the same integrated simulated NEA environment), and the ARGOS artificial weightless environment simulator for EVA crew members. The mission utilized 5 crewmembers rotating roles as part of a 4-person NEA exploration crew where the crews consisted of both geologists & engineers/flight controllers. The ground operations team was located in JSC Building 30 and included approximately 5 controllers (all with mission operations experience).

Communications consisted of voice (status/informational and two-way), text, video, and file exchange (procedures, timeline updates, etc.). The test continued to evaluate the effects of a NEA-like communications latency (50 second one-way light time) in an operational environment and assumed constant communications coverage through relay satellites/use of Deep Space Habitat (DSH) resources. The team conducted a single-day evaluation of the effects of 10 minute and 20-minute one-way light time communications latencies on NEA exploration. For all delayed communications, the team continued use of the texting client Pidgin as a communications tool. For these tests (similar to DRATS 2011), operations were re-set during each test day (i.e., no strategic re-planning between crew days).



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Results from these RATS 2012 investigations were still being documented as of the TIM.

In the future, the AES Integrated Test Project may evaluate the following un-vetted, notional goals with respect to delayed communications:

- 1) Communications delay considerations for robotic tele-operations on the Lunar surface. This would examine Cis-Lunar to Lunar surface operations (~400ms round-trip) vs. Earth to Lunar surface operations (~2.6s round-trip).
- 2) Quantify the operational effects of various Cis-Lunar orbital architectures on communications coverage.
- 3) Further evaluation of communications delay mitigation tools (texting clients, message tracking, mission planning tools, etc.) in collaboration with tool developers.
- 4) Investigation of time delay effects on human spacecraft system failure response and recovery. These evaluations would be performed in close collaboration with teams investigating crew autonomy and human spacecraft system design.

C. Exploration Analogs and Mission Development (EAMD)

Andrew Abercromby from JSC provided a presentation to the TIM on the time delays studies performed across several analogs by the EAMD office. The EAMD was initiated by the Directorate Integration Office (DIO) and Lunar Surface Systems (LSS) project in March 2009 to ensure a rigorous approach and the use of consistent operational products, tools, methods and metrics across all NASA analog activities to enable iterative development, testing, analysis, and validation of evolving exploration ops concepts. Note that the EAMD presentation was extensive with a lot of excellent supporting data about the studies performed. Only a high level summary is provided here.

The hypotheses for the EAMD studies was that the crew productivity during LER mission tasks (EVA and IVA science operations and vehicle maintenance tasks) would not significantly vary among different communications scenarios which included both continuous real-time communications and intermittent communications (66% coverage, 34% no coverage based on single highly-elliptical south pole coverage relay satellite). The study gathered productivity metrics (Exploration Productivity Index) from the crewmembers and the flight control team as well as observation and data quality measurements.

For DRAT S2009 the study found that unintended communication dropouts precluded meaningful comparison of modes using Exploration Productivity Index. Decrements were measured in the mean Data Quality and Observation Quality during intermittent communications, but were not found to be practically significant.

The overall conclusions and observations of the EAMD studies were:

- 1) Communication protocols developed and tested during DRATS, PLRP and NEEMO are acceptable overall for nominal science operations. However, there needs to be better integrated communication, traverse planning, timeline, and data curation capabilities. There was also significant variability in preferences (e.g. audible alerts, when to use voice) and resulting questions about how much flexibility the software and procedures should allow.
- 2) It would be valuable to have CAPCOMs on both ends of comm delay, especially if using voice. For voice communications, the verbal pre-alert protocol developed during PLRP proved important in DRATS and NEEMO testing. The voice communications was observed to be more important from space-to-ground than ground-to-space.
- 3) The configuration where the MCC CAPCOM talked to the crew IV/CAPCOM on separate loop from SEV pilot and EV crew worked well. The MCC hears and sees all loops but nominally only talks to Crew IV/CAPCOM.
- 4) All of the text-to-space communication (email, messaging, file transfer) was judged to be very important (possibly prime) based on DRATS and NEEMO testing. This had not been possible to test at PLRP.

EAMD recommendations from these studies included:

- 1) Establish standard metrics to be used across all test environments
- 2) Develop performance benchmarks for current spacecraft operations and identify those systems and tasks that are most susceptible to comm latency based on current designs & operations (ISTAR)

- 3) Develop hi-fidelity models, test articles, and procedures for vehicle systems and use integrated testing to understand the impacts of comm latency on the design and operation of these systems during nominal and off-nominal operations (JSC Integrated Testing)
- 4) Iteratively develop and test the integrated suite of software tools and procedures necessary to conduct human exploration missions
- 5) Extend approach implemented in NEEMO 16 and RATS12 using standard metrics and questionnaires to identify, prioritize, implement, and test capabilities in operational environments
- 6) Utilize PLRP Phase 3 (and other science testing?) to evaluate these tools and procedures during real scientific exploration
- 7) Utilize JSC Integrated Testing in simulation environment to evaluate during other mission operations and contingencies

D. International Space Station Test-bed for Analog Research (ISTAR)

Frank Moreno from JSC presented an overview of the planned analog activities for the International Space Station, also referred to as ISTAR. ISTAR was initially established in 2010 to 1) facilitate the use of ISS as a test platform to reduce risks for manned missions to Exploration destinations, 2) utilize ISS as a micro-g laboratory to demonstrate technologies, operations concepts, and techniques that mitigate the risks of crewed Exploration missions, 3) utilize the ISS facility as an in-space testbed to exercise crew activities during simulations of Exploration missions to mature operational capabilities for crewed missions, 4) conduct long duration Mars Transit and Landing Transition simulations utilizing technology and operational tools & concepts developed and tested during previous ISTAR and Earth-based Analogs, and 5) strategically plan increasingly complex ISS-based exploration mission simulations.



Early in 2012, HEOMD AA challenge to conduct a Mars analog mission before 2016. To date, initial ISTAR missions starting with ISS Increment 31, by necessity, have focused on discrete exploration forward activities (e.g., Comm Delay Countermeasures, Autonomous Procedures, Tele-robotics, EVA suit microbial sampling, Anthropometric measurements, Radiation Dosimetry). Additionally, ISTAR has developed a notional ISS Mars SIM plan and begun to coordinate with AES projects to refine Simulation objectives and solicit their participation.

Additionally, the ISS Expert Working Group (IEWG) Team 6, composed of NASA (including ISTAR) and IP members, was established to study ISS-based ops simulations and technique. This team is developing a response to a Russian Space Agency (RSA) proposal to fly a Russian crewmember on ISS for 1 year and execute a Mars simulation similar to the Mars 500 ground analog. ISTAR is a major contributor in the effort to develop and execute the ISS Mars simulation plan.

Since July 2012 ISTAR has been working with HQ/Human Exploration & Operations Mission Directorate to include ISS exploration risk mitigation testing and NEA/Mars simulations as part of an executable framework for spaceflight through 2021 and a strategy for BLEO missions post 2021. ISTAR is a member of a product team responsible for developing plans to support ISS testing and simulations.

ISTAR is currently involved in efforts of exploration risk mitigation, ops techniques and SIMS, ISS exploration testing “Scorecard”, and exploration planning.

Two ISTAR autonomous crew procedures have been performed to date including: 1) IMV Flow Measurement (VelociCalc), performed by Andre Kuipers on May 17, 2012 and 2) T2 Monthly Inspection, performed by Joe Acaba on July 16, 2012. From these experiences, there were several lessons learned. 1) The crew can perform these procedures without ground interaction; crew response has been favorable, 2) Procedures took nominal time (we anticipate time will actually be saved for many autonomous procedures), 3) Several procedure writing suggestions, 4) Identified the need for a better way to input large amounts of data, 5) Pictures are good, video clips are even better, 6) Need to add more rationale for the procedure – if the crew knows why something is performed, they can better respond to unexpected conditions, 7) Ground coordination improvements, and 8) Suggestion to use automation (such as Robonaut) for repetitive tasks.

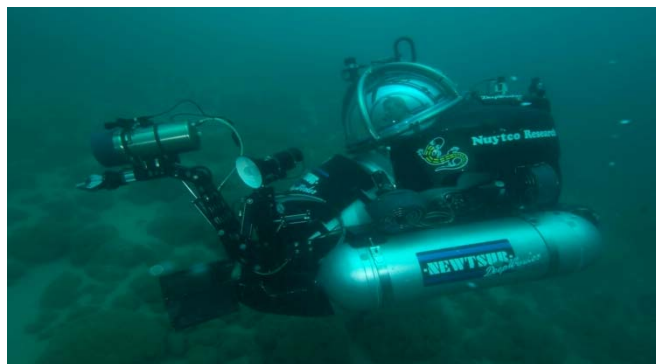


Figure 11 Deep Worker Submersible Exploring the lake bottom using delayed communications to the surface to simulate a NEA mission.

The ISTAR team forward work includes 1) Updating more procedures using the lessons learned to make them autonomous, 2) Performing more procedures, and include debrief (questionnaire), 3) Developing and using “Just In Time Training,” 3) Uplinking and using Text Messaging, the second aspect of the ISTAR-1 study, and 4) performing an HRP comm delay test is planned starting with Increments 35/36.

E. Pavilion Lake Research Project (PLRP)

Darlene Lim from ARC presented an overview of the work that has been going on with PLRP. PLRP is a multi-disciplinary science and exploration initiative with funding from NASA (MMAMA, DIO, ASTEP), CSA (CARN), Nuytco Research, NGS Science and Exploration Grant, NSERC, McMaster University, University of British Columbia. It is focused on determining what mechanisms and associated interactions control microbialite morphogenesis in Pavilion and Kelly Lakes, British Columbia, Canada examining biological, chemical, and physical mechanisms.

In 2011, PLRP operated at Kelly Lake that has been surveyed using SCUBA and was found to have similar microbialite formations to Pavilion Lake. The lake is sufficiently deep (~40 m) and large to support the deployment of the DW and the associated exploration program. This was an opportunity to apply PLRP exploration strategies beyond one site and to test their relevance on a broader scale, including in relation to NEO exploration architecture designs. PLRP 2011 utilized the SNRF communications infrastructure, which enabled real-time and Near Earth Asteroid (NEA) (50 sec one-way) delayed communications. The communications network utilized a fiber optic tether approx. 200 meters to connect the submersible to the surface control vessel. The surface vessel had a fiber optic to Ethernet converter similar to the hardware used on the Deep Worker. Two way “hardwire voice communication was available as well as real time video from the submersible’s main camera. This Ethernet data was then be broadcast wirelessly using the existing network system to the Science Back-Room.

Improved collaborative planning and tighter integration of traverse planning with a-priori science data. A web-based traverse planner was developed which supported smooth integration of a-priori map data (e.g. sonar data collected with an AUV) with an interactive planning tool. This provided the science team with essential context information to develop and annotate effective traverse plans on a very tight schedule. The web based centralized architecture of the planner provided our geographically distributed team the ability to view the most up-to-date version of a traverse plan at all times.

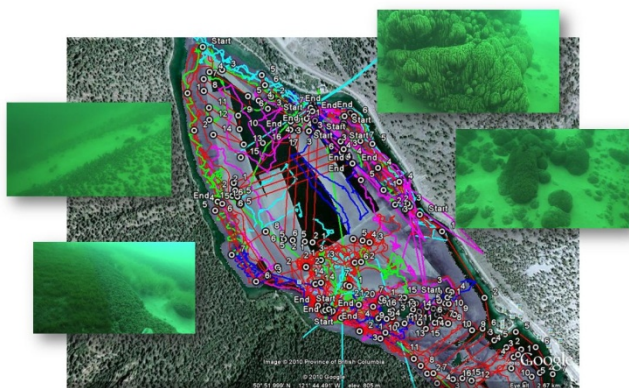


Figure 12 Tracks of the Submersible along the lake floor with images of microbialite formations.

The fiber optic and Wi-Fi connection from lake to shore allowed the Science Stenographer (SS) to be relocated from the chase boat to the Mobile Mission Command Trailer (MMCC) nearly 20 km away. This was a major operational shift for the PLRP team. While contingencies were developed to deal with Loss of Communications scenarios and the associated actions of the remotely located SS, we did not have to implement these emergency procedures given that the communications and gas

tools performed flawlessly throughout the 2011 mission. Science data from each sub flight was similarly collected without issue, and synthesized on a daily basis by the xGDS team to enable science discussion and video review on a nightly basis. This rapid turn around capability, even with the remotely located SS, enabled scientific discourse and flight replanning in response to daily discoveries.

An important finding to date is that time delayed communications did not significantly hamper the team’s scientific productivity or data return. This was enabled by the extensive training of the SP, surface support crew and SBT during the pre-mission phase, and by a reliable communications infrastructure and our xGDS data integration support tool. In some cases, the DQ increased during NEA communications mode. However, the Observational Quality did not waiver significantly between NEA and real time communications.

Results from these PLRP investigations were documented in the following publications:

- 1) *A Historical Overview of the Pavilion Lake Research Project – Analog Science and Exploration in an Underwater Environment*, Lim, D.S.S., Brady, A.L. and PLRP Research Team, GSA Special Paper: Analogs for Planetary Exploration. 2011
- 2) *PLRP Geobiology Special Issue due out Spring 2013*

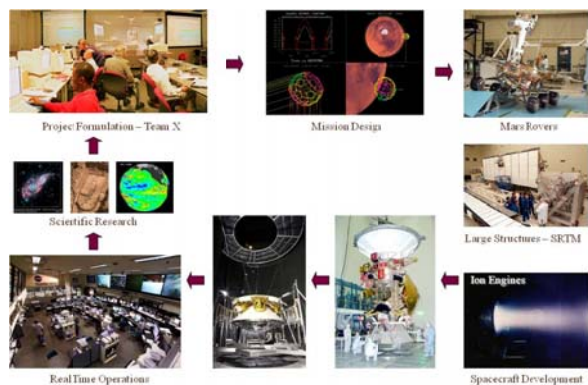
F. JPL Mars Orbiters/Rovers

Young Lee and Andy Mishkin (online) from JPL presented an overview of time-delayed operations for some of the JPL robotic planetary missions. The team identified several shared objectives between the robotic and human exploration missions including 1) enable safe, affordable, and compelling human-robotic space missions beyond LEO, 2) explore how to best address human-robotic deep-space mission operations challenges using a systems engineering approach, 3) leverage to the maximum extent the lessons-learned, tools, and processes developed to meet the challenge of communications time delay, and 4) identify joint efforts that will combine the strengths of NASA built up over many decades of human space flight and deep-space robotic science missions.

JPL emphasizes an end-to-end capabilities approach needed to implement missions, which includes a cycle of project formulation (Team-X), mission design, systems development (rovers, large structures/SRTM, and spacecraft development i.e. ion engines), integration and test, environmental test, real-time operations, and scientific research. This cycle then feeds back into the project formulation for the next mission.

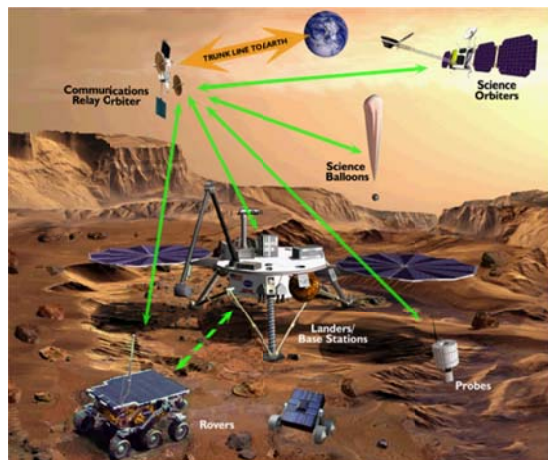
Currently, JPL is operating 24 active spacecraft and 10 Instruments across the Solar System and beyond, all via time delayed control. Some of the typical characteristics of these missions include flight systems that are highly automated with ground-built sequences that last for many weeks. These allow the flight systems to be self-sufficient for two weeks following any failure and always provide for fail safe in cruise. The flight systems are designed to be fault tolerant during critical events along with system fault management and GN&C assurance. Their ground systems are typically uplink-driven with a labor-intensive science

planning process. This includes automated rule enforcement, health and safety assessment, performance analysis, and out-of-bounds data flagging and notification.



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The primary enablers of time-delayed operations include 1) Sequencing capabilities which are event-driven or time-tagged execution of command sequences, 2) Fault Protection where the fault monitors are distributed throughout FSW, near source of item to be monitored. These local level responses are distributed and applied locally. Local responses are used when the problem can be handled within the subsystem such that it is transparent to the overall system. If local response does not solve the problem, system level response may be declared. System level responses are used if a coordinated response is necessary or if the response crosses multiple subsystems. 3) Device redundancy that is hardware redundancy that is managed by fault protection. This utilizes cold backups primarily and hot backups (active redundancy) for specific, time-critical events (i.e. Entry, Descent, and Landing or EDL). 4) Rover autonomy provides “Blind” drive and hazard avoidance capabilities and 5) Ground test and verification of all activities which includes hardware testbeds, software simulators (WSTS), and software tools for mobility planning/visualization (RSVP).



Architecture
and links used

The presentation provided significant detail on the methods and processes for planning and executing various types of deep space missions. Recommendations for human exploration beyond low-earth orbit included recommendations on fault management, automated GN&C/deep space navigation, and possible spacecraft impacts.

Some of the key challenges for providing fault management during crewed missions are that the presence of crew increases the set of concerns that must be managed in the presence of failures. This increased number of concerns increases the complexity of maintaining health safety during

nominal mission activities, and increases the complexity of attaining a “safe state” and remaining in this state for long periods. Current (unmanned robotic mission) fail-safe strategy allows for “pause” of mission activities and you have the luxury of long periods of time to diagnose/recover from problems without additional worries about S/C health (presume long “time to criticality”). However, the presence of crew puts additional time pressure on the diagnosis/recovery loop; additional health/safety concerns from crew may drive shorter time-to-criticality durations. But presence of crew also allows for on-site observations, troubleshooting (monitoring of equipment status) and repair; all of which can improve the rate at which diagnosis and recovery is performed. Limited ground contact may require transfer of fault management responsibilities from ground to flight system/crew. With the detect-diagnose-plan-respond (e.g., OODA loop), primary consideration will be time-to-criticality, but other factors may also contribute (efficiency, cost, resources, etc.). Additionally, ground contact may be shorter/less frequent, with lower data rates.

Human-rating requirements, that require multiple failure tolerance, dramatically increase the failure space that must be covered by a fault management solution. Current JPL spacecraft must be able to safe in the presence of any given single failure whereas human-rated spacecraft must keep the crew safe in the presence of any two failures. The implication is a much larger set of conditions that must be addressed, both by design/analysis, and operations procedures. The definition of crew controls for on-board fault management will require careful allocation of function between crew and flight system, and ability for crew to override or halt autonomous action.

The navigation for a deep space crewed mission might not be able to depend solely upon Earth-based radio-metrics (in comparison with Apollo era navigation). NASA has fewer tracking stations now than in the Apollo era, and the ranges will be much greater (reducing accuracy). If the next mission is to an asteroid, we generally will have a poor idea of where that asteroid is (unlike the Moon whose orbit is well determined). Unlike returning from the Moon, plotting a return course from 0.75 au range to Earth will not be possible with slide rules and view-port reticle measurements. A crewed flight to a NEO will likely utilize electric propulsion – requiring constant controlled guidance of the engines to achieve a fuel-optimal delivery of several km/s over many weeks – this cannot easily be managed by manual control. A ground/flight interface will be much more complex than what could be accomplished over a back-up voice link – there will be many Mb of data that need to be transmitted.

How Might these Differences Affect the Spacecraft? The spacecraft will likely have to have optical navigation in order to have target-relative navigation capability. Because manual navigation won’t be possible, a fully automated trajectory planning and navigation system will likely be required in order to insure safe return if com-links are compromised, and because the system will be too complex to have “cook-book” style manual procedures. Low-thrust (e.g. SEP) trajectory design requires highly compute-intensive non-linear path-planning operations. These trajectory design methods will have to be onboard at some level, for crew safety, with a high degree of automation. High interface-bandwidth requirements imply a high degree of automation and processing capability onboard to cope with a com-link degradation. (Anything the ground might have to do to support the navigation system, the s/c would have to do on its own in contingency situations)

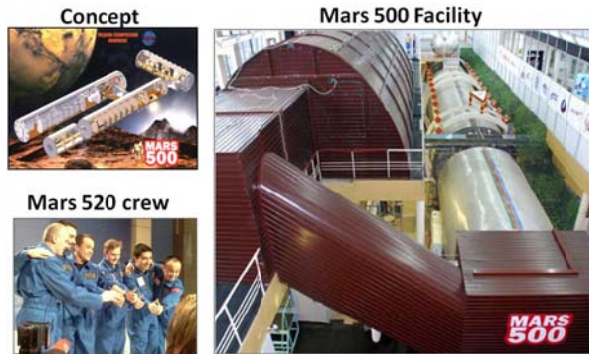
Additionally, there are likely to be other operational challenges to consider including:

- 1) Operations approach and implementation strategy for affordable and reliable crewed missions.
- 2) Complex on-board systems management including ECLSS, Navigation, Propulsion, Power etc.
- 3) Optimum level of automation and autonomy
- 4) Work allocation between crew and robotic systems
- 5) On-board information systems to maximum crew and mission safety
- 6) Shared responsibilities between flight and ground
- 7) Mission planning (strategic, tactical and short term)
- 8) On-board resource management
- 9) Crew activity planning and on-board schedule management
- 10) Mission control addressing response time and situational awareness needs

G. Mars 520

David F. Dinges, PhD and Mathias Basner, MD, PhD, MSc from the University of Pennsylvania Perelman School of Medicine presented a summary of the time delay studies that were conducted as part of the Russian lead Mars 520 analog mission (also referred to as the Long Duration Russian Chamber Study or Mars 520). In this

mission, a crew of 6 spent 520 days in a Mars mission simulation, which was the longest simulation, executed to date. By comparison, a total of 4 people spent more than 1 year in space, with the record of 437 consecutive days on the Mir space station set by Valery Polyakov. The longest Earth-based spaceflight simulation involved 4 Russians confined in connected hyperbaric chambers for 240 consecutive days. Antarctic winter-over missions have extended up to 363 days.



Ecological validity of the Mars 520-day mission simulation was based on a number of mission attributes including: 1) a multinational crew of healthy volunteers demographically similar to spacefarers. 2) 520 consecutive days of confinement in a pressurized facility with a volume and configuration comparable to a spacecraft with interconnected habitable modules. 3) A facility equipped with life support systems and an artificial atmospheric environment. 4) Activities simulated ISS with daily maintenance work, scientific experiments, and exercise. 5) Isolation from Earth's daily environmental light-dark

to cycles, temperatures, and seasons. 6) Realistic Mars flight simulation under the direction of mission controllers. 7)

Work throughout the mission included both routine and simulated emergency events. 8) Realistic changes in communication modes and time delays in transit to and from Mars. 9) Limited consumable resources (food and water), and 10) a crew that was aware of publicity and media attention regarding the mission. Note that simulation did not include microgravity, radiation, risk to life, or excitement of major discovery.

For communications, interfaces were restricted to be between the crew and mission control center with no direct outside communication. During the initial 8-Weeks, real-time communication was used with 30 minutes of communications coverage assumed every 1.5 hours during daytime. On week 9, time delay was introduced with the length of delay was dependent on the distance between the simulated spacecraft and earth. Written or pre-recorded (audio or video) hours.

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was sent to crew during a 2 hour window twice every 24 Messages sent from crew had no restriction. For the landing, there was a 3 person orbital crew and a 3 person Communication between orbiter and lander limited by communication satellite visibility. During the final 1.5 time communication was used with coverage of 30 1.5 hours during daytime.

al. concluded that personal communication (PC) was a coping with an isolated environment. However there variation in PC among the crewmembers. European had 6-8 times more personal communication than crewmembers. The Chinese crewmember received half communication as European crewmembers, but sent the average European crewmember. The main method personal communication varied with written preferred by Europeans and Russians and audio and communication preferred by Chinese. There were to special events (holidays, birthdays, etc.) and a sudden

months ("monotony phase") then stable (or slight Additionally, the presentation included very interesting volume on data exchanged and the communications used

H. Autonomous Mission Operations (AMO)

Jeremy Frank from AMO presented an overview of the Autonomous Mission Operations (AMO) Project. The goal of AMO experiments was to answer the following question: What aspects of mission operation responsibilities should be allocated to ground based or vehicle based planning,



monitoring, and control in the presence of significant light-time delay between the vehicle and the Earth? To answer the question the team: Constructed a 2 hour quiescent mission timeline; Inserted various unexpected events (systems failures, crew medical emergency) into the timeline; Varied the time delay (low, 50 second, 300 second one-way light-time delay); Varied crew responsibility, communications and support tools (baseline: ISS-like; mitigation: crew autonomy); Analyzed task completion, communications, crew workload, and team coordination for both flight controllers and crew.

For the mission operations simulation, the systems failures included an EPS failure (power converter failure), a fluid transfer failure (valve stuck open), and the fault isolation procedures and workarounds required in both cases. For the crew medical emergencies, the team simulated a urinary retention issue, a kidney stone, and an ultrasound diagnosis required in both cases. The experiment design included utilization of the Deep Space Habitat (DSH), which served as the analog spacecraft with one astronaut serving as CDR and three MOD flight controllers/trainers (one of whom is Chief Medical Officer). Additionally, certified Flight Controllers and Flight Directors staffed the Flight Control Team located in the Operations Technology Facility (OTF) within JSC's Mission Control Center (MCC) complex. For the experiment, there were 4 distinct crews; each crew has one astronaut who was commander. Each crew was set to experience every long (50 and 300 second) time delay and each crew experiences every scenario variation. Not all combinations of time delay and scenario variation were evaluated and each crew experienced the same combination of time delay / scenario in both Baseline and Mitigation configurations.



Figure 17 Deep Space Habitat prototype used in the AMO project simulation
Shown with inflatable upper section provided by a university as the winners of a competition of inflatable habitat designs.

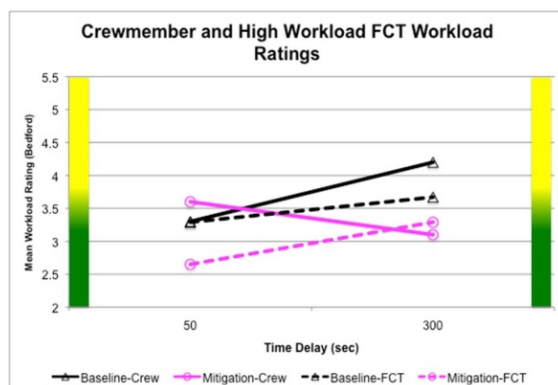


Figure 18 Workload Ratings Results from workload ratings for 50 and 300 second time delays.

questionnaires which were given to participants after each 2 hour run and after participants completed all runs. The ratings used were both the Bedford (Workload Rating – an anchored 10 point scale) and Likert (Coordination Difficulty Rating – a 5 point scale). Additionally, flight controller and crew comments were captured with explanations of ratings, assessment of simulation fidelity, and value of mitigation tools. The objective measurements provided empirical measures of performance. They included recording the number of tasks completed and the number and type of communications acts (voice activation, text messages, etc).

The resulting data was analyzed simulation fidelity, workload, coordination, task completion, and communications analysis. The package presented provides an in depth look at this analysis (highly recommended).

The conclusions from the AMO project were as follows.

- 1) The experiment was a medium fidelity simulation of space mission operations.

The experiment examined both baseline and mitigation methods to perform 4 main operations functions affected by time delay including communications, fault management, procedure format, and situational awareness. The baseline methods for providing these functions were voice, limit checking, PDF file format, and voice respectively. For time delay mitigation, a combination of voice and text messaging was used for communications, advanced caution and warning software was used for fault management, electronic procedures were used for procedure format, and a combination of voice and electronic procedures was used for situational awareness.

The experiment used both subjective and objective measurements to capture the differences in performance. The subjective measurements were captured by using

2) Workload and coordination difficulty increased with time delay.

3) Workload and coordination difficulty were reduced by the mitigation configuration.

4) Communications decreased in mitigation configuration; the decrease was larger at longer time delay.

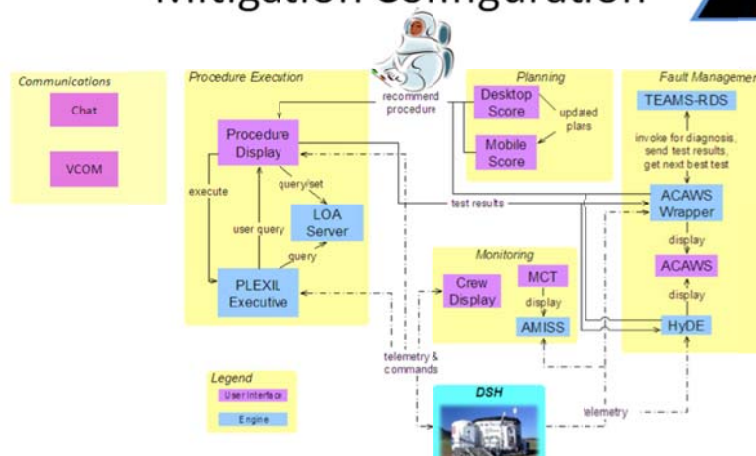
5) Flight controller workload and coordination responded differently to time delay and configuration variations than crew workload and coordination.

6) Communications patterns were influenced by the mitigation configuration.

7) Note workload is between satisfactory and unsatisfactory for medium fidelity simulation and quiescent flight phase operations

8) Reasonable to assume that implications of time delay for real spacecraft, serious failures, more difficult mission phases are more profound

Mitigation Configuration



Is used

In the future, the AMO project plans to examine some of the outstanding questions raised by the initial experiment. The reasons for less communication are still murky (is it due to shared procedure execution or tools? What happens when the crew is given autonomy but no tools? Would results change using higher fidelity simulations (such as SSTF, ISS failure cases)? If so, the team might be able to better assess task completion, refine assessments of workload and coordination. Is time delay of 50 seconds really acceptable (Analysis of activities at cis-Lunar time delays with high fidelity)? Is there more analysis of audio transcripts and chat possible to characterize communications more deeply? There were also many tools recommendations, including: Better interoperability between tools (e.g. cut-copy-paste, WebPD-Score notifications); Score Marcus-Bains line indicating time delay; MobileScore horizontal instead of vertical layout; WebPD flexibility to skip, undo procedure steps, goto step, clear completed procedures; Audibles in Pidgin to announce incoming messages.

I. Devon Island Analog Missions

Steve Hoffman from JSC presented a presentation titled "Polar Analogs Incorporating Time Delay and Other Related Examples." The presentation covered a brief summary of the Devon Island analog activities. Devon Island is located above the Arctic Circle and includes Haughton Crater, which provided an excellent analog for a planetary surface. This area included surface features such as impact/shocked rocks, impact ejecta, and hydrothermal vents. Additionally, this area provided a rich set of science opportunities including microbial extremophiles. These missions were carried out from 1999 through 2001 with recon and wrap-up activities spanning from 1997 through 2002. Activities at the outpost included: EVA traverse simulation; Airborne reconnaissance simulation; Site hazard; Interaction between simulated EVA, IVA and MCC; EVA safe haven; CBT/Just-In-Time training; Techniques for Earth-Mars voice/data delays; Traverse planning (including "science back-room" support). The Devon Island operations objectives included evaluation of planning/status/concepts (like development of non-synchronous communications



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techniques, tracking reported accidents or incidents, etc.), consumable tracking, logging training/CBT effectiveness, and unlinking useful information.



outposts built

For communications, the mission utilized both C-band and Ka-band links with data rates initially limited to 56/250 Kbps, but getting up to 2 Mbps later in the mission. The mission utilized a 20 minutes one-way delay (with some instances of shorter delay used to understand the time-delay effect).

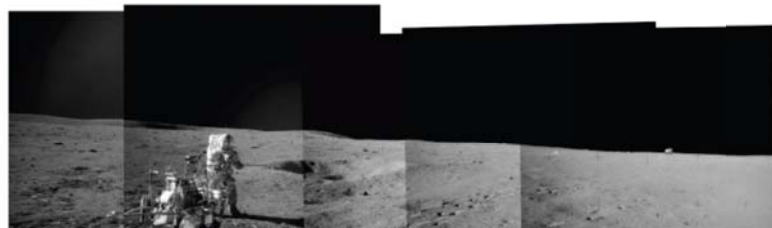
Overall, the missions gained experience with time delayed operations, long traverse planning and execution, and work with autonomous and semi-autonomous rovers.

Additionally, Hoffman presented materials

about historical polar region analogs from the Antarctic Explorers Workshop (NASA/TP-2002-210778) and Antarctic Traverses Workshop (NASA/CP-2012-217355). Finally, Hoffman provided an overview of the Antarctic Search for Meteorites (ANSMET) that has included 6 excursions by several NASA scientists and astronauts between 2000 and 2013.

J. Apollo experiences

Dean Eppler from JSC presented a briefing, “Apollo Program Lessons Learned for Comm Delay Considerations.” The briefing covered Apollo missions 8, 10-17. Each mission included 3 crew with 1 in orbit and 2 on surface (except Apollo 8), which occurred at irregular intervals



between December 1968-December 1972. The missions each lasted between 8-12 days (Apollo 8: 7d 3h; Apollo 17: 12d 14h) with a real communications time delay of ≈ 2.5 seconds round trip. The mission included surface science operations for up to 3 days on the lunar surface at a variety of landing sites. The Apollo Program landed six missions on the lunar surface after a preparatory series of missions to Earth orbit and lunar orbit. These included: Apollo 1 - first planned mission lost when a fire destroyed the spacecraft and killed the prime crew prior to launch; Apollo 2-6 - unmanned flights testing various pieces of Apollo hardware; Apollo 7 - low Earth orbit (LEO), check of Command/Service Module (CSM) system; Apollo 8 - first lunar orbital mission, CSM only; undertaken when the LM was behind schedule; Apollo 9 - checkout of CSM/LM stack in low Earth orbit; Apollo 10 - dress rehearsal for landing - CSM/LM stack testing in lunar orbit, including descent orbit insertion and rendezvous in lunar orbit. All the landing sites were on the front side, largely in the equatorial region.

There were several lessons for communications delay. The minimal communications delay (1.25 seconds OWLT) was still long enough that the ground cannot effectively provide “overwatch” for short time-scale, unfolding disasters. This was evident during the landing phases of each mission, where the MOCR front room at JSC was largely in an observe mode during each landing. Once the crew entered the Powered Descent Phase, the MOCR largely gave them status calls (e.g., time to fuel exhaustion), not directions on what to do next. Another good example is the torn-out heat flow cable on Apollo 16 – the LRV camera clearly showed the problem unfolding, but there wasn’t enough time to inform John Young to stop. Consequently, the CAPCOM is in, at best, an advisory role. We realized this on Apollo, and the surface CAPCOMs functioned largely as observers, encouragers and information sources for the crew, not in the “Mother-May-I” role as many think.

Extensive, exhaustive crew training is a critical component. This is a corollary to the first lesson – if the crew is well trained, then their interaction with the ground will be more of an inquiry/advisory-based interaction. This goes for both the dynamic phases of the mission as well as the surface operations. Hardware design needs to be robust, so the crew doesn’t need to depend on the ground for a more active role. An unfortunate fact from the Heat Flow

Cable damage is that John Young identified this as a problem prior to the mission, but he was ignored. After the cable was broken, Bendix made sure that the re-design and fix was completed in time for Apollo 17.

III. Summary Discipline Specific Perspective Presentations

The second day of the TIM focused on the discipline perspectives. These included a communications, Data management perspective, mission operations, flight crew, Capcom, EVA, behavioral health and performance (BHP), medical/surgeon, science, and education and public outreach (EPO)/public affairs office (PAO).

A. Communications Perspective

The second day of the TIM focused on the discipline perspectives. The first presenter of the day was Michael Downs from KSC. The communications presentation provided an overview of the communications tools and techniques used supporting multiple analog missions including NEEMO, Desert RATS, PLRP, ISRU, AMO, and the DSH Standalone test. It covered the tools of the trade with time-delayed communications (“what’s under the hood”). The communications systems utilize a mix of true operational systems, as well as hybrid systems that enable the simulation / test. Experience has shown a mix of functional flight like systems, and “faking it” by various groups. This has been effective since the real concern is about what is learned from operating under time delay. To date, what has been learned IS DRIVING the architecture of what will be flight systems.

There are several tools utilized for simulating and dealing with time delay. For data (telemetry/packet delay), a network-layer delay emulator enables test setup, development, and configuration and provides developers with a suite of powerful yet flexible capabilities to accurately emulate a variety of conditions of time delay, bandwidth, packet loss and jitter. Combined with the SNRF backbone, enables testing of a variety of network frameworks. The need for real-time AND delayed voice, video, and data communications for simulation supervision, or other operational needs required a unique setup. Voice was the easiest to delay (data stream, no controls). The team performed some extra work integrating delay system directly into voice system. For texting, the team started with a simple design for emulation of a delayed chat room and then transformed into a flight like architecture with a Disruption/Delay Tolerant Networking (DTN) tolerant open source system. Video is the hardest to delay. The sizes of the data, as well as TCP controls in current COTS products become the problem. DTN has enabled high definition cameras in work. For file/data transfer & management DTN was used along with a user GUI and data prioritization are highest priorities.

The analog delay emulator system is in use today in six locations across NASA for HEOMD/SMD Analog mission testing. Use of this system is more than just using a box, it’s becoming part of a team learning to operate human and robotic missions over delay. Knowledge is being shared across the “delay testing.” The system imposed deep space-link delays. Long deep space delays can be imposed, only limited by the size of the drive in the unit, and the “bandwidth delay product” For packet loss, the unit can impose packet losses similar to those that might be anticipated during a deep space mission. The unit can also restrict the total amount of bandwidth traversing the system, to provide a high-fidelity experience for users

learning to communicate over a data-constrained deep-space communications link. Jitter is configurable with this system. Additionally, packet duplication, corruption and re-ordering are addressed. While this is seldom used to emulate space links, but available features to those who choose to use them (ESMD versions are set for “pure FIFO queues”.

Along with the delay emulator, the KSC team provides the space network research federation (SNRF). This network provides a way to link teams working analog missions together in an organized manner to enable cooperative and coordinated missions around the world. It provides a private, secure “network of networks” linked together in a mutually agreeable manner, to ensure rapid changes can be made in near-real time as needed, and ensure connectivity and bandwidth. The SNRF is not owned by any single organization – each segment of the SNRF is owned and managed by partners who tap into the federation. It is a combination of “bandwidth assured” terrestrial circuits, “best effort” network tunnels over the Public Internet, and wireless systems linking mobile assets (robots, people, etc.) in remote locations with space agencies, universities, and commercial partners. SNRF is



Figure 23 Communications Delay Emulator
The network delay emulator allowed the analog missions to configure the communications time delay as well as the data bandwidth and link quality.

capable of imposing a variety of deep-space mission conditions to data flows (bandwidth limits, comm delays, jitter, bit errors, etc) through the federation. This network has a data storage facilities built in, so investigators can test mission data downlink and archiving techniques during analog missions. All of this is coordinated through a single tie point, to save partner cost (1 circuit links each partner to all other partners), and to simplify network security plans for all partners. The network is growing and adding more partners every year.

The underlying requirements driving design of the SNRF is the need for a “flight-like” network that could have complete network segments seamlessly move from one node in the federation to another. This allows for year round analog testing in center labs on the actual IP networks analog projects operate on. The need to securely and efficiently route voice, video and data within the federation, with 24/7/365 instant access to firewall rules and routing tables. (Flight lockouts can cancel a field outing) The SNRF network support needed for year round testing and deployment for 5 NASA analog projects, including Desert Rats, Pavilion Lake Research Project (PLRP), NEEMO, ISRU, and ISTAR. Use of the SNRF network is now part of the NASA HQ AES (Advanced Exploration Systems) Analogs Project (Managed by JSC).

Some additional thoughts from the communications perspective are that there are capabilities and scenarios that we are NOT testing including: AOS/LOS conditions; dynamically increasing/decreasing time delay’s (simulating departure and return); and dot testing deltas between uplink and downlinks; symmetric pipes have been used which are not flight like).

B. Data Management Perspective

Steve Rader from JSC presented the data management perspective. The function of data management is to ensure data (digital) products are produced, stored, managed, and transferred throughout the end-to-end system to meet mission goals and requirements. These functions include file management (identification, meta-data tagging, storage, life cycle, version mgmt., etc.), file transfer (downlink & uplink), text chat (and other collaborative tools), video stream management (network streams, file capture/management), voice loop/stream, command and telemetry (discrete or streams), software load & configuration file management (correct versions, updates on platforms), and integration of data producers and consumers with the communications network and platform provider(s) (accounting for network behaviors such as delay, bandwidth constraints, and intermittent comm. coverage).

From all of the analog missions (and the ISS missions and Constellation Project efforts) there have been several key lessons learned.

- 1) Situational awareness and actions/responses by crew and mission control when separated by a time delayed communications link can and will diverge rapidly in dynamic situations (i.e. emergencies, quick changing circumstances...). It is important that each side must maintain an awareness of the other’s context when communicating. Pre-Determined procedures, actions, scripts are key to appropriate responses.
- 2) Mission success can be driven by smooth & efficient flow of data through the end-to-end systems. Integration and management of data products, software, and communications network it key. Time delayed communications (especially when combined with limited bandwidth and communications availability) increases the complexity of data flow.
- 3) Increased time delay in communications increases the amount of operations that the crew and onboard systems must be able to handle without ground support. Increased automation must be very robust. The ground must be able to determine what onboard crew/systems have done (to resync).

The presentation provided several proposed mitigation strategies.

- 1) Increase use of DTN protocol for all delay studies/missions/tests. This protocol is currently being developed to support deep space missions and it will be useful to test and understand the protocol.
- 2) Develop/test file management capabilities including: automated/standardized meta-data tagging; directory/file list ghosting (to facilitate manual uplink/downlink); automated data life cycle tools (tag, downlink, sub sample, delete).
- 3) Ensure adequate communications coverage and bandwidth. The limits in communications throughput ultimately drive more costly complex operations that must either operate with limited information/situational awareness, or spend a lot of resources managing priorities to determine what to downlink.

Develop crew and ground tools for delayed interpersonal communications. This includes the need to provide time-shift context information, data/voice/video record/playback tools, and auto-voice transcription functions.

C. Mission Operations Perspective

Steve Gibson, standing in for Megan Rosenbaum, presented the first of two mission operations packages. Mission operations has participated in all listed Analog Projects (NEEMO, DRATS, AMO, PLRP, ISTAR, DSH). Most of these analogs tested some aspect of communications delay. For each of these tests has provided crew support in developing mission timelines, and other support products such as the Daily Plan Report (DPR). The team has used next generation planning systems (Score, Mobile Score, Playbook) for developing and displaying crew mission timelines. Additionally, the team used instant messaging client (Pidgin) for communications delay countermeasure. Lessons learned will be applied to future ISTAR testing. Lessons learned based on using communications protocols are also planned to be used for ISTAR. For ISTAR, operations is planning to:

- 1) Demonstrate operations techniques onboard ISS to build toward crew/vehicle autonomy
- 2) Following the mission autonomy roadmap (see figure below)
- 3) Autonomous procedure execution
- 4) Instant Messaging demo (Comm Delay Countermeasures)
- 5) Crew Autonomous Planning/Replanning

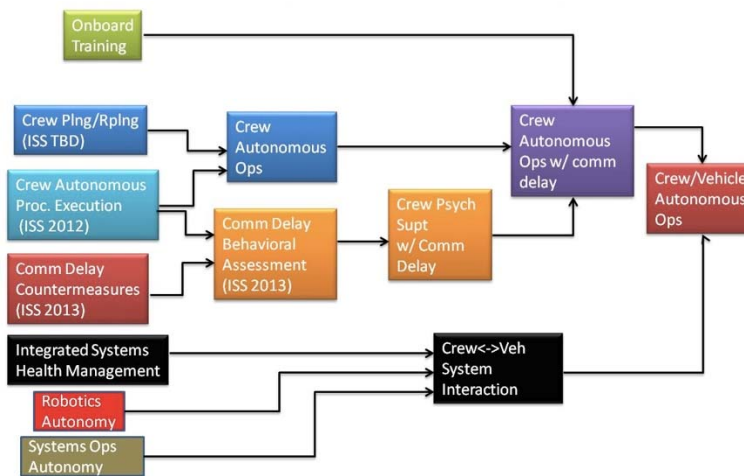


Figure 24 Mission Autonomy Roadmap Basic components and relationships

Operations provided recommendations for future analogs. These recommendations include:

- 1) Incorporate AOS/LOS periods for a more complete comm. experience
- 2) Test alternate texting software in 2013 test
- 3) Mission Operations (Integration group) would like to test G+ since it has many of the features that AES teams recommended for future texting software
- 4) Mission Operations (Integration group) will investigate further with the start of 2013
- 5) Practice Daily Planning Report for morning only
- 6) Evening DPR for AES projects did not provide much value added
- 7) DPR presentation to elaborate on lessons learned
- 8) Integrate crew mission log objective
- 9) ISS Increment 1 had crew logs which were beneficial to ground team cognizance
- 10) Future comm. delays and integration of AOS/LOS periods will continue to impact ground situational awareness. MOD will be adding this objective to help alleviate comm. delay cognizance issues.

The following texting lessons learned are solely related to the ISTAR Texting Protocol that will be used on ISS in the near future. The initial ISTAR tests will not use voice and will not have a comm. delay; those variances will be incorporated as the tests progress.

The texting concept worked well for all of the tests. All teams had similar experiences and comments for the ISTAR texting protocol. All teams found texting beneficial to various portions of the operations, noted issues with situational awareness, in addition to providing texting tool feature recommendations to improve the overall texting experience.

All of the tests used voice in conjunction with texting for all situations. The tests teams did not intend to use texting during emergencies (per protocol) but did so during the tests. Their experiences with various situations reinforced the recommended approach in the protocol (for the future ISTAR test), in addition to identifying areas of improvement. The protocol has been updated as a result of these tests.

ANALOG OVERVIEW OPERATIONAL SUMMARY			
	AMO	NEEMO	RATS
Work Classifications	• Quiescent operations	• Quiescent operations - Hab crew (non-IVA sppt) • Complex operations - EVA crew - IVA sppt crew	• Complex Operations - All crew
System Failures	• Critical • Non-critical	• None	• None
Emergencies	• Medical	• Medical	• None
Text-Only	• Nominal ops • Minor system failures	• Majority of timeline operations were texted between ground and crew to not interfere with IVA/EVA crew S/G conversations (~90%)	• Majority of timeline operations were texted between ground and crew to not interfere with IVA/EVA crew S/G conversations (~98%)
Voice-Only	• Intended practice for medical emergencies • Medical emergencies	• None	• None
Text + Voice	• Critical system failures • Medical emergencies • Notified crew of important incoming text messages	• Critical system failures • Medical emergencies • Notified crew of important incoming text messages (~10%)	• Notified crew of important incoming text messages (~2%)

Figure 25 Operations Analog Overview Operational Summary

A summary of lessons learned was presented, including:

- 1) Texting reduced talking on the voice loops which reduced clashes in voice conversations, reducing some of the negative effects of operating in a time-delay
- 2) Text is great for relaying complicated instructions or numbers and non-time critical information
- 3) Many agreed that it was easier to adjust to time delay in context of texting because people are used to delayed responses in text and email
- 4) Text made FCT logs easier
- 5) Practicing the voice-only, text-only, and voice + text conversation guidelines became easier as the tests progressed
- 6) Situational awareness is affected when prime operations are conducted with text, however additional texting tool features can help with the diminished situational awareness
- 7) The ground FCT chat-room made texting operations between CAPCOM and the crew easier
- 8) Emergency situations default mode of operations should be voice-only, unless the ground and crew determine that additional crew are able to provide texting liaison support
- 9) Texting did not impact the crew's interaction with their timelines
- 10) Ground team needs the ability to privatize and/or create a private conference room (i.e. medical emergencies and conferences)
- 11) Crew should initiate conversations during complex periods or MCC should provide audio call for a ground initiated text conversation

For the texting software, mission operations provided a set of future recommendations. There is a need for additional acknowledgement and notification features including audible and visual tones for incoming messages. Make use of Indicator that message was delivered to recipient. This feature was used by AMO and provided reception situational awareness, but not ideal. This feature was not used by NEEMO but could have improved situational awareness. If possible, numerically itemize entries. Add the ability to acknowledge texts by marking text comments as 'Read' or 'Copy.' Crew tags/labels should be easy to select from all SSCs. It is important to integrate texting application to timeline (Primarily FCT request). Organize texts by topic, not chronological order. Finally, differentiation for important/critical messages (i.e. use fonts, audible and visual tones).

Nick Winski from JSC Mission Operations planning presented the second half of the mission operations presentation. Mission operations has gained more and more operational experience with comm. delays, it has become increasingly apparent that daily operations between the crew and ground will need to evolve. Ops Planners have been exploring the use of a Daily Planning Report (DPR) as a substitute for morning and evening planning conferences. A DPR is essentially a summary file that originates on the ground and is exchanged with the crew. The crew reads the file and communicates any questions or concerns.

The mission operations objectives for these analogs have been to determine if the DPR is an adequate substitute to a daily conference, identify the types of information needed to relay to the crew prior to executing the day, and examining how well did the ground coordinate to generate the DPR?

In Mission Operations initial findings, they did not have 24-hour MCC support which would allow the ground team to develop the following morning's DPR overnight. Prior to the evening DPR, the ground would have real-time debriefs with the crew, which negated the relevance of the evening DPR content. This led to the decision to only perform the morning portion of the DPR protocol. Following the completion of all fieldwork, crewmembers were asked to fill out a short survey about the DPR. The survey questions aimed to determine the usefulness of the DPR, as well as possible improvements that could be made. Any potential enhancements were carried forward into the next analog and additional feedback was collected.

For the objective to determine if the DPR is an adequate substitute to a daily conference, the crew response to the DPR as a planning tool was overwhelmingly positive ("very useful," "efficient way to provide information," "vital"). Minimal interaction with the crew at the beginning of the crew day was achieved.

For the objective to identify the types of information needed to relay to the crew prior to executing the day, the crew consensus was that the type of information contained in the file was relevant to proper execution of the current day.

For the objective of answering the question, "how well did the ground coordinate to generate the DPR?" results here were mixed. While the DPRs were never lacking in content, it often felt like a chore trying to track down individual pieces of information. This was probably an artifact of the fact that not all team members have a mission ops background. This could be mitigated with additional training.

The conclusions reached were 1) The DPR is a sufficient alternative to traditional planning conferences (Minimal interaction with crew without compromising mission execution), 2) Some additional work to be done in terms of generating the file (Better define the process for submitting inputs and improve training for that process), and 3) DPR adds value to the mission by reducing the amount of time-lined conferences and increasing crew awareness. Use of the DPR should continue for future analogs.

D. Flight Crew Perspective

Astronaut Stan Love presented the flight crew perspective. He reviewed the problems of delayed voice communication. Specifically, this covered confusion of sequence (as demonstrated by the Apollo hoax story), blocked calls, wasted time (based on ISS calling timing study, might not say "say again", PAO events), reduced bandwidth, determining "Who has heard what?" slow answers erode rapport with ground, slow reaction by ground increases crew responsibility, and poor SA leading to needless ground calls.

Several general countermeasure techniques covered included prebriefing expectations, employing experienced Capcoms, employing Capcoms the crew knows, giving the crew more autonomy so they don't have to play "MCC-May-I", making decisions early (e.g., get permission to extend EVA ahead of time, rather than asking for and waiting for permission at the end.), and making fewer calls, with more topics packaged in each. More specific countermeasure techniques, included the following:

- 1) Make "Just In Time" calls: "when you receive this message, it will be time to terminate water flow..."
- 2) Say 'Message for crewmember X on topic Y in 10 seconds' so crewmember can stop what they're doing and be ready to listen.
- 3) Say 'Be ready to copy numbers' if the message has numbers to be copied, so crewmember can get pencil and paper ready.
- 4) Say 'Copy your message on topic Y' so crew knows which message ground received. Be rigorous about saying 'Over' if a response is requested. If no response needed, say so at the beginning of the call, or say 'Out' at the end of the call.
- 5) Never reference relative time ("Two minutes ago") because nobody knows what that means. Always use GMT, OBT, or other objective standard.
- 6) If you're talking when a call comes in and must pause to listen, say "Pausing" then "Resuming" when you start again so crew doesn't think there's a radio failure.

There was also discussion of countermeasure tools like text messaging. Crews like text messaging. You don't expect an instant response anyway. Words like "A/G 2" for messages not everybody needs to hear and for routine messages like reporting tasks complete. This also reduces audio clutter. Good text messaging builds rapport between crew and ground. Text messaging gives a record of what was said, avoiding time-consuming "Say again" calls. For numbers, it gives a verification of the data. Text messaging has challenges as well. Capcoms need to be properly trained for operational text messaging. Crews can't text and drive a spacecraft, or text and drive a robot arm, or text and do EVA. Need to assign a crewmember not involved in critical tasking to handle the text messaging (As IV does today with voice during an EVA.) Additionally, the text program needs time stamps for transmission and reception, and read receipts so you know when your message has gotten through. The text program also needs to indicate when the link is live and notify crew when a new message arrives. The notification should not be annoying. Also, it must be possible to turn notification off (e.g., for crew sleep). Other tools or approaches might include a reliable voice-to-text would be nice to avoid time-consuming "Say again" calls and/or instant voice playback would be nice for the same reason.

The conclusions were as follows. Delayed voice communication is hard. Operational tests and sims have identified good countermeasure techniques and tools. Even with those aids, delayed voice communication is hard. Delayed voice will force greater crew autonomy whether we like it or not.

E. Capcom Perspective

Marc Reagan from JSC presented the Capcom (Crew Communicator) perspective. The presentation emphasized the criticality of the emulator as a crucial enabler for testing. Without it, testing really would be barely scratching the surface on understanding time delay ops. The emulator itself has additional desired capabilities including file transfer and 2-way Videocon. Any tool improvements need to include the emulator. Voice and text improvement are tightly woven with emulator development. Good emulation allows tool evaluation. The limiting case was to understanding communications delay operations is to understand emergency response. The lessons learned from 2 emergency cases on NEEMO 16 dwarfed lessons from nominal ops. While the crew was autonomous for emergencies, there seemed to be long-term effects and crew mistakes. Neither voice nor text is inherently superior for dealing with communications delays. The "right" tool is situation dependent. Neither voice nor text jumps to the forefront inherently, which holds true for both nominal and emergency operations. The best choice is driven by demands of activity (i.e. EVA ops => text, Medical ops=> voice and video, Just-in-Time-Training or JITT =>video).

In comparing text messaging vs. voice communications during delayed communications, the "preferred method" conclusions are premature. We are not currently able to fairly compare dissimilar comm methods under time delay because both the texting and voice tools are not ready for prime time. With voice, there is no ability to replay the last transmission while with text messaging, there poor notification when you have a new one. Almost as severe is the dependency on a laptop (when practically everything else you want is on an ipad), leading to not having laptops around when you want them. So... as any good operators are inclined to do, you shift your method to the one that seems to get the job done better under those circumstances, rather than fairly comparing dissimilar methods under time delay.

When it comes to mitigation tools, context really matters; and is really hard to keep sight of sometimes. There are multiple strings of conversation to keep up with and multiple sources of information. A time stamp doesn't necessarily equal chronology. It is important to integrate all communications regardless of origin (including text, voice, video, pictures). This emphasizes the need for an ability to correct chronology and to tag by topic.

F. Extra-Vehicular Activity (EVA) Perspective

David Coan from JSC presented the EVA Flight perspective. EVA Flight Controllers supported the Remote Mission Control Center (RMCC) for NEEMO 15 & 16, and supported the Analog Mission Control Center (AMCC) for RATS 2012. These EVA Flight Controllers acted as the Flight Director, CAPCOM, and the EVA Officer. For all of the analog operations, these controllers monitored all simulated Space-to-Ground (S/G) voice loops and monitored all text chat conversations. Additionally, JSC\XA and \JSCDX3 personnel supported RATS as EVA and IV crewmembers. For these operations the EVA crewmembers were only tied into the S/G 1 voice loop while the IV was tied into several voice loops text chat rooms. EVA Instructors and Tools Engineers looked at tools concepts during NEEMO and RATS.

For Shuttle and Station EVAs, there is near constant voice communication with MCC and a fairly easy back-and-forth communication, with it being easy to ask for things to be repeated. The crew asks for permission for many steps, especially before moving onto another task. Additionally, the ground gives many GO/NO GO calls before, during, and after the EVA. Finally, the ground controls the detailed procedures. For these exploration analog EVAs, constant voice communication is not possible and back-and-forth conversations are not practical. Asking for

something to be repeated takes too much time. Situational Awareness for the ground team is reduced. The crew will be more autonomous, with the ground in more of a follow and observe mode. The crew can generally decide on their own how to do things, with MCC giving a delayed concurrence.

For these analog missions, the operations communications techniques caused some differences. EVAs managed much differently than on station. The MCC resorted to doing more monitoring and less commanding. The MCC utilized text instead of voice comm. Also, the MCC changed voice communications techniques. They only used voice calls when urgent, or possibly to inform of an incoming text. They packaged things into one long message rather than a back-and-forth conversation and used a short preamble statement before a long voice message to let the EVA crew know that a message was incoming. This allowed the EVA crew to pause their local communications and helped reduce missed or stepped-on calls.

Though proactive with station EVAs, MCC had to make decisions even earlier to get them to the crew in time for a Near-Earth Asteroid (NEA) EVA. Currently, MCC closely monitors the EMU, and provides real-time responses to emergencies. Many times the MCC see issues on the vehicle side before the crew. Depending on alignment of data pass, can see suit issues before crew calls. Currently, MCC closely monitors trends in system data. For example, MCC watches for trends in battery life, CO2 scrubbing, CO2 levels, temperatures, etc. The crew doesn't watch for these kinds of trends. These trends allow for things to be seen and responses developed/done before something becomes a problem. In the past, the MCC has terminated station EVAs due to a suit running out of CO2 scrubbing capability, which is a trend that the crewmember wouldn't see, and only realize when much closer to loss of scrubbing capability (CO2 level gets high). Exploration crews will have to be more autonomous with monitoring their own suit and responding to emergencies. This will require more advanced caution & warning and diagnostics with the advanced suit. Software will need to better monitor the entire EVA system, and provide guidance to the crewmembers.

There were several lessons learned from an EVA perspective.

- 1) Short, informative preamble to a long voice message allowed EVA crew to pause and not step on the call.
- 2) Packaging things into one long, yet concise, call saved time and helped reduce back-and-forth calls.
- 3) Being clear about references, such as "with respect to text message about XX sent at YY" helped reduce confusion over which delayed message was being answered.
- 4) Using text when possible, especially when not immediately required for the EVA crew, kept the delayed voice channels clear. This was also a little more intuitive, since it's typical that text messages aren't replied to immediately.
- 5) Using text to "read back" what was said made things clearer, made a record that could be referred to, and helped avoid asking to repeat something just for clarification.
- 6) Future analog missions will need to start looking at EVA System data to understand how to operationally handle the delay to MCC, and how that will change responses to emergencies and contingencies.

There were several future improvements suggested. Both crew and ground will require training to learn how to efficiently operate with a communications delay (preambles, packaging, stating "over" and "out," flight rules need to spell out what kind of things are voiced and what kind should be sent via text, and quick voice playback capability would aid in reducing asking for things to be repeated). Text client needs to be improved since it is not always clear what messages went together. Additionally, new messages need to be highlighted to bring attention to them and the ability to link text to time stamp on video would be useful. There will also need to be improvements to the EVA System's data monitoring, trending, and emergency response approaches to account for delay.

G. Behavioral Health and Performance (BHP) Perspective

Dr. Lauren Leveton, PhD, the manager of the Behavioral Health and Performance Element of the Human Research Program (HRP) presented on "Behavioral Health and Performance (BHP) Perspective on Comm. Delay for Exploration Missions."



Figure 26 Simulated Contingency Operations
NEEMO 16 crew working a poisonous fish sting contingency.

Previous HRP BHP studies have included Dr. Nick Kanas' studies on the "Effects of High vs. Low Autonomy on Space Crewmember Performance" (NEEMO 12 & 13, Haughton-Mars Project) and "Crew Interactions and Autonomy During Long-Duration Isolation and Confinement (105 Day Mars Chamber Study). In these studies, essentially participants react positively in autonomous environment; some negative outcomes for some ground controllers. Measures taken have included: Profile of Mood States, Cohesion, and Work Environment Scale. Results suggest there may

be adverse impacts with changes in autonomy if participants experience a lack of job clarity and role assignment. Overall, results suggest difference in performance and cohesion (and other team results) between low and high autonomy conditions.

On NEEMO 14, Dr. Kathryn Keeton performed an Autonomy Study with MOD to identify the impact on performance and crew well being utilizing both objective and subjective data. Generally, results suggest the crew realized a higher level of team cohesion, performance, and team interaction during the high autonomy condition. This lends to the support to the premise that increased efficiency and effectiveness of the crew can be realized under more autonomous conditions.

On NEEMO 16, Dr. Larry Palinkas performed a study “Assessing the Impact of Communication Delay on Performance.” The *study aim* was to examine the impact of lengthier communication delays likely to be experienced on a Mars mission, on behavior and performance; and to inform the upcoming ISS BHP Communications Delay study. The *approach* was based on a complex model of moderating and mediating variables on specific individual and team outcomes of performance and well being (which included many questionnaires of the *behavioral* kind). Originally, we were looking for the weak point in the curve where changes in performance and well being were impacted (test it on NEEMO 15). HRP ended up with one day, Mission Day 5, of a 12 day mission that had a nominal 50-second delay throughout the mission.

There were lessons learned for tools, training, and performance. Tools are needed for addressing communication, particularly under longer communications delays (5+ minutes). Particularly for texting, ability to play back audio/video messages, and tracking voice loops. Need for increased situational awareness of the limitations of communication technologies. Protocols used to communicate may be as, or more, important than technologies used.

Training for communicating under communications delay conditions is critical, especially for emergency scenarios. A key to performance under communications delay is shared situational awareness. Beyond the immediate situation to what tools are available, who is available to communicate with and what they are trained on, standard procedures, etc. Without training for working under comm. delay team performance breaks down under longer (5+ min) comm. delays. The safety of the crewmember in the 5-minute lionfish sting scenario was compromised by the delay in communications between the crew and the flight surgeon. Additionally, mission control responses were based on old observations of crew behavior and did not take into account behavior that had occurred since the last message or observation. Finally, standard procedures need to be re-written with comm. delay in mind.

Crew performance results showed that comm. delays 5 minutes or longer show similar effects to no comm. Boundary conditions for performance seem to be indicated by how a team functions in an emergency situation. As comm. delay increases, performance decreases as a function of the number of individuals communicating.

There were several tools to mitigate performance decrements identified.

- 1) Increased training for emergency scenarios.
- 2) More advanced text communication software.
- 3) Visual indicators of comm. delay to avoid cross-talk (Countdown to message received)
- 4) Software for tagging audio and video communications (i.e. Tag each message to time and topic as it is sent and allow repeated playback of each message).
- 5) Protocols written to comm. delay constraints (Procedure reliant on on-board tools and knowledge-bases rather than contact with ground).

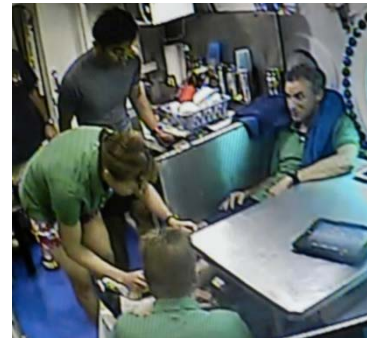


Figure 27 Contingency Simulation
NEEMO 16 crew simulating a medical emergency under 5 minute communications delay.



Figure 28 Mission Controller Monitoring crew operations with delayed voice, video, and data.

There are a couple of studies planned. Dr. Palinkas will be the Principal Investigator (PI) for the ISTAR Communications Delay study. This study will include data collection during upcoming ISS increment 35/36 where the crew performs tasks under no delay or a 50 second communications delay. The study aims to:

- 1) Determine the feasibility and acceptability of conducting a study of comm. delay on the ISS
- 2) Determine if there is an association between delays in communication, individual and crew performance and well being

- 3) Determine whether the association is affected by task complexity (criticality and novelty), social support, and task autonomy

Tasks assigned during this study will vary in terms of criticality and novelty (total of 16 tasks, 1 task/day, 4 days/week, 1 week early and late in the mission). There are eight tasks under no comm delay and eight with 50-second one-way delay. There are potential follow-on studies under increased comm. delay over longer periods.

There is also an Asynchronous Communications study lead by Dr. Fischer. This will be a lab-based study of effects of comm. delay on task and team performance as well as the development and testing of protocols (countermeasures) to support communication under comm. delay conditions. This study aims to:

- 1) Determine the impact of comm delays on communication, teamwork and task performance in relation to varying task demands (procedural vs. analysis and decision making) and different communication media (voice vs. text)
- 2) Develop and validate measures to assess and characterize team communication effectiveness and task performance
- 3) Develop and validate communication protocols to support joint problem solving and decision making by mission controllers and space crews

Future work in this area will include identification of comm. delay thresholds for performance effects (is a 5 min comm. delay functionally the same as 10 min?), studying the effects of delayed comm. between crew and family/friends, understanding the impact of variable levels of comm. delay (increasing at beginning of mission, decreasing on return to Earth), examining the changes in communication patterns over time, and the development of countermeasures to support team cognition and performance under comm. delay.

H. Medical/Surgeon Perspective

Dr. Ben Douglas from the European Space Agency (ESA) provided a presentation on the Medical/Surgeon perspective. The focus of this presentation was the experiences on NEEMO 16 where the flight surgeon conducted 4 Private Medical Conferences (PMCs) and 4 Private Psychological Conferences (PPCs), all conducted with 50-second delay. Additionally, this analog mission executed an Emergency Medical Simulation on day 5 which included no delay, a 5-minute delay, and a 10-minute delay.



All routine medical conferences were conducted with a 50 second one way time delay for communications. All crew commented that the 50s delay was not as irritating as expected for medical conferences, although one crewmember mentioned that it did add some inconvenience for staying in contact with family/friends. Multi-tasking non-critical light tasks during the conferences (checking emails or the timeline) during the delays was regarded as helpful by the crew. Using a countdown timer was sometimes helpful, but predicting incoming responses became fairly easy at 50s delay with experience. Use of radio etiquette was found to be useful during these sessions to mitigate delay issues. Crewmembers are known to be very busy, so the impression of repeatedly keeping them waiting was somewhat unnerving! For routine PMCs and PPCs, structuring the conference with a list of questions texted to the crewmember was found to be efficient. This limited the back and forth questioning to points of clarification, which reduced the total time required for a routine conference. Answering routine questions in batches of three was found to be effective and there was no noted reduction in the quality of the medical information provided by the crew using this format. The crew suggested being able to text questions to the flight surgeon would also be useful. It is estimated that unscheduled medical conferences would require more time. Some crewmembers



ring

did not feel it necessary to be able to see the flight surgeon, but others commented that it was a positive benefit, due to improved interaction (particularly seeing someone smiling or nodding in response to their answers) and not feeling so far away.

Natural eye contact was felt to be impossible with a 50s delay. It was suggested that this should be a specific training point, to counteract the normal impression of rudeness/disinterest with lack of eye contact. One crewmember did not do other tasks during a PMC to specifically avoid being perceived as rude. The flight surgeon will also break eye contact to take notes during conferences. Lack of eye contact is exacerbated if the

camera is out of the normal eye line – this is likely to be reduced by using a tablet with inbuilt camera. The audio-only conferences were found to impart a significant amount of information from the crewmember to the flight surgeon, however they obviously lack the capability to visually assess body language and demeanor. Many health conditions will require the flight surgeon to see the crewmember. Comparison between audio-only PMCs and audio-visual PMCs suggested a considerable improvement in the flight surgeon's ability to fully assess the crewmember's overall health status. An improved level of personal connection would be more critical during times of increased stress or illness.

There also seem to be other observations of the effects of the 50-second delay. Family interactions are very important – even short messages have a big impact when there is a time delay. Also, for scheduled communications (such as PMCs) the time delay is less problematic, but for unscheduled communications (such as EVAs) the crew noted that direct audio communication from MCC imparted little to no useful information due to the unpredictable arrival of messages. One crewmember commented that not having direct eye contact during video communications is getting more common and acceptable, with the increased use of Skype, FaceTime, etc.

For the Emergency Medical Simulation a 5-minute delay was used. Due to technical limitations imposed by the equipment simulating the time delay, the crew did not use the full suite of communication methods during the simulation – specifically the text function. This was not apparent to the flight surgeon for the majority of the simulation. Additionally, there was not an IV/CAPCOM crewmember dedicated to communicating with MCC, so audio communication became unreliable, with coinciding/missed/garbled messages. As a direct result of this unanticipated 'loss of comms' several important issues were recognized. Relevant and timely medical information and advice was being provided by the flight surgeon via text. The crew received none of this information. Despite this, it appeared to the flight surgeon that the crew was responding to his directions, for the majority of the simulation. This was later discovered to be entirely coincidental. Requests for advice from the crew were misperceived as requests for further advice by the flight surgeon, due to ambiguous phrasing. The crew, carried out inappropriate medical interventions, which were not reported via audio, and the flight surgeon was only aware of them via video. The crew was carrying out their trained medical procedures, which created two highly similar, but completely disconnected timelines.

Other factors involved (time delay, poor communications procedures, plus expectation that the crew would be too busy to respond) meant that the loss of communications was not recognized for the majority of the simulation – far longer than in any real-time situation. Without communications, as long as the crew was correctly responding to the situation there was no way to know about this disconnect. Video can be extremely deceptive for evaluating whether or not the crew are receiving information, if they are not confirming this via audio or text. However, video might also be the only method of obtaining critical information on the crew's activities (such as the crew performing inappropriate medical interventions). Having an IV/CAPCOM crewmember responsible for communication between MCC and EVA crew was deemed essential when operating with a time delay – this should also be true for emergency situations. Knowing what methods of communication to use (and are available) in an emergency is vitally important.

The crew reported in their post-simulation and post-mission debriefs – based on their perceived lack of medical support during the emergency simulation – that the crew for a mission involving a communication delay would need much more medical autonomy. On reviewing the communication logs it was noted that, had communications been intact, the crew would have received critical advice from the flight surgeon ...but sometimes only just. On balance, this suggests that increased crew autonomy is desirable for any communication delay of 5 minutes or more (and possibly less than 5 minutes).

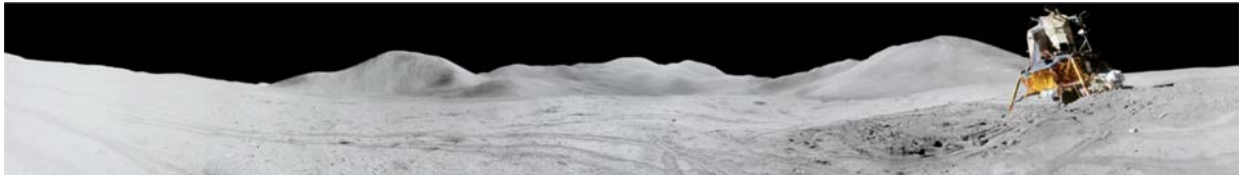
Additionally, there were several other emergency simulation observations. It is difficult/impossible to understand audio communications from the crew when they are wearing emergency breathing masks. Emergency masks should ideally have integrated communications equipment. If the crew reports they are evacuating their habitat but subsequently change their plans, and then there was a loss of communication, MCC would continue to believe that the crew were safe when they might remain at risk.

In summary, communication delays pose broad-ranging challenges to providing medical care for exploration-class human missions. Routine tasks require more time, although this can be somewhat counteracted by advanced planning. Two-way video is likely to be important for medical conferencing. Video can be useful for assessing emergency situations, but must be used with caution. Somewhere around 5 minutes it is likely that critical medical information cannot always be relayed effectively to the crew. Increased crew medical autonomy is therefore important for emergencies. Having an IV/CAPCOM crewmember specifically assigned to communicating with MCC is critical for all unscheduled situations (EVAs and emergencies).

I. Science Perspective

Dean Eppler from JSC presented the Science Perspectives. As background, Eppler presented that he had participated in a number of related missions, tests, and studies including: Apollo 17 (sample Preliminary Examination Team); ISS (Lead for WORF design and build); RATS 1998-2006 (Suit Test Subject), RATS 2007-2009 (Science Team Member); RATS 2010-2012 (Science Team Lead and science operations design); RATS 2012 (SCICOM).

There were several key lessons learned (due to time delay) for science. There is a difference between “management oversight” and “collegial interaction.” When we’re talking about crew-ground interaction, we often think of the management oversight function – a “do this, don’t do that” interaction. The science operations team, in contrast, spends more time considering science return, which is a two-way street, regardless of the time delay. This is critical to understand – the science operations team is not telling the crew how to do science, the crew is an extensions of the science operations team, exercising the concept that more brains on the geologic problems results in better science return and enables us to be more “nimble” in taking advantage of serendipitous discoveries. This kind of interaction will be critical, regardless of whether we’re working on the Moon, a NEO or Mars. There is also a difference between what I call “pure” science data versus science operations management data. The science operations management data is about planning and feedback. It’s used by the science operations team to determine and plan/re-plan surface science operations in the near- to far-term. The “pure” science data is about the total future



improvement of what we know about the Universe. It’s the data that informs science discoveries, in essence, forever... We’re still using Apollo data, and will use it even after we go back to the Moon. Science operations management data needs to be available in a timely fashion, probably daily; to help make on-going changes to the surface science plans. It can be limited in volume, based on the requirements by both the science operations team, as well as other operations teams. Pure science data is, well, everything, so by definition is it high volume, but it can be downlinked as the communications system capacity allows. It should be possible to use the results from RATS 11 to begin to understand the minimum bandwidth we need for science operations management data.

Under almost any situation of time delay, the ground is largely in an advisory function, while the in-space assets (DSH on NEO missions, Mars habitat on Mars missions) form the “FCR-Forward” role. Good crew science training, for all crewmembers, is the key to good science return; we need to develop the ability of all crewmembers to act as competent science observers. Crews are not carbon-based robots. They cannot be trained for observational science by uplinking a CBT-file prior to an EVA. If we are not willing to embrace this, then we might as well send robots. Interaction with the ground science team is critical to the quality science return. Tactical ops will be difficult to implement for a mission outside of cis-lunar space. Strategic science operations teams (as opposed to tactical teams) will be critical to evaluating the science mission accomplishments as the mission progresses, and revectoring the exploration mission as new discoveries are made. This is how JPL is running MSL, and there is a need to keep tabs on their lessons learned over the next couple of years. Extensive crew training, particularly for disciplines and operations that cannot be trained by CBT (e.g., emergency operations that rely on timely and correct execution of procedures, and field observation tasks that rely on long-term experience with real situations in the field). Developing “high-density” science information systems that allow the ground to understand and manage science data. xGDS-type of geographic information systems, coupled with crew transcripts (NOT voice recordings!!!), sample data management systems (e.g., DRIIMS) and images available ASAP after each crew exploration day will allow strategic science analysis of daily operations, and will allow good crew/ground interaction, planning and execution for an extended science mission. Matt Deans is well on the way with xGDS as is Danny Labasse with DRIIMS, and there are promising developments with the Glenn efforts on the EVAIS, but there is a need to integrate the parts in a complete architecture and test them in the field.

As a result, there may be some proposed future testing/development to consider. When we have prototype information systems (suggested above), the best place to test them will be in the field, with geologists doing a field problem and a “ground crew” analyzing the results of each day’s activity.

J. Education and Public Outreach (EPO)/Public Affairs Office (PAO) Perspective

JSC's Wendy Watkins provided a presentation on the EPO/PAO perspective. Simulated communications delay for EPO/PAO events were only performed during NEEMO 16. For these events, the team performed a real-time 50-second communications delay question & answer event with the crew. Video was posted on YouTube, unedited. In it, the interviewer asks a question, the crew hears 50 seconds later, and then responds. The interviewer hears response after another 50 seconds. This video can be found on the Internet at <http://youtu.be/eUsEk5BoNOI>.

Additionally, the team performed a real-time 50-second communications delay event with crew where questions were provided in advance to the crew. This method was significantly more palatable. For this event, the interviewer opened with greeting and advised crew to begin. This was still technically not "live" but it doesn't lose audience with silent spots. SPACE.COM also performed a communications delay interview with crew. (This was similar to the simulated one we did internally, but a real interview). This interview can be seen on the Internet at <http://www.space.com/16248-asteroid-explorers-delayed-communication-with-earth-simulated-video.html>.

There were a few key lessons learned from these experiences. The audience will not sit still or stay tuned in for a true time delay event. They lose interest; fall asleep, or something shiny distracts them more easily than usual. The best methods seem to be sending the questions to the crew in advance, or having crew provide recorded video – meaning that a "live" interview may not be possible depending on the length of the time delay. Efforts are ongoing to find additional methods or suggestions for dealing with these issues.

IV. Multi-Study Study of Domain Coverage

Prior to this TIM, the participants participated in a survey of analog missions and studies to compile a summary understanding of what aspects of time delay have been studied. The following tables summarize the compiled results from those survey questions.

	AMO	DRATS	DSH	ISTAR	NEEMO	PLRP
Year Performed	2012	2010 2011 2012	2012	Will be Incr 35/36	7: 2004 9: 2006 13: 2007 14: 2010 16: 2012	2011
Test Duration	8 days	2010: 14 2011: 9 2012: 10	10 days	90-180 days	7:15 days, 9:18 days, 13:10 days, 14: 14 days 16:12 days	7 Days
Time Delay (One Way Light Time)	1.2, 5, 50, 300 s	2010: 0s 2011: 50s 2012: 50, 600, 1200s	50 sec	50s?	7: 0-2s, 7: 0-2s, 13: 20m, 14: 20m 16:50s,5m,10m	NEA (50s)
Continuous Operations (with Time Delayed Communications)	2hrs	2010: - 2011: 9 hrs 2012: 9 hrs	5 days	16 hrs (audio), cont.	6 days	3 hrs
Communications Coverage	Cont.	2010: Cont., 2x/day 2011: Cont. 2012: Cont.	Cont.	16 hrs (audio), cont.	Cont.	Cont.
Number of Crew	4	2,4,4	4	1	6,6,6,6,6	1(sub pilot)
Number of Ground Controllers	8	42,19,5	12	varies	2,2,8,10,20	15

Table 1: Comparison of Missions/Studies/Tests Parameters

Operations Regime Used	AMO	DRATS	DSH	ISTAR	NEEMO	PLRP
Emergency Ops (min)			12		14,16	
EVA Ops (min)		10, 11, 12	12		13,14,16	
Contingency Ops (hrs/days)	12	10, 11	12			
Troubleshooting Ops (days)	12		12			
Medical Ops (hours)	12	11	12			
Maintenance Ops (days)	12	11	12	X		
Repair Ops (days/weeks)	12					
Personal Crew Ops (days/weeks)	12				13,16	
Normal Systems Ops (days/wks)	12	11	12	X	13,14	
Science Ops (min/hours)		10 (4 hrs), 11 (2 min), 12 (2 min)	12			11
Health Science Ops (ms – sec)	12				7 (ms), 9 (0-2s), 16 (50s)	
Public Affairs Ops (min)					16 (50s)	
Education/Outreach Ops		11 (2 min)	12			

Table 2: Coverage of the Operations Regimes

Systems/Functions Used	AMO	DRATS	DSH	ISTAR	NEEMO	PLRP
Closed Loop Control Commanding	12	11			7	
Discrete (1 Shot) Commanding	12		12			
Remote Monitoring (Telemetry)	12	11	12		9	
Voice (One way status/info, situational awareness)	12	10, 11, 12	12		16	
Voice (Two way conversational)	12	10, 11, 12	12		16	11
Video	12	10, 11, 12	12		9,14,16	11
Text Chat	12	10, 11, 12			14,16	
E-Mail			12		13,14?,16?	
Web Access					16?	
File Transfer	12	10?, 11			13,14?,16?	
File Management (from ground)	12?		12?			
Disruption Tolerant Networking (DTN)	12	11			16?	
2-Way Video Conferencing					16	

Table 3: Comparison/Summary of Systems/Functions Tested

V. Conclusions

Steve Rader presented a summary of the recommendations based on the compiled major lessons learned that were communicated during the TIM in both presentations and discussion as well as a discussion of proposed future steps.

A. Recommendations based on Lessons Learned

The lessons learned are expressed in the following list of recommendations:

- 1) Incorporate bandwidth and coverage limits with delayed communications to best understand how operations are affected. It is also recommended to include multi-day operations (with planning cycle based on downlinked data) to understand how limits on total data volume downlinked affects operations. This will help to develop a compelling story on communications bandwidth and coverage requirements to drive missions.
- 2) Develop a custom tool(s) that provides a “Voxer” (commercial application for iOS devices introduced at NEEMO 16) like capability and incorporates noted requirements. It is recommended to first compile a full set of functional requirements.
- 3) Work with developers on understanding/incorporating voice transcription and voice commanding capabilities.
- 4) Pursue additional studies of emergency/contingency operations under delay to include better/more consistent training & procedures, increase the number of participants and runs. (Include standard measures), and to consider leveraging military experience (subs, out of comm, etc.) or others?
- 5) Document GPS/Positioning requirements for exploration missions and design test(s) to determine effects (and requirements) of different positioning methods (manual, limited, full).
- 6) Consider integration of tools and timeline-based data (i.e. console logs and texting logs and procedures).
- 7) Note JPL is developing timeline based file formats/protocols. These should be considered/included in the requirements for any custom tool development.
- 8) For texting application, include “new message” alert and message read (sent back to the sender) indicators. This could include the software with a “read”, “yes”, or “no” buttons.
- 9) Text message applications should include grouping/threading
- 10) Better studies are needed to start more concretely understanding flight/ground autonomy split/allocation and the crew/SW partition (for onboard autonomy). This should also include the allocation to robotics.
- 11) There still is a need for voice call & texting ID/subject/sequence tagging to ensure responses are correlated.
- 12) Establish rigorous voice protocols (“over”, “out”, references, etc.)
- 13) Consider multiple simultaneous text (and possibly) voice conversations/threads (multi end points on both ends) (vs. single Capcom to all crew).
- 14) There is a need for additional studies of the effects of extended delay on humans, which should include development, and testing of mitigations.
- 15) Study any requirements changes that may be introduced due to upcoming heads-up displays and voice to text (transcription and commanding).
- 16) There is a need to make progress on how we will realistically make EVA work with the required crew autonomy caused by time-delayed communications. This includes the study how do we reduce the risk compared with current EVA technologies/techniques. There should also be consideration of adding simulated EMU data for future integrated testing with simulated issues.
- 17) Add a leading and trailing line on the timeline (by the time delay) that shows the relative times on the remote side.
- 18) Develop the tools that work through the delay emulator to support 2 way video and file transfer/management.

B. Recommendations Future Steps

The meeting participants discussed future steps that might be appropriate after this TIM. The first recommended action was to compile and distribute a paper summarizing what came out of this TIM by the end of the first quarter of 2013 and to publish this paper if possible. Additionally, the group tentatively plans on a follow on TIM for 1 year (if needed). It was proposed that the participants consider telecons to tag up every quarter to evaluate any future meetings/activities. It was suggested that the first of these would be scheduled in early 2013 with a suggested agenda to include: a) Status/Outbrief of TIM paper; b) Updates on upcoming studies/missions/test (with time delay objectives); c) Possibly requirements for proposed tool development; d) Any partnerships that have grown out of the TIM; e) Define objectives for 1 year ISTAR study (which starting in 2015); f) Any proposals for Russian Chamber study.

Appendix

ACRONYMNS

A/G	Air-to-Ground
AES	Advanced Exploration Systems
AMCC	Analog Mission Control Center
AMO	Autonomous Mission Operations
ANSMET	Antarctic Search for Meteorites
AOS	Acquisition of Signal
ARC	Ames Research Center
ARGOS	Active Response Gravity Offload System
ASTEP	Astrobiology Science and Technology for Exploring Planets
AUV	Autonomous Uncrewed Vehicle
BHP	Behavioral Health and Performance
BLEO	Beyond Low Earth Orbit
CAPCOM	Crew Communicator
CARN	Canadian Analogue Research Network
CBT	Computer Based Training
CDR	Commander
CO2	Carbon Dioxide
COTS	Commercial-Off-The-Shelf
CSA	Canadian Space Administration
CSM	Command/Service Module
DIO	Directorate Integration Office
DQ	Data Quality
DPR	Daily Plan Report
DRATS	Desert Research and Technology Studies
DSH	Deep Space Habitat
DTN	Delay/Disruption Tolerant Networking
DW	Deep Worker
EAMD	Exploration Analogs and Mission Development
ECLSS	Environmental Control and Life Support System
FCR	Flight Control Room
EDL	Entry, Descent, and Landing
EPO	Education and Public Outreach
ESA	European Space Administration
EVA	Extra-Vehicular Activity
FIFO	First-In-First-Out
GLEK	Global Space Exploration Conference
GMT	Greenwich Mean Time
GN&C	Guidance, Navigation, and Control
HEOMD	Human Exploration & Operations Mission Directorate
HQ	Headquarters
HRP	Human Research Program
IEWG	ISS Expert Working Group
IMV	Inter-Module Ventilation
ISS	International Space Station
ISTAR	International Space Station Test-bed for Analog Research
IVA	Intra-Vehicular Activity
JITT	Just in Time Teaching
JSC	Johnson Space Center
JPL	Jet Propulsion Laboratory
KSC	Kennedy Space Center
LM	Lunar Module
LSS	Lunar Surface Systems
NEA	Near Earth Asteroid

LEO	Low Earth Orbit
LER	Lunar Electric Rover
LOC	Loss of Communications
LOS	Loss of Signal
LRV	Lunar Rover Vehicle
MMAMA	Moon and Mars Analog Mission Activities
MCC	Mission Control Center
MMCC	Mobile Mission Control Center
MMSEV	Multi-Mission Space Exploration Vehicle
MOD	Mission Operations Directorate
NASA	National Aeronautics and Space Administration
NEEMO	NASA Extreme Environment Mission Operations
NGS	National Geodetic Survey
NOAA	National Oceanic and Atmospheric Administration
OODA	Observe Orient Decide Act
OTF	Operations Test Facility
OWLT	One-Way Light Time
PAO	Public Affairs Office
PC	Personal Computer
PCT	Portable Communications Terminal
PDF	Portable Document Format
PLRP	Pavilion Lake Research Project
PMC	Private Medical Conference
PPC	Private Psychological Conference
PUP	Portable Utility Pallet
RATS	Research and Technology Studies
RSVP	Rover Sequencing and Visualization Program
RTL	Round-Trip Light Time
S/C	Spacecraft
SCUBA	Self-Contained Underwater Breathing Apparatus
SEV	Space Exploration Vehicle
SIM	Simulation
SMD	Science Mission Directorate
SNRF	Space Network Research Federation
SRTM	Shuttle Radar Topography Mission
SS	Science Stenographer
TCP	Transport Control Protocol
TIM	Technical Interchange Meeting
xGDS	Exploration Ground Data System

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References

Presentations from the TIM

These presentations are available within the NASA NDC security domain at the [Time Delay in Human Exploration TIM](https://oasis.jsc.nasa.gov/projects/advdev/analogs/Delay%20TIM/) web site: <https://oasis.jsc.nasa.gov/projects/advdev/analogs/Delay%20TIM/>

For those external to the NASA networks, these presentations are available upon request to James Johnson at james.e.johnson@nasa.gov or 281.244.8305.

The presentations are listed below in order of agenda:

¹Rader, S., “TIM on the Impacts of Time Delay on Human Exploration - Introduction & Agenda”, Johnson Space Center (JSC) Time Delay TIM (Time Delay TIM Agenda v6.0.pptx)

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³Reagan, M., Chappell, S., Abercromby, A., Todd, W., “NEEMO Time Delay and Crew Autonomy Lessons Learned, October 2012”, Johnson Space Center (JSC) Time Delay TIM (NEEMO Time Delay TIM.pptx)

⁴Johnson, J., Research and Technology Studies (RATS) Analog Missions - Time Delayed Communications, Johnson Space Center (JSC) Time Delay TIM (RATS Overview for Delay TIM.pdf)

⁵Abercromby, A., “Exploration Analogs & Mission Development (EAMD) – Communications Delay TIM”, Johnson Space Center (JSC) Time Delay TIM (Comm_Delay_TIM_EAMD_10-16-12d.pptx)

⁶Moreno, F., “What ISTAR is doing – Accomplishments and work in progress – Presentation to Time Delay TIM”, Johnson Space Center (JSC) Time Delay TIM (ISTAR_Comm_Delay_TIM_Oct_17_2012.pdf)

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¹³Downs, M., “TIM on the Impacts of Time Delay on Human Exploration – Communications”, Johnson Space Center (JSC) Time Delay TIM (Time-delay-v3.ppt)

¹⁴Rader, S., “TIM on the Impacts of Time Delay on Human Exploration – Data Management Perspective”, Johnson Space Center (JSC) Time Delay TIM (Data Management Perspective.pptx)

¹⁵Rader, S., “Reference Charts: Delay Communications Tracking (Concept)”, Johnson Space Center (JSC) Time Delay TIM (Ref - Delay Comm Context Tracking Concept.ppt)

¹⁶Rader, S., “Reference Charts: ISS and Shuttle Uplink-Downlink Metrics Graphs”, Johnson Space Center (JSC) Time Delay TIM (Ref - ISS and Shuttle Uplink-Downlink Metrics Graphs.ppt)

¹⁷Rosenbaum, M., Gibson, S., “Comm Delay in Analogs from an Ops Perspective - Texting Protocol Lessons Learned from Analogs”, Johnson Space Center (JSC) Time Delay TIM (Ops Perspective Pt. 1.pptx)

¹⁸Winski, N., “Daily Planning Report Lessons Learned – NEEMO and RATS 2012”, Johnson Space Center (JSC) Time Delay TIM (Ops Perspective Pt. 2 - revA.pptx)

¹⁹Love, S., “Flight Crew Perspective on Delayed Voice Communication”, Johnson Space Center (JSC) Time Delay TIM (Crew Perspective.ppt)

²⁰Reagan, M., “Time Delay TIM: Observations from a Capcom Perspective”, Johnson Space Center (JSC) Time Delay TIM (Time Delay TIM Capcom.pptx)

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