NEEMO 20

NASA Extreme Environment Mission Operations

Exploration EVA Results

EVA-EXP-0052

December 9, 2015

David Coan *(XX4/CX3)*
EVA Strategic Planning & Architecture Integration
Integrated EVA Testing & Operations Concepts

EVA Office (XX) Goals for Operational Field Tests

Background

- Future Exploration missions will potentially take humans to destinations where EVA work will be done on natural bodies that don't have built in aids
- These missions will also be at distance that precludes instantaneous real-time communication with the crew
- There are numerous technology and operations gaps associated with translation and stabilization tools, science sampling tools, and operational techniques for dealing with comm latency

XX4 / Integrated EVA Testing Duties

- Advance the future of the EVA system and operations through integrated operational field testing
- Understand EVA gaps and operations concepts for a wide range of Exploration destinations being considered by NASA
- Determine and document closures to gaps in EVA capabilities for Exploration missions and inform the EVA Systems Maturation Team (**SMT**)
- Develop and document operations concepts for EVA at the Exploration destinations **(EVA-RD-004)**
- Realize the needs of EVA tools and hardware and enable the development of requirements and designs

Benefits of Operational Field Testing

1. Operations concepts can be accurately tested to determine their viability and changes
2. Purpose built prototype hardware can be evaluated in a field test to provide data for design maturation
3. Communication latencies can be simulated in an operational environment in order to assess the ops cons and needs associated with EVAs
4. A range of destinations and gravity gradients can be evaluated

What is NEEMO?

NEEMO is a project that utilizes Aquarius, the only operational undersea research facility in the world, as a setting for accomplishing a host of NASA and synergistic partner objectives

- Managed by XM (Exploration Mission Planning Office)
- Funded by partners and collaborators each year
  - Partners come from across JSC, other NASA centers, DoD, universities, and industry
- 1-2 missions/year, 10 – 20 days in length
- Rapid prototype environment
- Highly responsive to user needs
- Robust comm infrastructure
- Shore side Mission Control, staffed by experienced operators
- Crew largely consists of astronauts from CB and IPs
- Missions have high operational rigor by design
  - Timelines, Flight Rules, Procedures, etc.
- Enables evaluation of both IVA and EVA objectives

NEEMO 20 Partners / Collaborators

- NASA
  - JSC
    - XX: Investigating micro- and partial gravity EVA techniques, tools development, funding
    - XM: Leadership, EVA tools and techniques, (esp. related to Mars moon)
    - XI: Science backroom support, consulting for tools development
    - EA (EC, ER): PI for multiple evaluation objectives, building EVA tools
    - CB: Crewmembers
    - SA: Co-investigator on some mission objectives
    - PAO: Public Affairs activities
  - ARC: Mission planners and timeline tool
  - JPL: Co-investigator on some mission objectives
  - KSC: Communications, data management, and logistics support
- IPs (ESA, JAXA): Crewmembers, research objectives, funding
- Academia
  - Embry-Riddle Aeronautical University (ERAU): Research objectives, funding
  - Naval Postgraduate School (NPS): Synergistic robotic objectives (ROV & AUV), funding
  - Air Force Research Labs (AFRL): Research objectives, funding
  - Florida International University (FIU): Aquarius owner and operator, marine science support
  - Georgia Institute of Technology: EVA Cognitive Work Analysis graduate study
- Industry
  - Teledyne: PI for research objective, providing engineering management and support for ERAU objectives
  - Shark Marine: Providing a diver propulsion and navigation system for man-machine work system evaluation, in-kind contribution
  - VOXER: Providing communications application and support for time-delayed voice playback, in-kind contribution

NEEMO 2015 Missions Program Relevancy

Category	Gap/Risk	Experiment	Program
Technology Maturation for Ops	Sample Collection Tools and Techniques	Geo Sampling Kit	ARCM ----> Exploration
		ARCM Boom	ARCM ----> Exploration
		Microspines	ARCM ----> Exploration
		Phobos Boom	Exploration
	Exercise Countermeasures	Bluetooth receiver	ISS ------> Exploration
Ops Tools Maturation	Mobile Crew Planning Tool	Playbook	ISS ------> Exploration
	Crew Task Efficiency	MobiPV (ESA)	ISS ------> Exploration
		HoloLens telementoring	ISS ------> Exploration
	Human Factors Capture	iShort	ISS ------> Exploration
Ops Concept Maturation	Crew Task Efficiency	Augmented Reality Procedures	ISS ------> Exploration
		Pinnable Procedures	ISS ------> Exploration
	Exploration Surface Ops with Comm Delay	Crew Self Scheduling	ISS ------> Exploration
		Integrated Science Team	Exploration
		Man-machine work systems	Exploration
		Low Latency Teleoperation	Exploration
		Use of 3D printers	ISS ------> Exploration
		Incapacitated Crew	Exploration
Pure Science	N/A	Coral Science	N/A
Crew Preparation	Expeditionary Training	CDR upgrade	ISS ------> Exploration
		Rookie mission experience	ISS ------> Exploration
Outreach Opportunities	N/A	PAO events	ISS ------> Exploration
		Educational Outreach	ISS ------> Exploration

Note: EVA evaluation highlighted in yellow

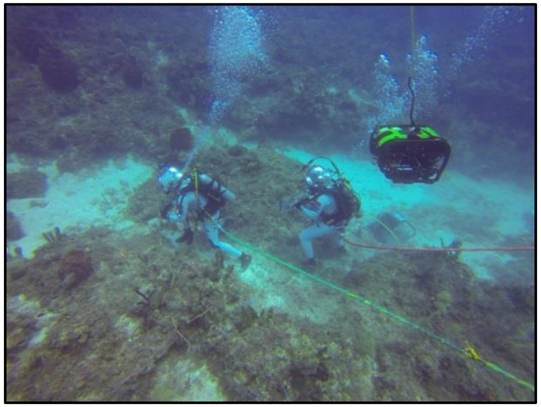
EVA Operational Field Testing at NEEMO

Why NEEMO for EVA?

- Provides a flexible environment that can mimic microgravity, milli-gravity, and partial gravity missions with EVA crewmembers performing tasks
- Allows for end-to-end testing of techniques and hardware in an operational scenario, with the crew in-situ and the ground team separated from them, which drives out problems not found in standalone testing and things that do and do not work in a mission situation
- Enables evaluation of ops concepts pertinent for exploration in large areas, which is something that can't be done in smaller facilities (like the NBL)
- Supports ability to conduct real analogous science
  - Marine science is an analogous proxy to planetary geology science
  - Similar tools and instruments are utilized
  - Real scientists in MCC with a vested interested in the results debate priorities with actual mission time pressure provide a high level of realism
- Facilitates integration of time latency for evaluation of the EVA ops con that integrates an active Science Team on Earth

EVA Office Goals for NEEMO 20

- Inform updates to the **EVA Ops Con document** (EVA-RD-004)
- Evaluate objectives that facilitate **SMT gap closure**
- Address Curation and Analysis Planning Team for Extraterrestrial Materials (**CAPTEM**) findings for EVA collection of science samples
- Provide data for hardware design maturation to assist in road-to-flight, especially the EVA science sample collection tools
- Assess ops cons and needs associated with EVAs that require input from MCC over a comm latency
- Explore a range of destinations and gravity gradients
  - Micro-g at asteroid/cis-lunar
  - Milli-g at Mars' moons (Phobos)
  - Partial-g on Mars and lunar surface



NEEMO 20 Exploration EVA Objectives & Gaps

EVA Objective	Applicable Mission	EVA SMT Gap Closure & ARCM CAPTEM	Hardware and Technique
Evaluate EVA hardware and operations for science sampling	Asteroid Moons of Mars Mars surface	502: Micro-g tool for loosely adhered particles 503: Micro-g tool for chip samples 504: Micro-g tool for subsurface samples 505: Sample Storage and Curation 801: DRM Maturity 805: Scientific Objectives CAPTEM 5: Collection of 1000 g from two sites	Integrated Geology Sampling System
Investigate crew driven multi-day planning of EVA operations utilizing scenarios with variables and a task list that must be planned and carried out over the course of multiple days	Mars surface	703: EVA use model 801: DRM Maturity	Playbook
Assess potential operations of a robotic asset for EVA and inform functional needs of a robot for EVA tool management	Mars surface	510: Tool management device 801: DRM Maturity	NPS ROV
Continue to enhance understanding of comm limitations by including MCC/ST response time and comm with IV, and continue to investigate practicality of directing EVA operations from MCC over a comm latency	Moons of Mars Mars surface	703: EVA use model 801: DRM Maturity	Science Team Comm latency ops con
Evaluate an EVA tool for identifying and high grading samples	Mars surface	509: In-situ High Grading, EVA Tool 805: Scientific Objectives	Sample markers Helmet cams
Assess hardware and techniques for incapacitated crew rescue	Mars surface	406: Rescue Incapacitated Crew Member 801: DRM Maturity	ICM rescue gurney
Investigate building EVA hardware in situ	Mars surface	512: Common tools for vehicle maintenance 801: DRM Maturity	3D printer
Examine a manually deployable truss structure for EVA translation and sampling ops	Moons of Mars	501: Microgravity stability and anchoring tools 511: Microgravity translation aids for non-engineered surfaces 801: DRM Maturity	Phobos Deployable Structure (boom)
Begin looking at types of hardware needed and techniques for navigating on a foreign body	Mars surface	214: Navigation Short Range 801: DRM Maturity	Navigator

NEEMO 20 Mission Summary

Dates

- May 18-22: Engineering runs at ARB
- June 2-3: Crew training at JSC (non-EVA)
- June 30: Crew training at JSC for EVA
- July 13-18: Aquanaut training and mission prep at ARB
- July 20-Aug 2: 14 day saturation mission

Crew

- Luca Parmitano (ESA Astronaut)
- Serena Aunon (NASA Astronaut)
- Norishige Kanai (JAXA Astronaut)
- David Coan (EVA Operations Engineer)
- Mark Hulsbeck (FIU Habitat Technician)
- Sean Moore (FIU Habitat Technician)

High Level Objectives

- Exploration EVA evaluations
- ISS Objectives (Playbook, HRM, JITT, Hololens, ODG, etc.)
- IP Objectives (mobi-PV)

From left: Sean Moore, Mark Hulsbeck Luca Parmitano, David Coan, Norishige Kanai, Serena Aunon

NEEMO 20 EVA Team

EVA Objective Integration & Prioritization
PI – Jesse Buffington (XX)
Lead – David Coan (XX4/CX3)

Exploration EVA Ops Con (XX)
Lead – David Coan (XX4/CX3)

Exploration EVA Hardware
Lead – Drew Hood (EC7)
Lead – Adam Naids (EC7)

HAT Moons of Mars Objectives
Lead – Steve Chappell (SK)
PI – Mike Gernhardt (EA)
Co-PI – Chappell / Abercromby (SK)

XX – EVA Office
XM – Exploration Mission Planning Office
XI – ARES
EA – Analog Project Management Office
EC7 – EVA Tools
SK – EVA Physiology
SF – EVA Cognitive Work Analysis
HAT – EMC Moons of Mars
CX3 – EVA Operations

EVA Plan & Timelines
David Coan (XX4/CX3)
Steve Chappell (SK)
Marc Reagan (EA/XM)

Study Design & Metrics
Steve Chappell (SK)

MCC
Marc Reagan (EA/XM)

Science Team
Trevor Graff (XI)
Matthew Miller (SF)

Exploration Science
Paul Abell (XI)
Kristen John (XI)
Trevor Graff (XI)

External Integration
Bill Todd (XM)
Jason Poffenberger (XM)

Exploration EVA Hardware
Drew Hood (EC7)
Adam Naids (EC7)
Mary Walker (EC7)

External Stakeholders
ERAU (CORAL Towers)
FIU (Marine Science)
NPS (ROV/Robotics)
Commercial (Navigator)

Exploration Missions Evaluated During NEEMO 20

Asteroid in cis-lunar space

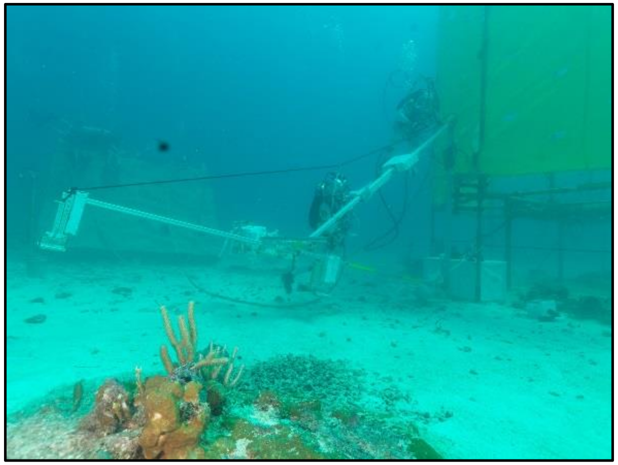
- Micro-g environment
- Retrieve geology samples with tools while based on a stabilization boom deployed from an Asteroid Retrieval Vehicle (ARV)
- No comm latency
- EV crew directed by Ground IV

Moon of Mars (Phobos)

- Milli-g environment
- Retrieve geology samples with tools while based on a boom deployed from a mobile habitat
- Deploy science instruments while based on a boom
- 5 min one way comm latency
- Directed by IV crewmember
- Direction from ST given during the EVA

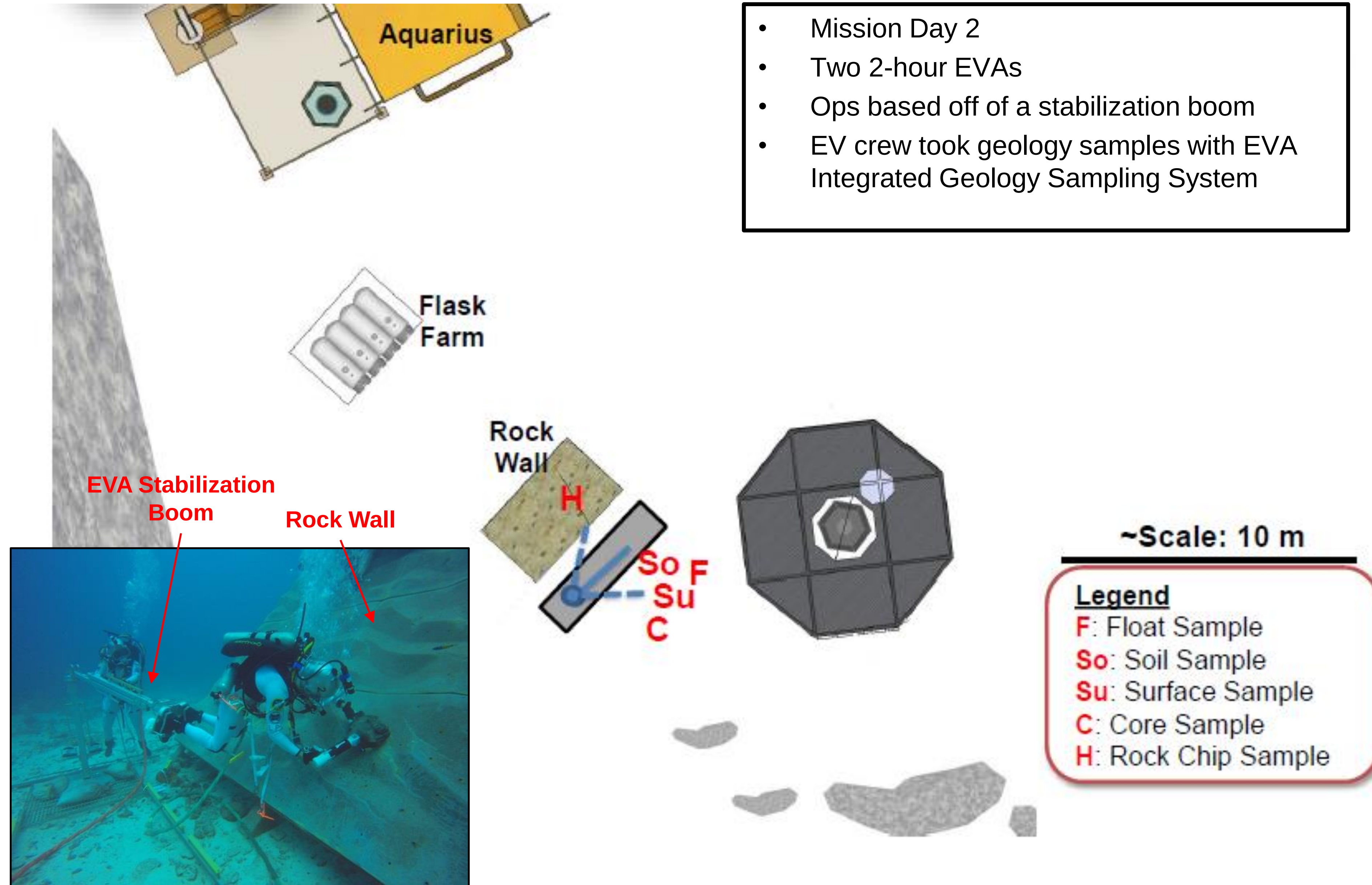
Mars surface

- Partial-g environment
- Conduct pioneering tasks to assemble base infrastructure
- Perform geology and astrobiology (marine science) sampling tasks
- 10 min one way comm latency
- EV directed by IV crewmember
- Direction from ST given during the EVA
- EVAs planned MCC and crew



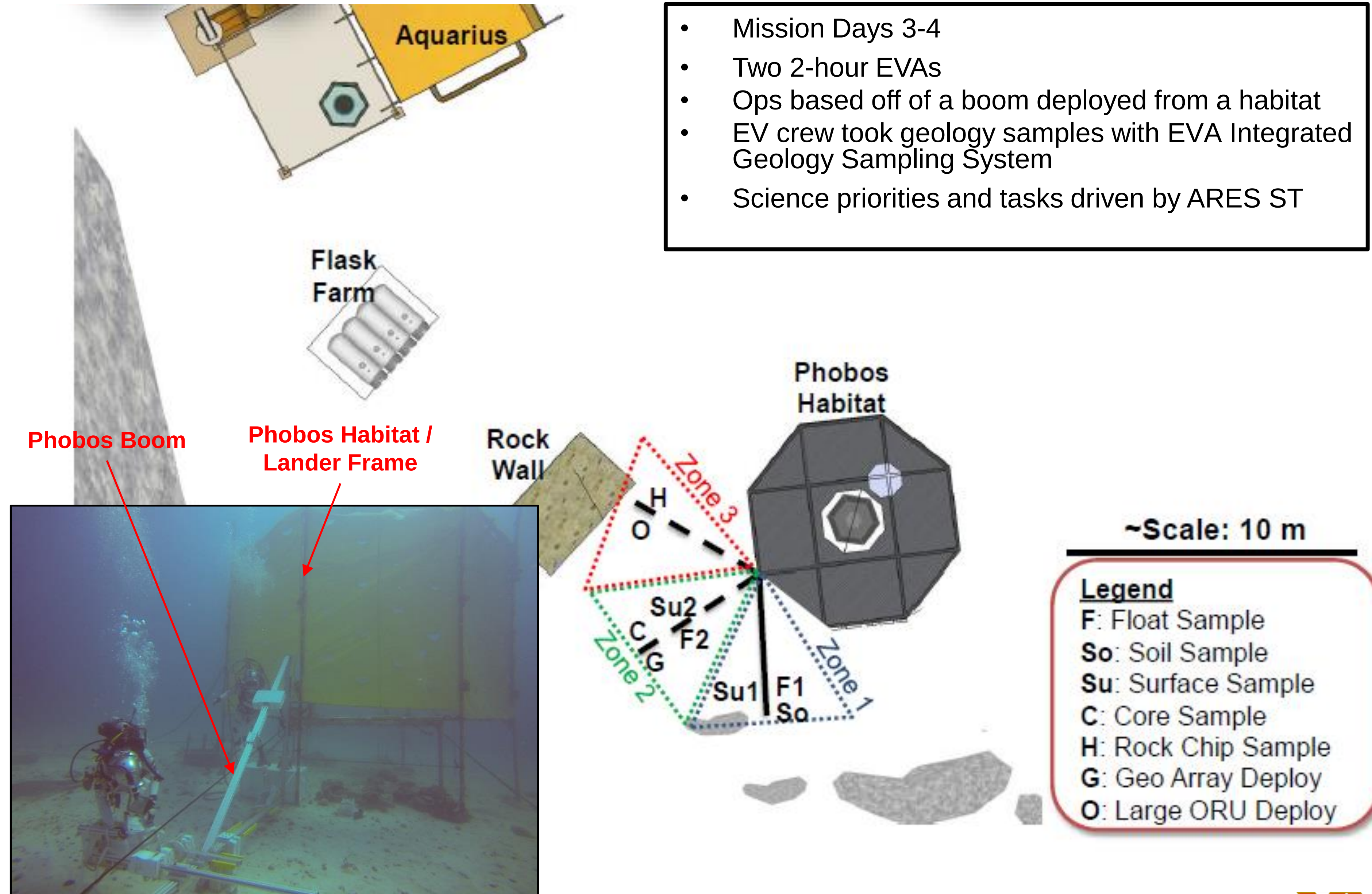
Asteroid / Micro-g EVA Overview

- Mission Day 2
- Two 2-hour EVAs
- Ops based off of a stabilization boom
- EV crew took geology samples with EVA Integrated Geology Sampling System

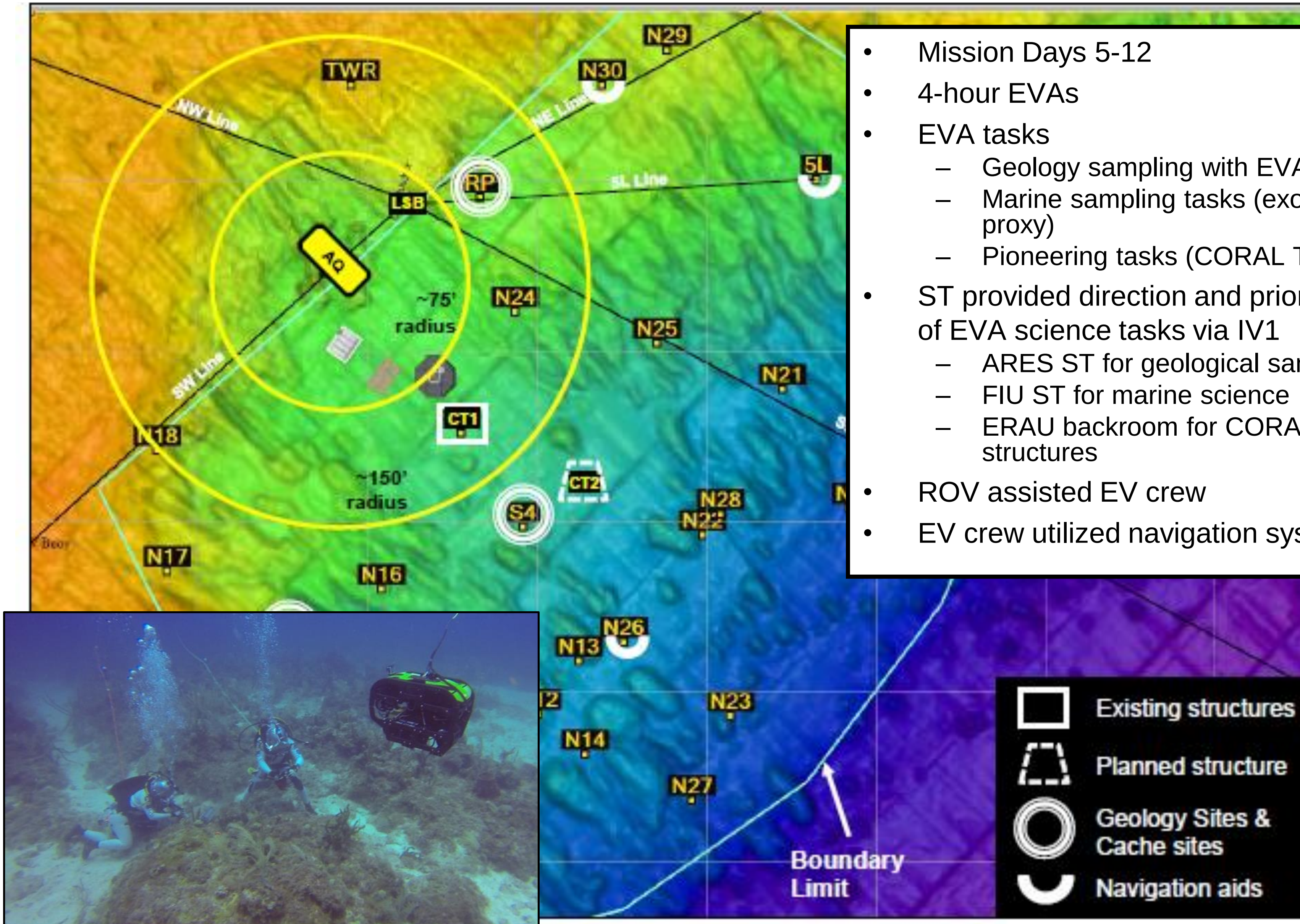


Phobos / Milli-g EVA Overview

- Mission Days 3-4
- Two 2-hour EVAs
- Ops based off of a boom deployed from a habitat
- EV crew took geology samples with EVA Integrated Geology Sampling System
- Science priorities and tasks driven by ARES ST



NEEMO 20 Mission Architecture for EVA Surface / Partial-g EVA Overview

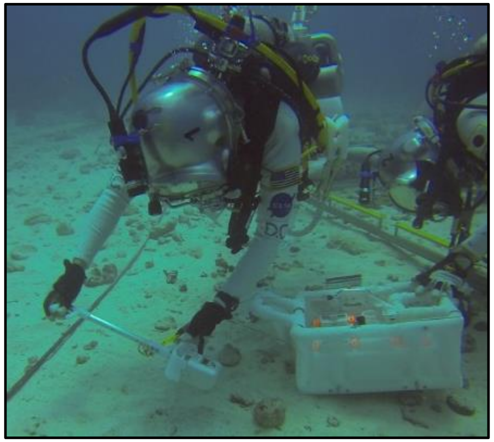


- Mission Days 5-12
- 4-hour EVAs
- EVA tasks
  - Geology sampling with EVA tools
  - Marine sampling tasks (exobiology proxy)
  - Pioneering tasks (CORAL Towers)
- ST provided direction and prioritization of EVA science tasks via IV1
  - ARES ST for geological sampling
  - FIU ST for marine science
  - ERAU backroom for CORAL structures
- ROV assisted EV crew
- EV crew utilized navigation system

EVA Sample Collection Hardware and Operations Key Summary Points

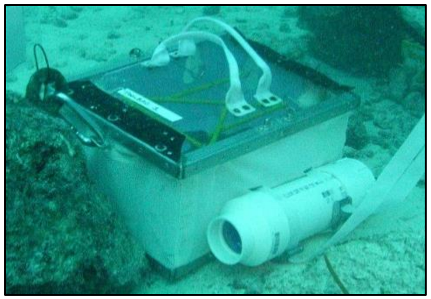
EVA Integrated Geology Sampling System

- Objective
  - Evaluate EVA hardware and operations for science sampling
- Purpose
  - The *integrated* sampling kit is focused on sample containment and a more flight-like contamination protocol
  - Design concept consists of a “briefcase” designed for sample management, ease of operation, and consistency across sampling activities
  - The Sample Briefcase houses various End Effectors (float, soil, surface, chip, core)
  - Two different Drivers enable crew to secure samples manually or with a powered device
- Summary Take-Away for EVA
  - Concept proved feasible for EVA collection of geology and astrobiology (marine science) samples, and was easy to deploy and utilize
  - Provides a viable method for minimizing sample contamination, though its size and mass are rather large compared to the actual samples obtained
- Recommendations for Forward Work
  - XX, EC7, and XI need to look at minimizing the size/mass of the tools while maximizing return samples
  - Further work should be done on methods or modifications to keep the EV crew from contaminating areas as they arrive to take samples, especially if utilized on a partial-g surface EVA
  - Recommendations for possible improvement of individual components (drivers, end effectors, and container) should be incorporated into the next version of prototype tools, including looking at tools specifically for surface ops

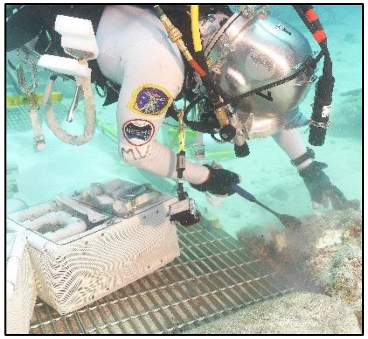


EVA Sample Containment Hardware Road To Flight

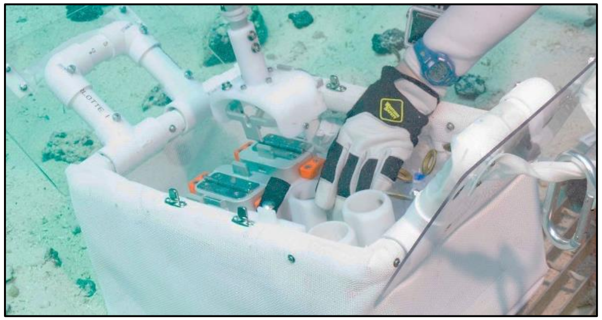
- Tool improvements for potential use on an asteroid will be incorporated into designs for the next generation of hardware
- Designs will be iterated between evaluations at NEEMO and in the NBL



Metal Frame Crew Lock Bag
NEEMO 17 (SEATEST 2)



PVC Crew Lock Bag
NEEMO 18/19

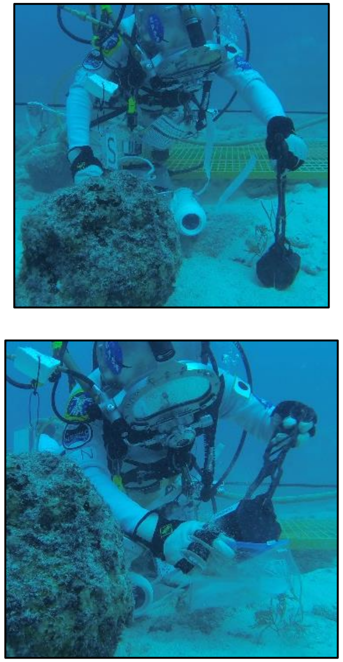


PVC Sample Briefcase
NEEMO 20

Sample Containment Briefcase (ARM DRM animation)

EVA Sample Collection Tools
Road To Flight

- Tool improvements for potential use on an asteroid will be incorporated into designs for the next generation of hardware
- Designs will be iterated between evaluations at NEEMO and in the NBL
- Team will look at modifying tools for better use in a partial-g/surface environment



Soil Sampler
NEEMO 17
(SEATEST 2)

Manual Driver w/
Float/Soil End Effector
NEEMO 20

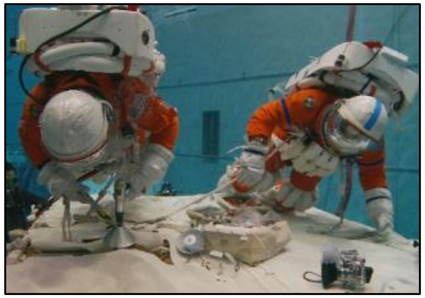
Manual Float/Soil Sample
(ARM DRM animation)

EVA Sample Collection Tools Road To Flight

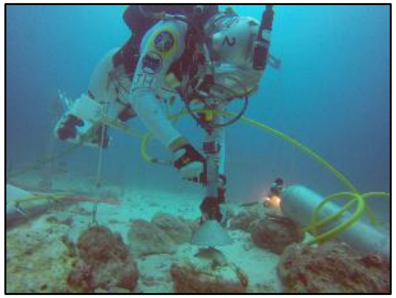
- Tool improvements for potential use on an asteroid will be incorporated into designs for the next generation of hardware
- Designs will be iterated between evaluations at NEEMO and in the NBL
- Team will look at modifying tools for better use in a partial-g/surface environment

Pneumatic chip - NEEMO 20

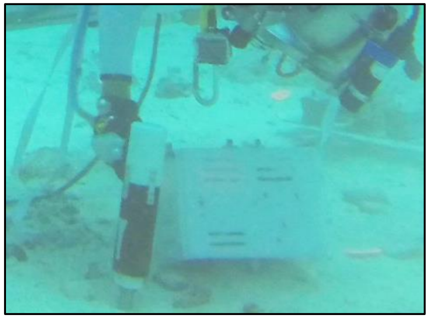
Pneumatic hammer
NEEMO 17
(SEATEST 2)



Pneumatic hammer
NBL/MACES



Pneumatic hammer
NEEMO 18/19



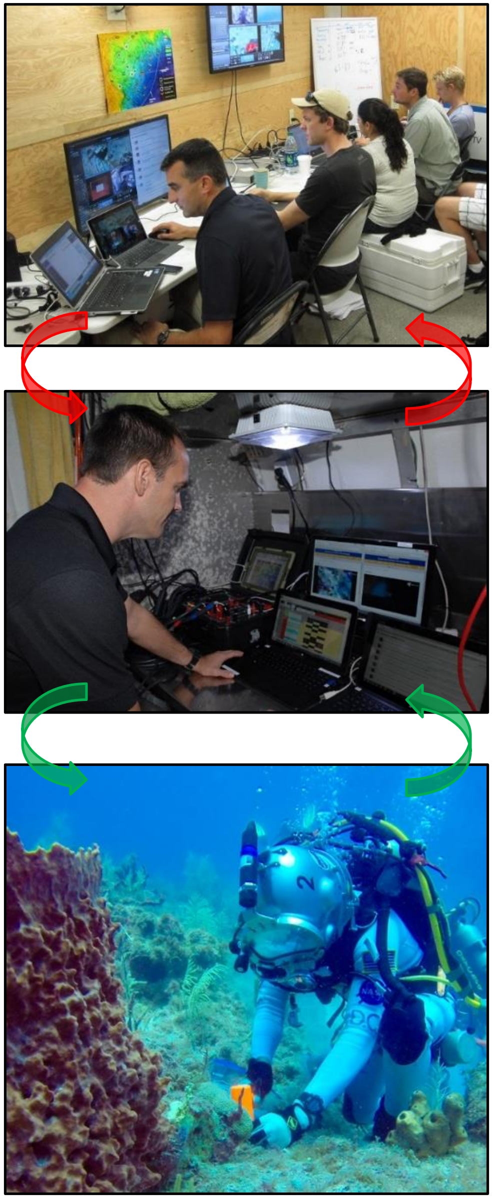
Pneumatic core - NEEMO 20

Powered rock chip hammer/core drill concepts (ARM DRM animation)

EVA Interaction with MCC/ST Over Comm Latency Key Summary Points

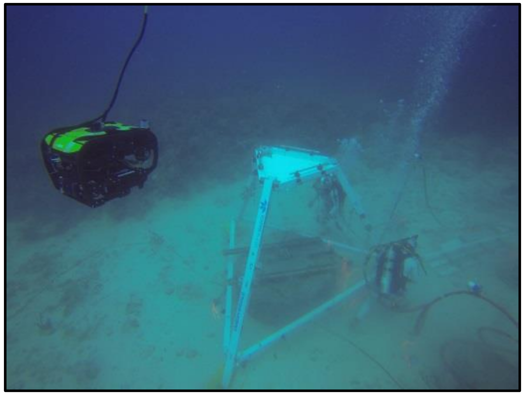
Science Team Integrated with EVA Ops

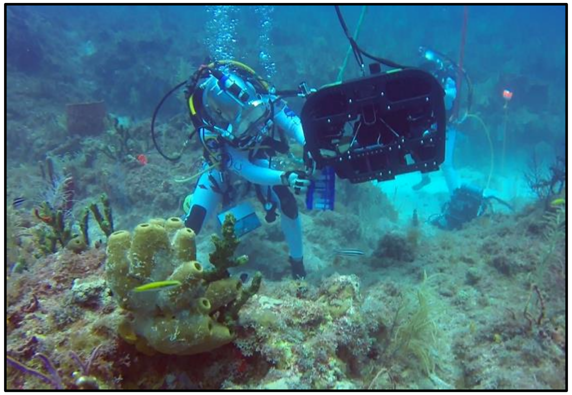
- Objective
  - Continue to enhance understanding of comm limitations by including MCC/ST response time and comm with IV, and continue to investigate practicality of directing EVA operations from MCC over a comm latency
  - Investigate how a Science Team engages with the crew in order to influence an EVA
- Summary Take-Away for EVA
  - Science ops can be constructed such that a Science Team on Earth can provide relevant, timely feedback to influence the plan and sampling tasks during an EVA, provided that the EVA is timelined such as to allow the transmission of data back and forth (i.e., having multiple sites to move between and having some tasks that don't require MCC input), though it may be better to have well trained crew that can operate autonomously from a plan, and only have the ST call for deltas/go-backs
  - The Science Team needs to be a focal point of the primary MCC team (not a "backroom"), and be fully integrated with all other operations taking place
  - The geology tasks and the coral science tasks (used as an analogous proxy to exobiology with similar sampling techniques) provided planetary science tasks that were realistic enough to effectively test and evaluate these ops concepts during an integrated mission
  - Some sort of IV support system will be critical due to the amount of information and tasking the IV crewmember must contend with (essentially performs the roles of IV, Flight Director, partial EVA Officer, and partial BME)
- Recommendations for Forward Work
  - Further examine the role of a Science Team as a primary MCC team and how that team can influence an EVA during future NEEMO missions
  - Engage planetary protection personnel during NEEMO to begin looking closely at how ops cons will effect the planet



Robotic Asset for EVA

- Objective
  - Assess potential operations of a robotic asset for EVA and inform functional needs of a robot for EVA tool management
- Summary Take-Away for EVA
  - The ROV was successfully flown by an IV crewmember at two of the sites for situational awareness and to assist the EVA crewmembers
  - Low latency robotics (in this case the ROV controlled from the Aquarius) are able to offload EV workload for tasks like transporting samples, tools, etc. when the robotic element is working alongside the EV crew
  - Stabilizing features (like autopilot, or ability to "park") are necessary to offload the pilot and allow him to concentrate on other tasks (e.g., science, timeline/ops, and safety)
- Recommendations for Forward Work
  - Continue to explore the ops con associated with making the man-machine work system more efficient in the end-to-end environment enabled by NEEMO
  - Significant opportunities remain to investigate Man-Machine Work System when the robotic element is working in parallel to the EV crew
    - It could be doing site recon today at a site the EV crew will visit tomorrow, while the EV crew is working a different site today
    - Robotic element could also be utilized to transport more things to/from the EV crew

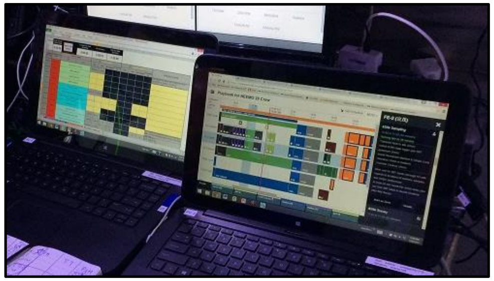


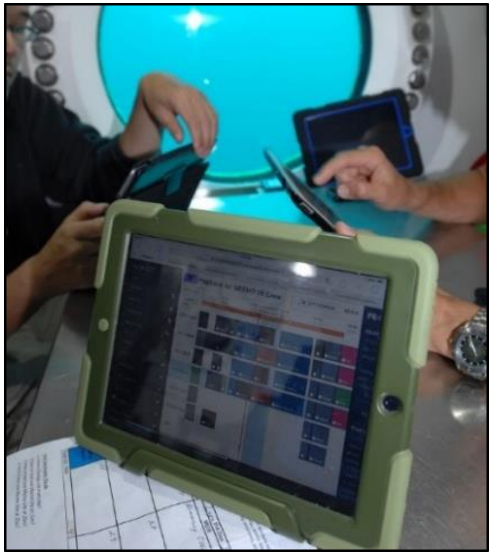


Crew Self-Scheduling & EVA Sample Marker Key Summary Points

Multi-Day Crew Self-Scheduling of EVAs

- Objective
  - Investigate crew driven multi-day planning of EVA operations utilizing scenarios with variables and a task list that must be planned and carried out over the course of multiple days
- Summary Take-Away for EVA
  - The crew was able to successfully self-schedule executable EVA timelines; however, the time penalty was large (~4 man-hours/day) and the advantages did not outweigh the costs
  - A better ops concept than crew self-scheduling would be crew “self-determination”, meaning that they determine what tasks get done on which EVA, but the actual scheduling is done by professional planners who are more adept at manipulating plans and more intimately familiar with all the myriad of constraints
- Recommendations for Forward Work
  - Test concepts for optimizing EVA multi-day planning that incorporates crew input based on the unique in-situ knowledge they’ve acquired, while taking advantage of the skills and efficiencies that ground based planners bring



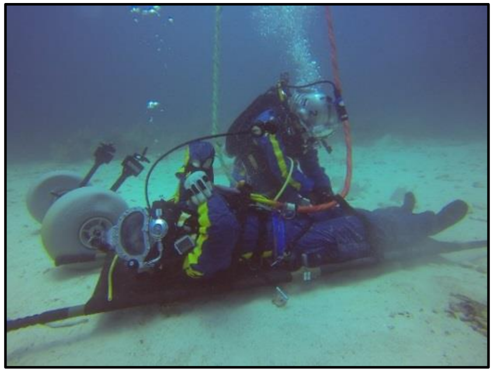


EVA Sample Marker

- Objective
  - Evaluate an EVA tool for identifying and high grading samples
- Summary Take-Away for EVA
  - Temporary markers are critical when communicating with IV and ST/MCC
  - It was difficult to deploy the markers in the middle of a site without disturbing the area - it would be good to have a way to deploy markers further away
- Recommendations for Forward Work
  - Current version has color bars and scale markings - look further into what gives the ST the information needed to evaluate potential samples, iterate the design, and test the next version during future NEEMO missions

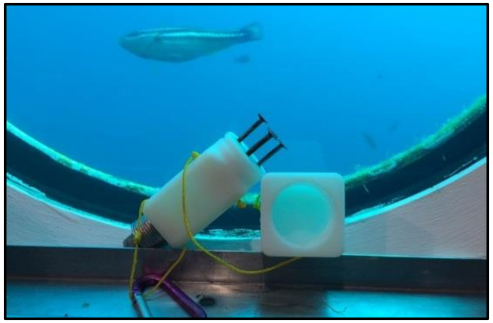
Incapacitated Crew Rescue

- Objective
  - Assess hardware and techniques for incapacitated crew rescue
- Summary Take-Away for EVA
  - Crew were able to use the litter in both configurations to rescue each other, though the litters will need significant modifications to make them more EVA compatible
- Recommendations for Forward Work
  - Further research and testing should include equipment improvements and heavier simulated crew weight to drive out required methods



Building EVA Hardware In Situ (3D Printer)

- Objective
  - Investigate building EVA hardware in situ
- Summary Take-Away for EVA
  - The 3D printer proved useful numerous times during the course of the mission for:
    - Designing and printing broken end effectors
    - Printing a missing part (an alignment pin)
    - The design from scratch and rapid delivery of a part whose need hadn't been anticipated pre-mission (nail holder)
  - The speed with which pieces can be fabricated proves its promise as a rapid turnaround parts solution
- Recommendations for Forward Work
  - Continue utilizing the 3D printer during the next NEEMO missions for creating unforeseen items that the crew needs



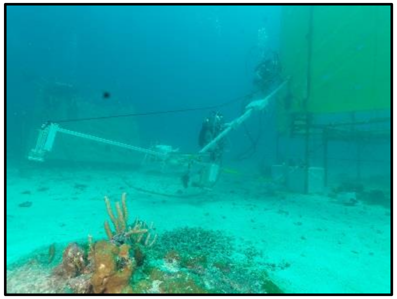
EVA Navigation & Deployable Boom for Sampling Key Summary Points

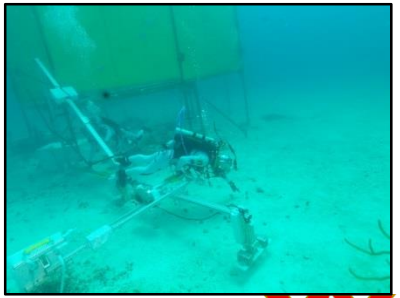
EVA Navigation

- Objective
  - Begin looking at types of hardware needed and techniques for navigating on a foreign body
- Summary Take-Away for EVA
  - Since the planetary science goal of an Exploration mission is to characterize an area more than pick up a specific rock, a navigation system more needs to get the crew close to a target that landmarks an area rather than locate a specific sample
  - Electronic navigation will be critical in areas where the terrain looks similar, especially when marking new locations and returning to a site
- Recommendations for Forward Work
  - Continue investigating electronic navigation that allows the crew to locate a specific area to characterize, mark new locations, and return to sites

Phobos Habitat EVA Deployable Boom

- Objective
  - Examine a manually deployable truss structure for EVA translation and sampling ops
- Summary Take-Away for EVA
  - A boom deployed from a Phobos mobile habitat will work for performing EVA geology sampling (16 ft. boom tested)
  - Lack of mechanical advantage and control made use difficult, and ability to control exactly where the feet landed (so as not to land on top of a good sample) was sub-optimal
  - The movable foot restraint and crewlock bag stanchion worked well for sampling operations and helping to minimize contamination of the worksite
- EVA Recommendations for Forward Work
  - Develop improvements in equipment and methods for deploying, stowing, and manipulating the boom
  - Perform evaluations of a full length boom if this type of sampling continues to be a significant part of HAT's Moons of Mars reference mission

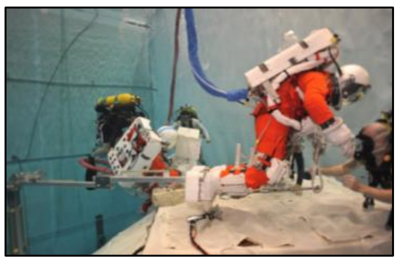




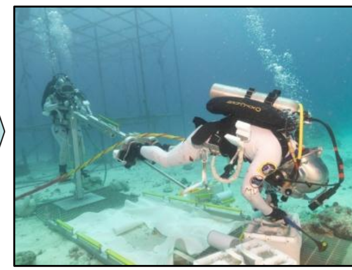
EVA Stabilization Aids
Road To Flight

- Boom improvements for potential use on an asteroid and/or Phobos will be incorporated into designs for the next generation of hardware
- Designs will be iterated between evaluations at NEEMO and in the NBL

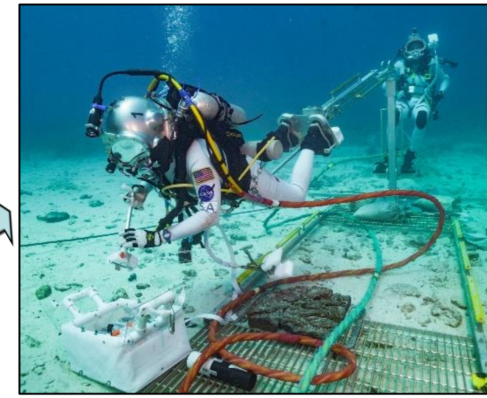
Booms
NEEMO 15/16



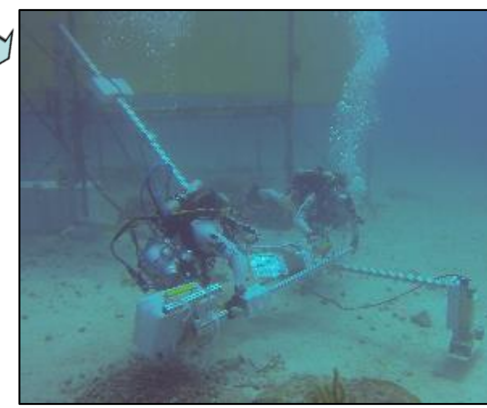
"Boom 1.0"
NBL/MACES Evals



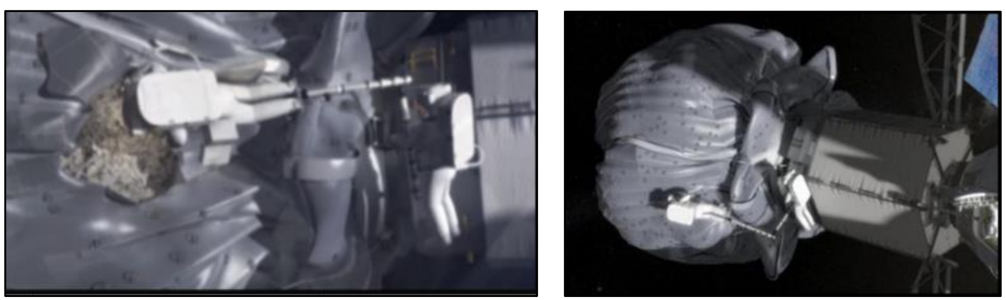
"Boom 2.0"
NEEMO 18/19



"Boom 2.0" - NEEMO 20



"Phobos Boom" - NEEMO 20



Stabilization Boom concept
(ARM DRM animation)

ISS and IVA Objectives Key Summary Points

Project Sidekick with Hololens

- NEEMO 20 crew evaluated the NASA JPL project "Sidekick", which uses the HoloLens mixed-reality headset for remote assistance of crew members on ISS
- Take-away for EVA: Inclusion of this type of technology in a spacesuit could allow an IV crewmember to more easily guide an EV crewmember through both pioneering and science tasks

ODG R6 Headset and Augmented Reality

- NEEMO 20 crew evaluated the Osterhout Design Group (ODG) R6 Augmented Reality Headset to conduct maintenance tasks within the Aquarius habitat
- Take-away for EVA: This type of procedure delivery and augmented reality, if incorporated into a spacesuit, could help EVA crew perform construction and maintenance tasks for which they haven't been trained or for which it's been a long time since training

MobiPV

- MobiPV is an ESA developed set of assistive communication tools and displays enhancing Crew–MCC interaction for hands-busy crew activities
- Take-away for EVA: This type of technology could be useful in talking crew through non-standard procedures, such as the R&R of an FPS

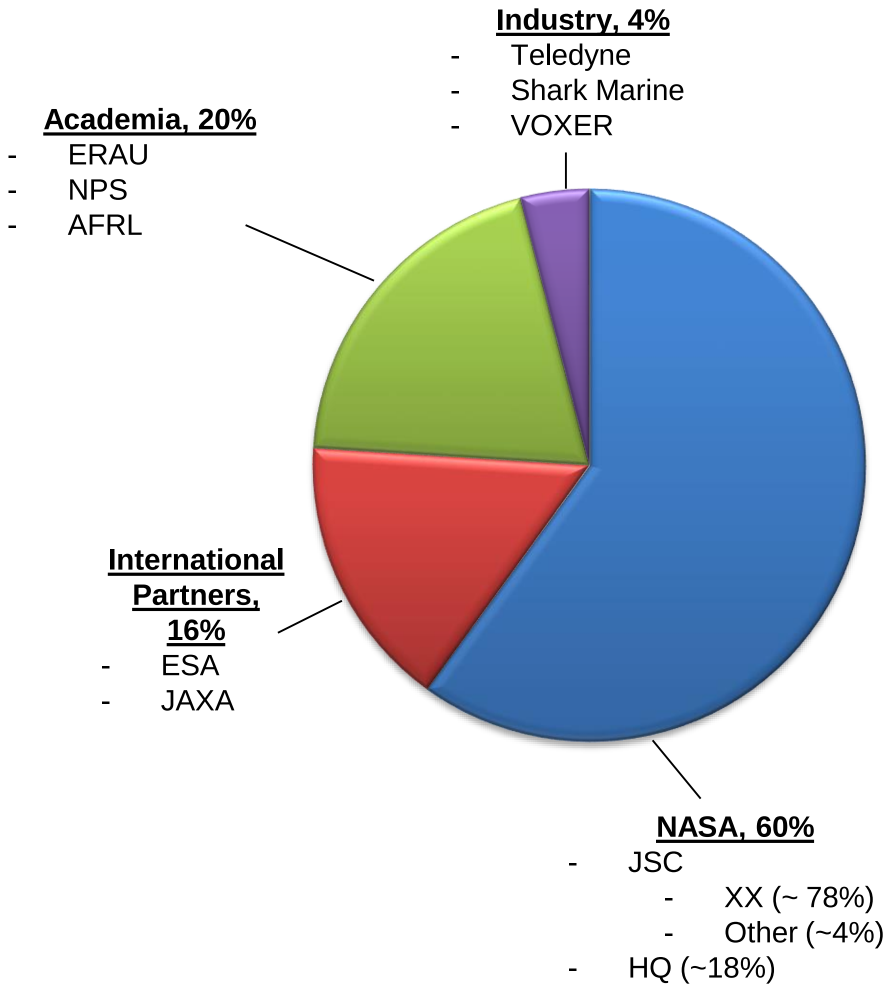
For all: EVA Office involvement as these tools and techniques are being developed and tested ensures we are well positioned to take advantage of future advances in this field.

NEEMO 20 Funding through Collaborations

- Mission funding raised by collaborations with interested partners
  - ⇒ No line item budget to pay for mission costs

- XX spent $200K total, plus CS travel for 2 from EC7
  - $125k ➡ FIU (facility)
  - $65k ➡ EC (tools)
  - $10K ➡ ARC (scheduling tools)

- XX received
  - Cat 1 Priority on mission design (EVA objectives were top mission priority)
  - 52 hrs EVA time
  - Embedded engineer on Crew
  - Leveraged assets that we did NOT pay for:
    - Pioneering tasks
    - ROV access



Local Facility Testing vs Operational Field Testing

NBL

- Strengths
  - Hi-fi pressurized suits, including gloves
  - Hi-fi vehicle hardware interfaces for select reference missions (Orion and ARV)
  - Local access (no travel for most of team)
- Weaknesses
  - Run availability is limited
  - Only able to conduct one EVA per day with a single pair of crew
  - Test subjects limited by suit fit, especially for non-EMU suits like MACES
  - Unable to support partial-g ops con evaluations (due to space and terrain)
  - Not set up to operate 24 hours a day to evaluate multi-day planning and operations
- Cost
  - Safety Review/TRR: $8,260
  - EMU run: $52,560+ per run
    - Assumes 2 suits for 6 hours
    - Does not include costs for suits or tools
  - MACES run: $44,150+ per run
    - Min of 2 runs required (1 for egress)
    - Assumes 2 suits for 4 hours
    - Does not include cost for suits or tools
  - SCUBA run: $1,790+ per run
    - Does not include costs of tools

NEEMO

- Strengths
  - Hi-fi vehicle hardware interfaces for select reference missions (Mars surface, ARV, Mars Moon)
  - Availability
    - We are the priority user
    - Full mission or engineering modes
    - Multiple consecutive days
  - Infrastructure and test configuration already supports the following:
    - IV workstation to support Exploration EVA
    - Operational comm latency
    - 24 hour-a-day operations (to allow evaluation of multi-day planning and operations)
    - Professional science team with vested interested in the sampling operations
  - Exploration terrain and scale (large areas to evaluate ops cons)
  - Able to conduct multiple EVAs per day with different crew
  - Test subjects not limited by suit fit
  - Provides an opportunity for team members to gain operational experience for professional growth
- Weaknesses
  - Lo-fi suits and gloves
  - Requires travel
  - Somewhat weather dependent (rare and can be mitigated)
- Cost
  - $15k per day
    - Assumes 4 hours of EVA for 2 crew
    - Includes dive system and support boats
    - Does not include travel

Summary of Benefits to XX

- Due to the high fidelity operations nature of NEEMO missions, with experienced end operators, we were able to significantly advance XX4 objectives across a range of destinations and gravity gradients with respect to:
  - Informing updates to the **EVA Ops Con document** (EVA-RD-004)
    - Next update containing N20 lessons learned scheduled for release in mid FY16
  - Evaluating objectives that facilitate SMT gap closure and CAPTEM findings
    - Provided closure data for 14 open **SMT gaps**, 5 of which required the large operational area afforded by NEEMO
    - Addressed 2 open **CAPTEM findings**
  - Providing data for hardware design maturation to assist in road-to-flight, especially the **EVA science sample collection tools**
    - Evaluations of prototype EVA hardware are directly leading towards more refined tools that allow for sample containment and a more flight-like contamination protocol
  - Assessing ops cons and needs associated with EVAs that require input from MCC over a comm latency
    - Cooperation between EVA engineers and scientists brought the two groups further in sync on addressing CAPTEM findings and figuring out how to conduct sampling at future destinations
- Enhancing relationships with international partners, academia, and other NASA orgs
  - Russian counterparts interested in participating with 1-2 crewmembers and mission objectives for a future NEEMO mission due to XX facilitation of their observation

Recommendations

- Operational field tests of EVA operations concepts and hardware should continue to be evaluated on future missions, with focus on furthering closure of SMT gaps
- Action to XX4/EEWG to develop proposed NEEMO 21 objectives for XX Management consideration
  - Due 12/18/15, with goal to have a decision on level of XX support for NEEMO 21 by mid January

BACKUP

Additional Information in Backup

- EVA Objectives & SMT Gaps Addressed
  - NEEMO 20 EVA Objectives (with gap mapping)
  - EVA SMT Gaps to Address at NEEMO
- NEEMO 20 Overview & EVA Objectives
  - EVA at NEEMO
  - EVA Schedule
- EVA Hardware & Tools
  - Integrated Geology Sampling System
  - Phobos Habitat EVA Deployable Boom
  - EVA Sample Marker
  - Incapacitated Crew Rescue
- EVA Operations Concepts
  - EVA Interaction with MCC/ST Over Comm Latency
  - Robotic Asset for EVA (Man-Machine Work System)
  - Multi-Day Crew Self-Scheduling of EVAs
  - EVA Navigation
  - Building EVA Hardware In Situ (3D printer)
- Science Observations for EVA
- ISS & IVA Objectives
  - Project Sidekick with Hololens
  - ODG R6 Headset and Augmented Reality
  - MobiPV
- NEEMO 20 High Level Info

NEEMO 20 Dive Team!

Additional Backup Details

EVA OBJECTIVES & SMT GAPS ADDRESSED

EVA SMT Gaps to Address at NEEMO (in blue)

- 101: Identify CG for Suited Crew
  - Determine CG of the PGS & AEMU. Analyze how a suitport interface plate (GC#400) would effect the CG.

- 214: Navigation Short Range
  - DDT&E for a navigation system that can be packaged and integrated into an AEMU which provides less than 1m position error at a range of 200m or less from a known starting point, such as a rover.
  - NEEMO 20 began looking into the types of systems and techniques needed for EVA navigation on a foreign body.

- 405: Suit Maintenance Location
  - Perform a trade study (jointly with ECLSS and vehicle) of vehicle design options for an internally located EVA maintenance area. Trade to include ingress/egress methods (401), vehicle services at maintenance area, volumes, mudrooms, dust mitigation (408), and commonality across vehicles. Trade study should also include cleanliness levels needed for each R&R, dust mitigation & cleaning.

- 406: Rescue Incapacitated Crew Member
  - Perform trade study with testing for incapacitated crew rescue for each DRM and each lock concept (airlock, suitport, etc).
  - DDT&E to develop necessary aids to allow an incapacitated crewmember to be moved in a planetary environment by a single healthy crewmember.
  - NEEMO 20 provided an initial look at the types of hardware and techniques needed to rescue an incapacitated crewmember while on EVA.

- 411: Umbilical Trade for Life Support
  - DDT&E for joint ECLSS-EVA umbilical system for non-PLSS EVAs. Based on 801, 802, and 810; perform trade study to determine method of life support umbilical to use for non-PLSS based contingency EVA (open loop, closed loop, etc.).

EVA SMT Gaps to Address at NEEMO (in blue)

- 501: Microgravity stability and anchoring tools
  - DDT&E for crew anchoring/stabilization tools/methods at microgravity destinations which do not include "engineered surfaces" such as Asteroids and Mars Moons
  - NEEMO18-19 provided information on a prototype EVA Stabilization Boom
  - NEEMO 20 investigated the use of an EVA boom deployed from a Phobos mobile habitat

- 502: Micro-g tool for loosely adhered particles
  - DDT&E of a microgravity EVA tool to sample loosely adhered particles from a micro-gravity body such as a NEA
  - NEEMO18-19 evaluated a prototype EVA Powered Rock Chip Hammer and EVA Sample Bag Dispenser
  - NEEMO 20 investigated a soil/float end effector as part of the Integrated Geology Sampling System

- 503: Micro-g tool for chip samples
  - DDT&E of a microgravity EVA tool to sample from the surface of a solid object such as a NEA or Mars Moons. Tool will include features to separate a "chip" from the object as well as capture the chip before it floats away
  - NEEMO18-19 provided information on a prototype EVA Powered Rock Chip Hammer and chisel bell:
  - NEEMO 20 investigated a chip end effector as part of the Integrated Geology Sampling System

EVA SMT Gaps to Address at NEEMO (in blue)

SMT Gaps (con't)

- 504: Micro-g tool for subsurface samples
  - DDT&E of a microgravity EVA tool to capture a subsurface sample from a solid object - Tool is expected to include any necessary mounting features to allow it to remain in contact with the object as it "drills" into the object.
  - N18-19 provided information on a prototype EVA Deep Core Drill
  - NEEMO 20 investigated a hand-held coring tool as part of the Integrated Geology Sampling System, the results of which are being combined with that of the HBR ARM BAA

- 505: Sample Storage and Curation
  - DDT&E for sample curation, packaging and labeling. Some samples may be considered volatile and/or require special handling. Hardware development and evaluation to be conducted with scientific community input.
  - NEEMO 20 investigated the "sample briefcase" as part of the Integrated Geology Sampling System

- 509: In-situ High Grading, EVA Tool
  - DDT&E of tool suite to perform in-situ high-grading of samples collected during EVA to determine subsequent sample handling, disposal, or other curation plans.
  - NEEMO 20 investigated operations with a temporary sample marker that provided the science team some basic information about the potential sample

- 510: Tool management device
  - Conduct trade study, based on operational concept for each mission (801), to determine what tool management methods will be most efficient (e.g. tool caddy/type of tool caddy, robotic assistant, translating going back and forth to a central tool box, etc).
  - N18-19 to evaluated a prototype EVA Sample Bag Dispenser
  - NEEMO 20 evaluated using a robot (ROV) to assist EVA crew

EVA SMT Gaps to Address at NEEMO (in blue)

SMT Gaps (con't)

- 511: Microgravity translation aids for non-engineered surfaces
  - Based on 501 (DDT&E for crew anchoring/stabilization tools/methods at microgravity destinations), DDT&E installable EVA translation aids for "non-engineered surfaces" such as Asteroids and Mars Moons. Develop and evaluate prototype crew deployed translation systems
  - N18-19 provided information on a prototype EVA Stabilization Boom for ARM
  - NEEMO 20 investigated the use of an EVA boom deployed from a Phobos mobile habitat

- 512: Common Tools for vehicle maintenance
  - Refine & update the list of Common EVA Maintenance Tools/interfaces that vehicles should use to design their maintenance interfaces (i.e. all bolts which are EVA accessible are 7/16" double height bolts).
  - NEEMO 20 evaluated printing tools in situ with a 3D printer

- 703: EVA use model
  - Continue working on EVAs per DRM spreadsheet tool to determine sensitivities in ops con assumptions concerning number and frequency of EVAs, ex: two 3 hour EVAs, 24 hour max per week per crewmember
  - N18-19 to evaluated autonomous crew self-planning of EVAs
  - NEEMO 20 evaluated multi-day crew self-scheduling of EVAs
  - NEEMO 20 tested the use of the Science Backroom Team to influence an EVA over comm latency

EVA SMT Gaps to Address at NEEMO (in blue)

SMT Gaps (con't)

- 801: DRM Maturity
  - Further matured DRM details are needed to clarify mission level requirements, mission elements, exploration goals, EVA model, duration, etc.
  - N18-19 to evaluated the following:
    - Prototype EVA Stabilization Boom
    - Prototype EVA Deep Core Drill
    - Prototype EVA Powered Rock Chip Hammer
    - Prototype Unpressurized Rover for use during milli-gravity EVAs
    - Remotely Operated Robot for EVA assistance
    - Autonomous crew self-planning of EVAs
    - Effects of comm latency on EVAs (also evaluated at PLRP 2014)
  - NEEMO 20 evaluated the following:
    - Integrated Geology Sampling System
    - Multi-day crew self-scheduling
    - Use of a robotic (ROV) assistant during an EVA
    - Effects of comm latency on EVAs, including having a Science Backroom Team influence operations during an EVA
    - Hardware and techniques for rescuing an incapacitated EVA crewmember
    - Building hardware in situ (3D printer)
    - Prototype EVA boom deployed from a Phobos mobile habitat
    - Techniques needed for EVA navigation on a foreign body

EVA SMT Gaps to Address at NEEMO (in blue)

SMT Gaps (con't)

- 805: Scientific Objectives
  - Conduct coordination with science community to define common list of extraterrestrial geology activities/samples and supporting tools required to conduct sampling activities
  - N18-19 to evaluated the following:
    - Prototype EVA Deep Core Drill
    - Prototype EVA Powered Rock Chip Hammer
  - NEEMO 20 evaluated the Integrated Geology Sampling System
  - NEEMO 20 evaluated a temporary sample marker to help a science Backroom Team high grade samples
- 807: Mission Module capabilities
  - Based on 801, for each DRM, need development of the assets (modules, rovers, cargo carriers, in-space habs, landers, etc.) to include functional requirements for each asset and its capabilities
  - N18-19 to evaluated the following:
    - Prototype Unpressurized Rover for use during milli-gravity a EVA
    - Use of a Remotely Operated Robot for EVA assistance
- 808: Human Performance Per EVA Model
  - Need trade study / test of human performance compared between various EVA models; for example, is a daily 8-hr EVA more/less productive than two 3-hr EVAs daily. Human performance is measured by number of EVA tasks completed, injury rate, etc.
  - Use resulting human performance metrics to inform EVA timelines for each mission and overarching mission objectives. Also informs vehicle designs and technologies.
- 810: DRM, Contingency EVA Definition
  - Based on DRM (801), need agency/program level endorsed definition of contingency EVA per mission. What modules have contingency EVA scenarios? Are the contingency EVAs PLSS based or Umbilical based? What suit will be worn? What tasks will be performed via EVA crew?

CAPTEM

- CAPTEM 5: Collection of 1000 g from two sites
  - N18-19 to evaluated the following:
    - Prototype EVA Stabilization Boom
    - Prototype EVA Deep Core Drill
    - Prototype EVA Powered Rock Chip Hammer
    - EVA Sample Bag Dispenser
  - NEEMO 20 evaluated the Integrated Geology Sampling System

- CAPTEM 6: Core Samples
  - Demonstrate powered core sampling (pneumatic hammer with core tube attached)
  - Manual/powered sampling device that obtains a minimum 4cm deep but maintains stratigraphy (possible spring loaded linear tube or tree planter)
  - N18-19 to evaluated the following:
    - Prototype EVA Deep Core Drill
    - Prototype EVA Powered Rock Chip Hammer
    - EVA Sample Bag Dispenser
  - NEEMO 20 evaluated an EVA handheld power driver with core end effector

NEEMO 20 EVA Objectives (in priority order)

	Objectives	Details/Goals	Gap closures addressed	Mission
1	Evaluate EVA hardware and operations for capturing rock chip samples and protecting them against contamination	Test prototype rock chip hammer Chip Capture Mechanism (CCM) end-effector that interfaces with a common powered driver	503: Micro-g tool for chip samples 801: DRM Maturity 805: Scientific Objectives CAPTEM 5: Collection of 1000 g from two sites	Micro-g (Cis-lunar asteroid) Milli-g (Mars' moons) Partial-g / surface (Mars, Lunar)
2	Evaluate hardware and operations for stowing samples collected during an EVA	Test plug-and-play sample collection containers (briefcases) that house a variety of tool end effectors and sample types (chip, float, surface, soil, core)	505: Sample Storage and Curation 801: DRM Maturity 805: Scientific Objectives CAPTEM 5: Collection of 1000 g from two sites	Micro-g (Cis-lunar asteroid) Milli-g (Mars' moons) Partial-g / surface (Mars, Lunar)
3	Evaluate EVA hardware and operations for capturing float samples and protecting them against contamination	Test prototype sample collection end effectors (float, surface, soil) that interface with a common handle/actuation mechanism	502: Micro-g tool for loosely adhered particles 801: DRM Maturity 805: Scientific Objectives CAPTEM 5: Collection of 1000 g from two sites	Micro-g (Cis-lunar asteroid) Milli-g (Mars' moons) Partial-g / surface (Mars, Lunar)
4	Evaluate EVA hardware and operations for capturing soil samples and protecting them against contamination			
5	Evaluate EVA hardware and operations for capturing surface samples and protecting them against contamination			
6	Evaluate EVA hardware and operations for obtaining a core/subsurface sample and protecting it against contamination	Test prototype hand core drill end-effector that interfaces with a common powered driver	504: Micro-g tool for subsurface samples 801: DRM Maturity 805: Scientific Objectives CAPTEM 5: Collection of 1000 g from two sites CAPTEM 6: Core Samples	Micro-g (Cis-lunar asteroid) Milli-g (Mars' moons) Partial-g / surface (Mars, Lunar)

NEEMO 20 EVA Objectives (in priority order)

	Objectives	Details/Goals	Gap closures addressed	Mission
7	Investigate crew driven multi-day planning of EVA operations	Build scenarios with variables and a task list that must be planned and carried out over the course of multiple days in order to more thoroughly investigate challenges associated w/ crew driven multi-day EVA planning Mature ops tools (Playbook) before ISS flight demo	703: EVA use model 801: DRM Maturity	Milli-g (Mars' moons) Partial-g / surface (Mars, Lunar)
8	Assess potential operations of a robotic asset for EVA	Continue systematically understanding how robotics will be valuable during EVAs Inform functional needs of a robot for EVA tool management	510: Tool management device 801: DRM Maturity	Micro-g (Cis-lunar asteroid) Milli-g (Mars' moons) Partial-g / surface (Mars, Lunar)
9	Enhance understanding of comm limitations (latency, bandwidth, and coverage) during EVA operations	Continue to enhance understanding of comm limitations by including MCC/ST response time and comm with IV, and continue to investigate practicality of directing EVA operations from MCC over a TBD comm latency	703: EVA use model 801: DRM Maturity	Milli-g (Mars' moons) Partial-g / surface (Mars, Lunar)
10	Evaluate an EVA tool for identifying and high grading samples	Upgrade and evaluate EVA sample markers that provide pertinent information to MCC/ST	509: In-situ High Grading, EVA Tool 805: Scientific Objectives	Micro-g (Cis-lunar asteroid) Milli-g (Mars' moons) Partial-g / surface (Mars, Lunar)
11	Assess hardware and techniques for incapacitated crew rescue	Use analog environment to provide data for type of rescue equipment needed and techniques used during rescue	406: Rescue Incapacitated Crew Member 801: DRM Maturity	Partial-g / surface (Mars, Lunar)

NEEMO 20 EVA Objectives (in priority order)

	Objectives	Details/Goals	Gap closures addressed	Mission
12	Investigate building EVA hardware in situ	Test using 3D printer to make EVA hardware	512: Common tools for vehicle maintenance 801: DRM Maturity	Micro-g (Cis-lunar asteroid) Milli-g (Mars' moons) Partial-g / surface (Mars, Lunar)
13	Evaluate EVA translation aids from a Mars' moons mobile habitat	Examine a manually deployable truss structure for EVA translation and sampling ops	501: Microgravity stability and anchoring tools 511: Microgravity translation aids for non-engineered surfaces 801: DRM Maturity	Milli-g (Mars' moons)
14	Begin investigating concepts for navigating EVA crew	Begin looking at types of hardware needed and techniques for navigating on a foreign body Make use of terrain at analog (features to avoid) and use transponders for GCA nav during multi-day EVA and possibly a crew rescue scenario If available, look at utilizing Navigator's electronic maps for navigation and way point updates	214: Navigation Short Range 801: DRM Maturity	Milli-g (Mars' moons) Partial-g / surface (Mars, Lunar)

Additional Backup Details

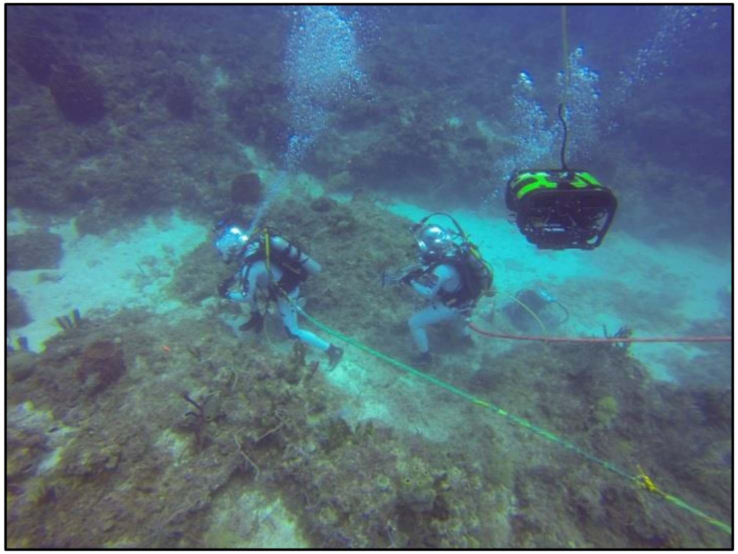
NEEMO 20
OVERVIEW & EVA OBJECTIVES

Background

- Future Exploration missions will potentially take humans to destinations where EVA work will be done on natural bodies that don't have built in aids
- These missions will also be at distance that precludes instantaneous real-time communication with the crew
- There are numerous technology and operations gaps associated with translation and stabilization tools, science sampling tools, and operational techniques for dealing with comm latency
  - EVA Systems Maturation Team (**SMT**) gaps
  - Curation and Analysis Planning Team for Extraterrestrial Materials (**CAPTEM**) findings
- EVA Office (XX) formulated a series of objectives for NEEMO 20 to begin closing these gaps

Why NEEMO?

- NEEMO provides a flexible environment that can mimic microgravity, milli-gravity, and partial gravity missions with EVA crewmembers performing tasks
- NEEMO allows for end-to-end testing of techniques and hardware in an operational scenario, with the crew in-situ and the ground team separated from them, which drives out problems not found in standalone testing and things that do and do not work in a mission situation

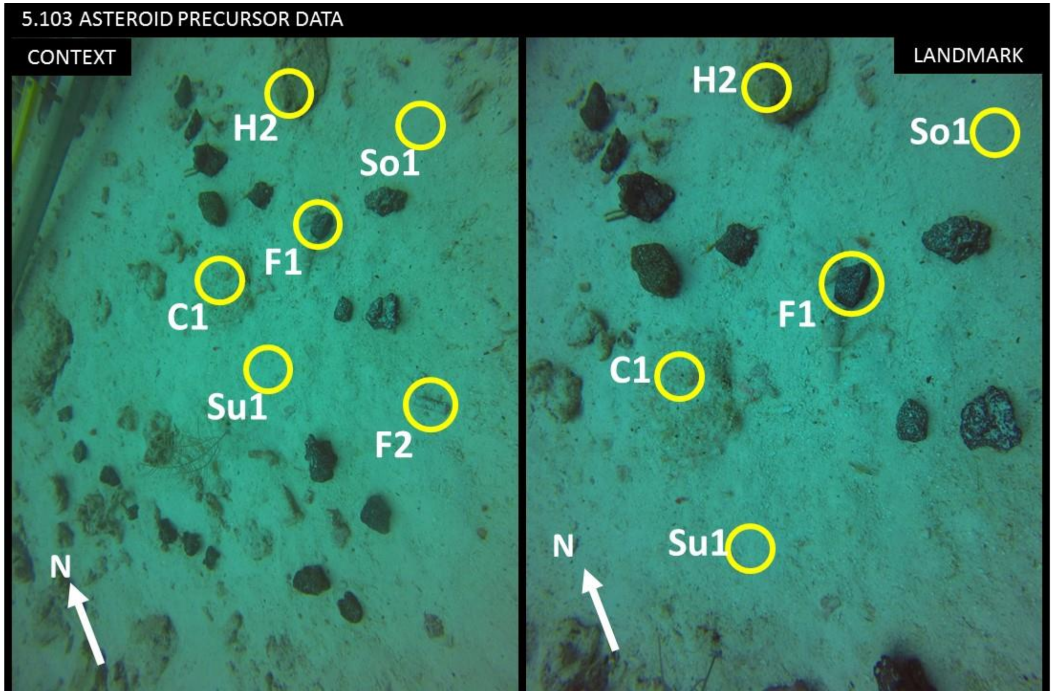


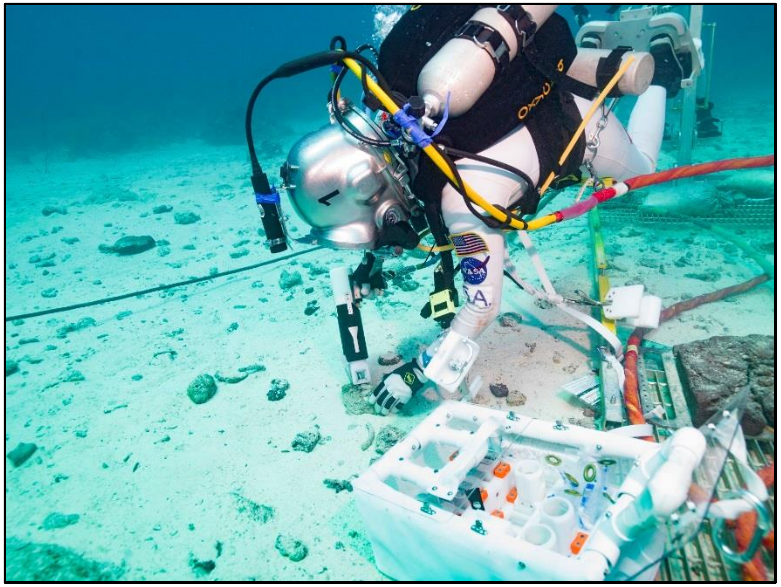
EVA Exploration Goals for NEEMO 20

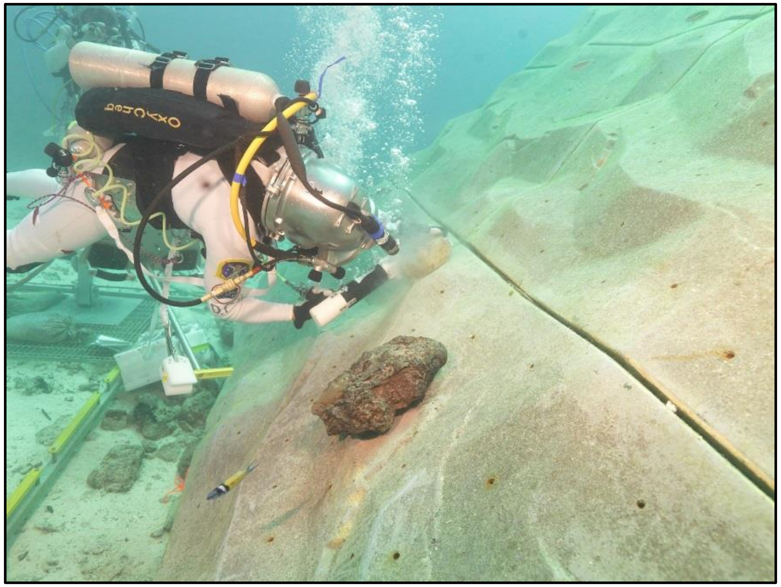
1. Evaluate EVA objectives that facilitate SMT gap closure
2. Address CAPTEM findings for EVA collection of science samples
3. Inform updates to the EVA Ops Con document (EVA-RD-004)
4. Provide data for hardware design maturation to assist in road-to-flight, especially the EVA science sample collection tools
5. Evaluate ops cons associated with more crew autonomy over a comm latency, such as self-scheduling of EVAs across multiple days
6. Assess ops cons and needs associated with EVAs that require input from MCC over a comm latency
7. Explore a range of destinations and gravity gradients
   a. Micro-g at asteroid/cis-lunar
   b. Milli-g at Mars' moons (Phobos)
   c. Partial-g on Mars and lunar surface

NEEMO 20 Mission Architecture for EVA
Asteroid EVA Tasks Overview

- Collected geology samples with Integrated Geology Sampling System
  - Based on precursor data
  - Per delta direction from the ST
  - Sampling on seafloor with all geology tools
  - Chip sampling from rocks mounted on the rock wall
- Utilized a stabilization boom while sampling

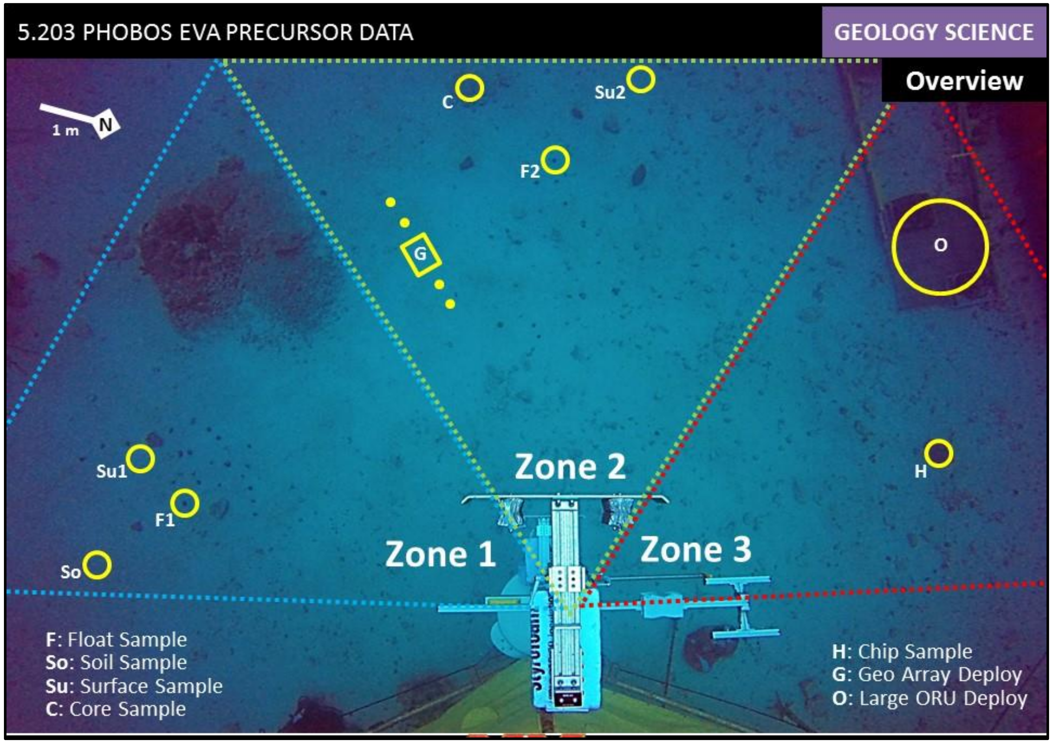


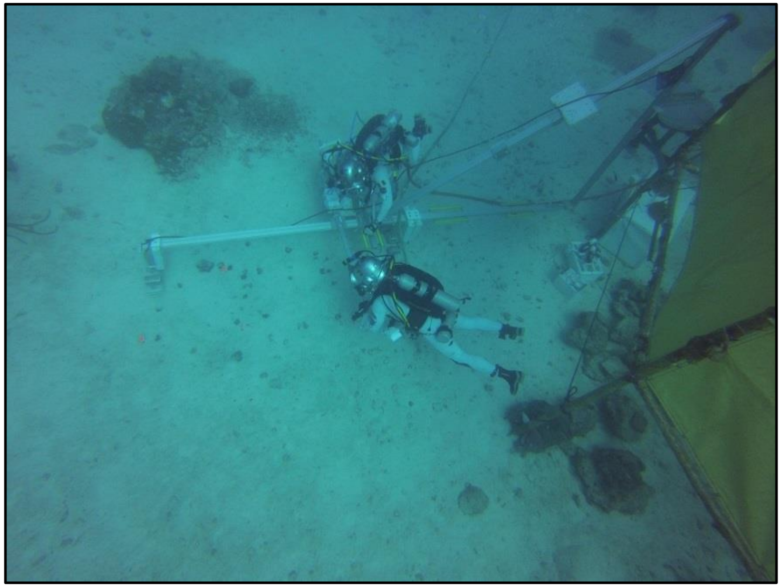




NEEMO 20 Mission Architecture for EVA
Phobos EVA Tasks Overview

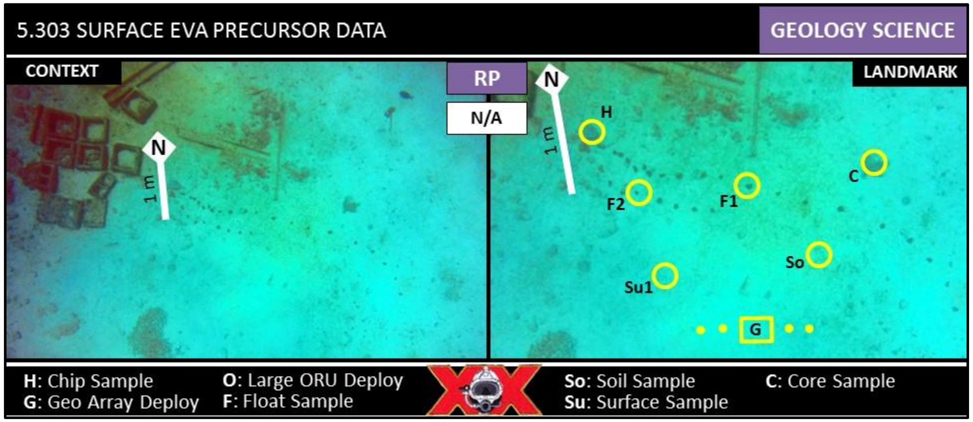
- Collect geology samples with EVA Geology Sampling System
  - Based on precursor data
  - Per delta direction from the ST
  - Geology sampling on seafloor with all geology tools
- Utilized a boom deployed from a "habitat"

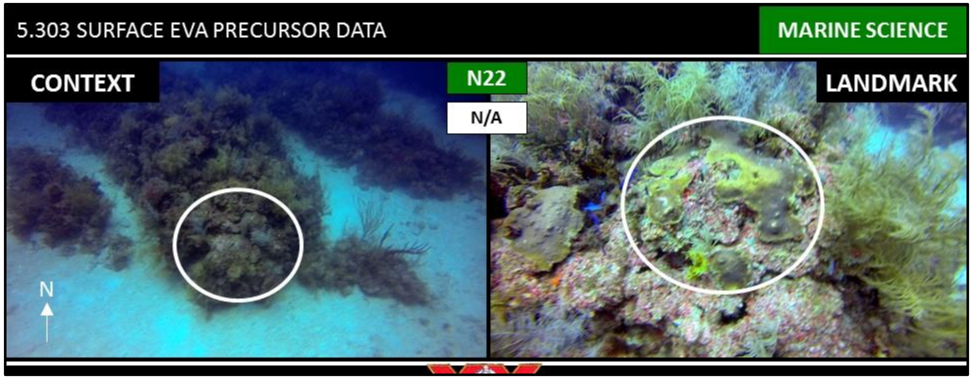


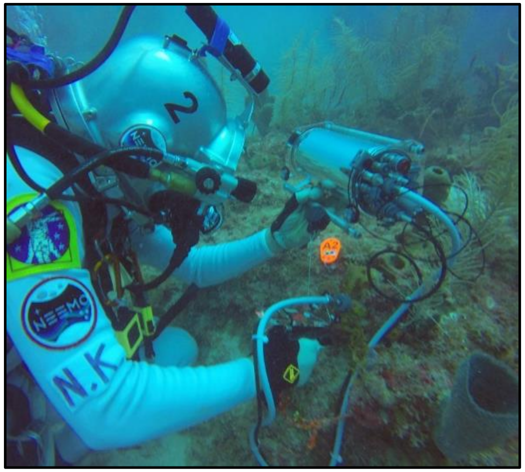


NEEMO 20 Mission Architecture for EVA
Mars Surface EVA Tasks Overview

- Took geology samples based on precursor data and direction from the ST
- Collected marine science samples (as real science proxy to astrobiology/geology sampling methods) based on precursor data and direction from the ST
- Performed pioneering construction tasks
- Utilized an ROV to assist EVA crew





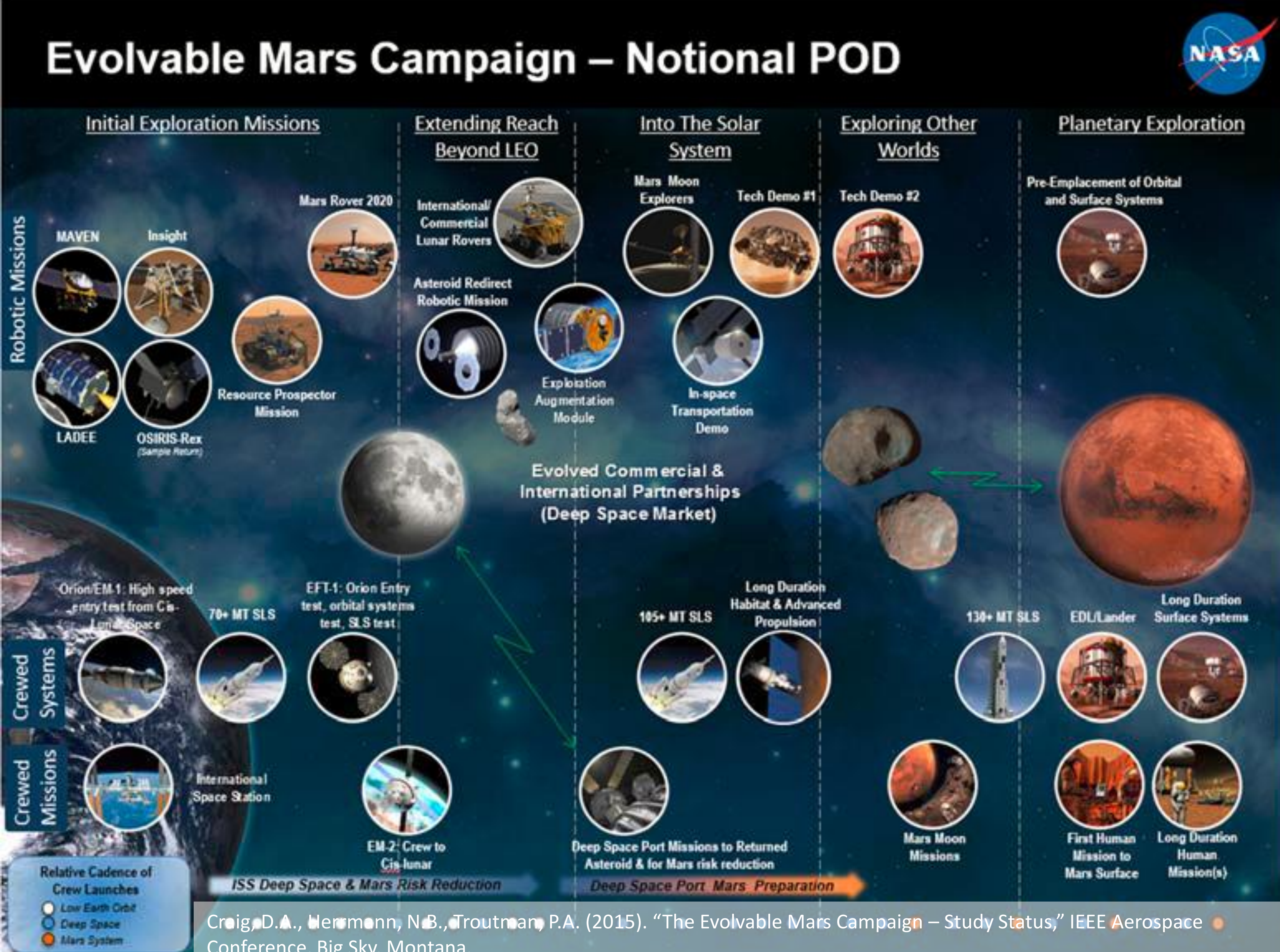


NEEMO 20 EVA Schedule
Mission Days 1 - 7

Day of Week	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Date	20-Jul	21-Jul	22-Jul	23-Jul	24-Jul	25-Jul	26-Jul
Mission Day	MD 1	MD 2	MD 3	MD 4	MD 5	MD 6	MD 7
Morning	**Splash-down**	**EVA 1**	**EVA 3**	**EVA 5**	**EVA 7**	**EVA 9**	**EVA 10**
		Micro-g / Cis-lunar asteroid	**Milli-g / Mars' moons**	**Milli-g / Mars' moons**	**Partial-g / Surface**	**Partial-g / Surface**	**Partial-g / Surface**
		2 hours	2 hours	2 hours	2 hr	4 hr	4 hr
		End-to-end sample collect	Eval hab boom - fixed time	Eval hab boom - dynamic time	EVA recon for marine sites	MCC planned	MCC planned
						End-to-end EVAs	End-to-end EVAs
						Science tasks	Science tasks
						Pioneering tasks	Pioneering tasks
						ROV recon & EVA support	ROV recon & EVA support
Afternoon	**Fam Dive 1**	**EVA 2**	**EVA 4**	**EVA 6**	**EVA 8**		
	1 hr - Fam	**Micro-g / Cis-lunar asteroid**	**Milli-g / Mars' moons**	**Milli-g / Mars' moons**	**Partial-g / Surface**		
		2 hours	2 hours	2 hours	2 hr		
		End-to-end sample collect	Eval hab boom - fixed time	Eval hab boom - dynamic time	EVA recon for marine sites		
	Fam Dive 2						
	1 hr - Fam						
Comm latency	0	0	5 min	5 min	10 min	10 min	10 min
IV	Ground IV	Ground IV	Hab IV	Hab IV	Hab IV	Hab IV	Hab IV
ROV	No	No	No	No	Hab ROV pilot (TBR)	Hab ROV pilot (TBR)	Hab ROV pilot (TBR)
Nav	No	No	No	No	EVA / ROV nav	EVA / ROV nav	EVA / ROV nav
MCC / SBT	MCC	MCC & ARES SBT	MCC & ARES SBT	MCC & ARES SBT	MCC & FIU SBT	MCC/FIU & ARES SBT	MCC/FIU & ARES SBT
Dive support	Topside	Topside	Topside	Topside	Hab Tech	Topside & Hab Tech	Topside & Hab Tech
	MD 1 Overview	**MD 2 Overview**	**MD 3 Overview**	**MD 4 Overview**	**MD 5 Overview**	**MD 6 Overview**	**MD 7 Overview**
	Crew makes their first fam dives from the habitat. No specific EVA objectives.	Two 2-hour EVAs to evaluate geology sampling tools in an asteroid mission condition (micro-g). Crew will use stabilization boom 2.0 to sim reaching the asteroid from the ARRV.	Two 2-hour EVA. Tasks focus on eval of the Phobos hab deployable structure. Crew will utilize the geology sampling tools for their tasks on the boom.	Two 2-hour EVA. Tasks focus on eval of the Phobos hab deployable structure. Crew will utilize the geology sampling tools for their tasks on the boom.	Two 2-hour EVAs for the crew to conduct recon of the area in order to start planning the surface EVAs. EVA crew will use the Navigator/dive planes and IV crew will use an ROV.	One 4-hour EVA to begin evals of the pioneering (hardware) tasks, eval tools in partial-g, science tasks, and examine MCC/SBT interaction over a comm latency. This EVA will be planned by MCC. Crew will utilize an ROV.	One 4-hour EVA to begin evals of the pioneering (hardware) tasks, eval tools in partial-g, science tasks, and examine MCC/SBT interaction over a comm latency. This EVA will be planned by MCC. Crew will utilize an ROV.

NEEMO 20 EVA Schedule
Mission Days 8 - 14

Day of Week	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Date	26-Jul	27-Jul	28-Jul	29-Jul	30-Jul	31-Jul	1-Aug	2-Aug
Mission Day	MD 7	MD 8	MD 9	MD 10	MD 11	MD 12	MD 13	MD 14
Morning	**EVA 10**	**EVA 11**	**EVA 12**	**EVA 13**	**EVA 14**	**EVA 15**	**EVA 16**	**Splash-up**
	Partial-g / Surface	**Partial-g / Surface**	**Partial-g / Surface**	**Partial-g / Surface**	**Partial-g / Surface**	**Partial-g / Surface**	**Partial-g / Surface**	
	4 hr	4 hr	4 hr	4 hr	4 hr	4 hr	2 hr	
	MCC planned	MCC planned	Crew self-scheduled	Crew self-scheduled	Crew self-scheduled	Crew self-scheduled	ICM rescue	
	End-to-end EVAs	End-to-end EVAs	End-to-end EVAs	End-to-end EVAs	End-to-end EVAs	End-to-end EVAs		
	Science tasks	Science tasks	Science tasks	Science tasks	Science tasks	Science tasks		
	Pioneering tasks	Pioneering tasks	Pioneering tasks	Pioneering tasks	Pioneering tasks	Pioneering tasks		
	ROV recon & EVA support	ROV recon & EVA support	ROV recon & EVA support	ROV support of EVA	ROV recon & EVA support	ROV recon & EVA support		
Afternoon							**EVA 17**	
							Partial-g / Surface	
							2 hr	
							ICM rescue	
		Self-schedule EVA						
			Self-schedule EVA	Self-schedule EVA				
Comm latency	10 min	10 min	10 min	10 min	10 min	10 min	0 (?)	
IV	Hab IV	Hab IV	Hab IV	Hab IV	Hab IV	Hab IV	Ground IV	
ROV	Hab ROV pilot (TBR)	Hab ROV pilot (TBR)	Hab ROV pilot (TBR)	Hab ROV pilot (TBR)	Hab ROV pilot (TBR)	Hab ROV pilot (TBR)	No	
Nav	EVA / ROV nav	EVA / ROV nav	EVA / ROV nav	EVA / ROV nav	EVA / ROV nav	EVA / ROV nav	EVA nav	
MCC / SBT	MCC/FIU & ARES SBT	MCC/FIU & ARES SBT	MCC/FIU & ARES SBT	MCC/FIU & ARES SBT	MCC/FIU & ARES SBT	MCC/FIU & ARES SBT	MCC	
Dive support	Topside & Hab Tech	Topside & Hab Tech	Topside & Hab Tech	Topside & Hab Tech	Topside & Hab Tech	Topside & Hab Tech	Topside & Hab Tech	
	MD 7 Overview	**MD 8 Overview**	**MD 9 Overview**	**MD 10 Overview**	**MD 11 Overview**	**MD 12 Overview**	**MD 13 Overview**	
	One 4-hour EVA to begin evals of the pioneering (hardware) tasks, eval tools in partial-g, science tasks, and examine MCC/SBT interaction over a comm latency. This EVA will be planned by MCC. Crew will utilize an ROV.	One 4-hour EVA to eval pioneering (hardware) tasks, eval tools in partial-g, science tasks, and examine MCC/SBT interaction over a comm latency. This EVA will be planned by MCC (TBR). Crew will utilize an ROV.	One 4-hour EVA to eval pioneering (hardware) tasks, eval tools in partial-g, science tasks, and examine MCC/SBT interaction over a comm latency. This EVA will be planned by crew (TBR). Crew will utilize an ROV.	One 4-hour EVA to eval pioneering (hardware) tasks, eval tools in partial-g, science tasks, and examine MCC/SBT interaction over a comm latency. This EVA will be planned by crew. Crew will utilize an ROV.	One 4-hour EVA to eval pioneering (hardware) tasks, eval tools in partial-g, science tasks, and examine MCC/SBT interaction over a comm latency. This EVA will be planned by crew. Crew will utilize an ROV.	Two 2-hour EVAs to evaluate ICM rescue hardware and techniques.	Day reserved for TBD objectives and as a weather contingency day.	



Craig, D.A., Herrmann, N.B., Troutman, P.A. (2015). "The Evolvable Mars Campaign – Study Status," IEEE Aerospace Conference, Big Sky, Montana.

Additional Backup Details

Technology Maturation for Ops

EVA HARDWARE & TOOLS

Exploration EVA Objectives & Gaps Hardware and Tools

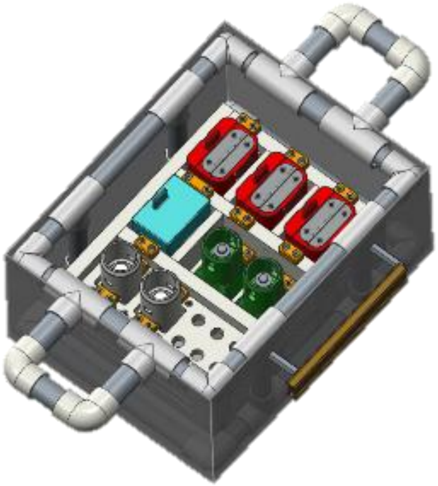
EVA Objective	Applicable Mission	EVA SMT Gap Closure & ARCM CAPTEM	Hardware and Technique
Evaluate EVA hardware and operations for science sampling • Rock chip sample • Float sample • Soil sample • Surface sample • Core sample • Sample collection container (briefcase)	Asteroid Moons of Mars Mars surface	502: Micro-g tool for loosely adhered particles 503: Micro-g tool for chip samples 504: Micro-g tool for subsurface samples 505: Sample Storage and Curation 801: DRM Maturity 805: Scientific Objectives CAPTEM 5: Collection of 1000 g from two sites	Integrated Geology Sampling System
Examine a manually deployable truss structure for EVA translation and sampling ops	Moons of Mars	501: Microgravity stability and anchoring tools 511: Microgravity translation aids for non-engineered surfaces 801: DRM Maturity	Phobos Deployable Structure (boom)
Evaluate an EVA tool for identifying and high grading samples	Mars surface	509: In-situ High Grading, EVA Tool 805: Scientific Objectives	Sample markers Helmet cams
Assess hardware and techniques for incapacitated crew rescue	Mars surface	406: Rescue Incapacitated Crew Member 801: DRM Maturity	ICM rescue gurney

Overview

- Evaluate EVA hardware and operations for science sampling
- The *integrated* sampling kit is focused on sample containment and a more flight-like contamination protocol
- Design concept consists of a “briefcase” designed for sample management, ease of operation, and consistency across sampling activities
- The Sample Briefcase houses various End Effectors (float, soil, surface, chip, core)
- Two different Drivers will enable crew to secure samples manually or with a powered device
- **NOTE: This system was optimized for asteroid geology sampling**

Sample Briefcase

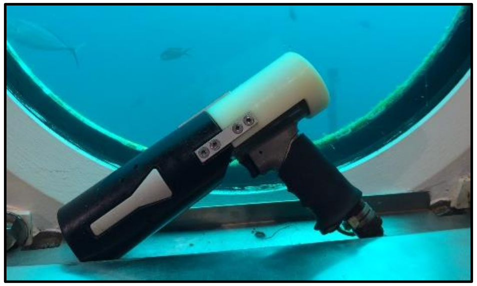
- The Sample Briefcase is the carrying case in which the end effectors are housed prior to and after use
- Serves as a method to transport end effectors and provide final containment once a sample is collected
- Volume is allocated for soft sample bags to collect contingency samples and/or targets of opportunity once all end effectors have been used



EVA Hardware and Tools
Integrated Geology Sampling System

Drivers

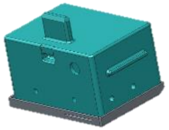
- Manual Driver is used to obtain loosely adhered samples that can be liberated using hand strength alone
- Powered Driver is used when an increased force is needed to remove samples from the surface
  - Pneumatics were used as an analog at NEEMO because of their low cost and easy implementation in the underwater test environment
  - Flight design would be electrically powered, similar to the PGT



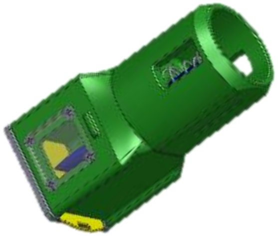
End Effectors

- Scientists are interested in obtaining 5 types of samples:
  - *Float:* rocks that are loosely adhered to the surface
  - *Soil:* a collection of unconsolidated rock fragments loosely adhered to the surface
  - *Surface:* the very top layer of dust on the surface
  - *Chip:* pieces of a parent body forcibly removed
  - *Core:* cylindrical section of the parent body
- Different end effectors were designed to obtain each type of sample.

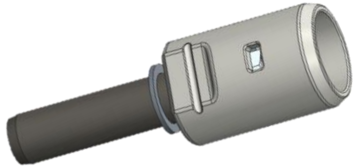
Float/Soil



Surface



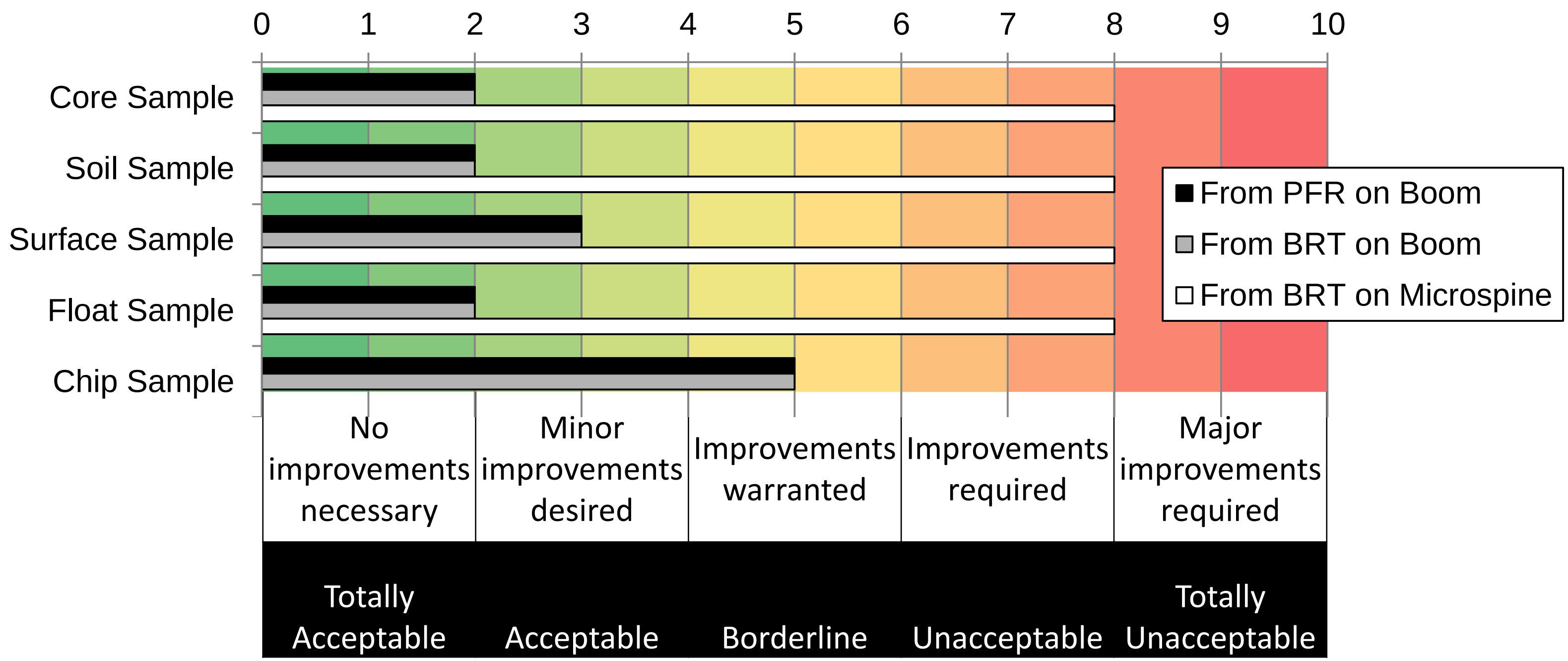
Chip



Core

EVA Integrated Geology Sampling System
Post-Asteroid EVA Tools Crew Consensus Acceptability

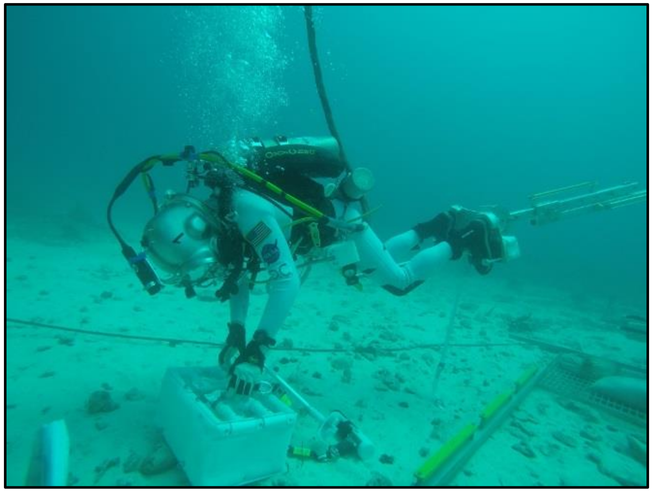
- Float, Core & Soil Samples: acceptable except for microspine; "microspine slipping off rock"
- Surface Sample: "It wasn't possible to lock the EE open or closed without reaching near the sample surface and possibly contaminating it."
- Chip Sample: "It was challenging to get a properly sized sample into the small EE. The door is difficult to open and close, especially without getting a gloved hand near the sample and possibly contaminating it."



EVA Integrated Geology Sampling System Results & Observations

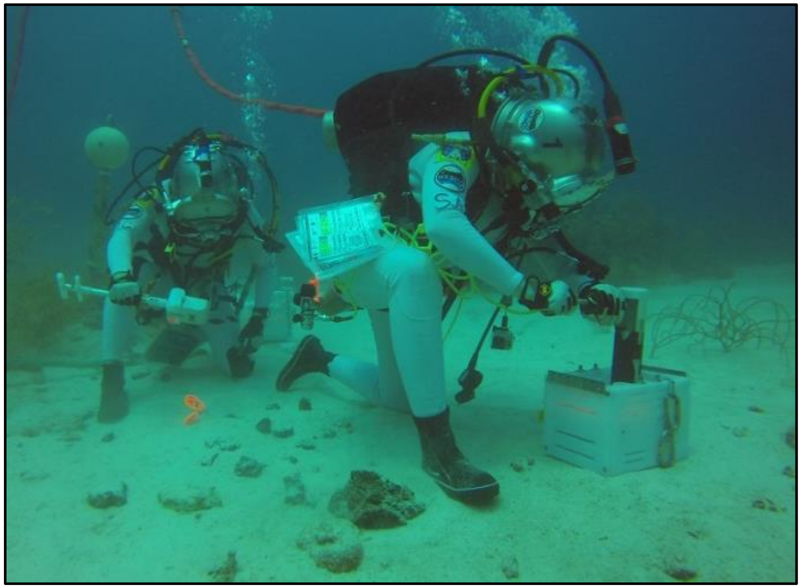
Overall Integrated Geology Sampling System

- Concept proved feasible and provides the potential for pristine sample collection
- Provides viable method for minimizing cross contamination between sample sites and crew to sample contamination



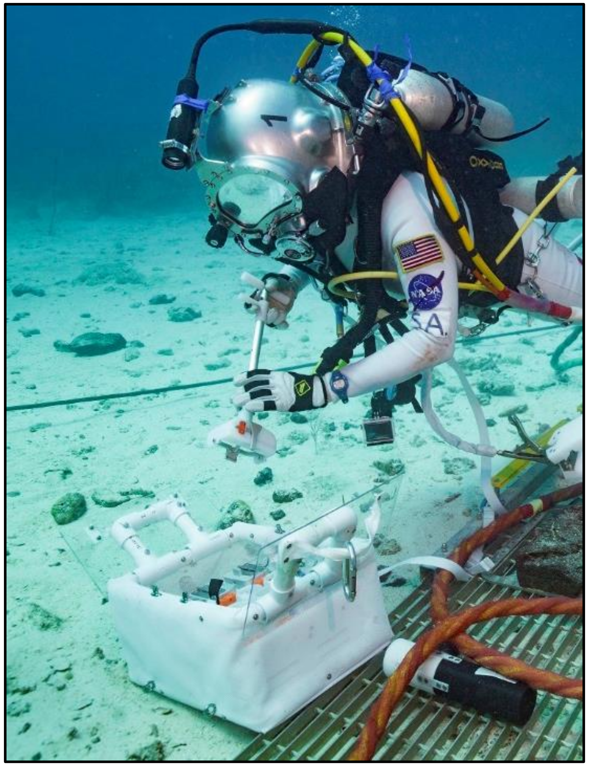
Recommendations/Forward Work

- Large mass and volume implications compared to Apollo methodology that needs to be examined for viability (single collection tool with multiple sample bags)
- Further discussion with ARES personnel is needed to understand the acceptable level of cross contamination
- Need to work out methods or make modifications to keep the EV crew from contaminating areas



Sampling Briefcase

- No major comments or recommended changes from crew
- Recommendations/Forward Design Work:
  - Determine sealing protocol at sample level (impacts briefcase design) and briefcase level
  - Add witness plates, which will be required for a flight version (determine number, size and placement)

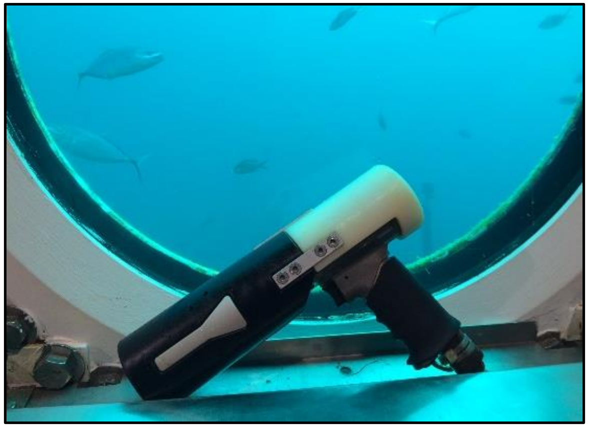


Manual Driver

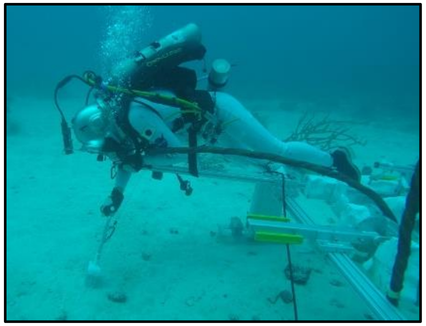
- It would be better if the “unlatching” action was up around the handle to enable one handed operation
- Recommendations/Forward Design Work:
  - Upgrade latching mechanism
  - Check tolerances to guarantee that when parts are mated latches engage

Power Driver

- End effector attachment needs to be more seamless with more pronounced orientation marks
- 3D printed components worked well
- Recommendations/Forward Design Work:
  - Ensure tolerances guarantee that when parts are mated latches engage

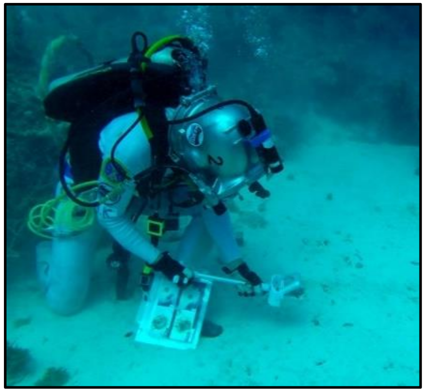


EVA Sampling System End Effectors Results & Observations



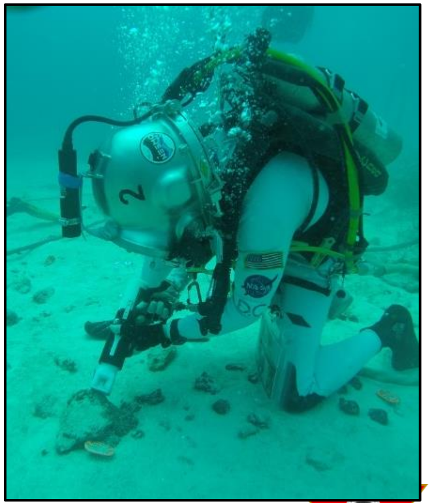
Surface Sample End Effector

- Opening and closing the lid presented a contamination risk
- Recommendations/Forward Design Work:
  - Find a way to ensure gloved hands does not touch/contaminate sample area
  - One concept is to emulate a self inking stamping tool, where the stamping is recessed and protected and flips out upon being pressed into a surface or when a handle is squeezed depending on surface properties



Soil/Float End Effector

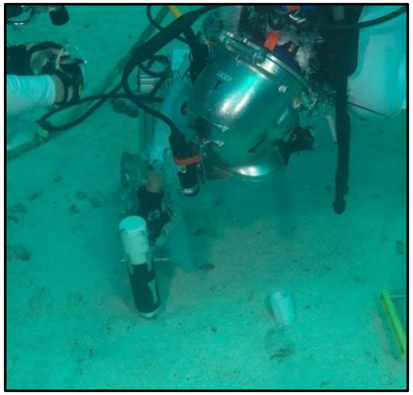
- For float rocks the crew looked to double grip sample (i.e. sample cannot be collected in one motion)
- Ability to confirm sample collection through viewing windows is important
- Recommendations/Forward Design Work:
  - Look into using a mini-microspine as an end effector for collecting float rock samples; the mini-microspine could capture rocks from a greater stand-off distance while a separate container or clamshell enclosure could seal around the sample



Chip Sample End Effector

- Large chips can became jammed in the device and prevented door from closing
- Improvements in fracturing capability needed
- Recommendations/Forward Design Work:
  - Look for ways to prevent large chips from jamming the door
  - Non-perpendicular angle-of-attack is needed to improve fracturing ability
  - Bellowed end effector would provide more compliance on non-uniform surfaces
  - Perform zero-g testing

Core Sample End Effector



- Ops con of swappable end effectors worked well
- Ops did not involve evaluating a spinning core bit, which is being worked through IRB work with Honeybee robotics.
- Recommendations/Forward Design Work:
  - Continue to evolve the rock coring end effector as a high priority as this will likely be a tool that can be used for multiple planetary bodies (asteroid, Mars, lunar) and address numerous contamination control concerns
  - Continue work with Honeybee Robotics
  - Further discuss and determine the required capabilities and design options for the core end effector for collecting regolith (soil) vs rock samples - likely very different tools

Sample Baggies

- Recommendations/Forward Work:
  - Important to allow for contingency samples or samples of opportunity that may not fit into an end effector
  - Provide adequate stowage space in sample briefcase for samples taken with baggies

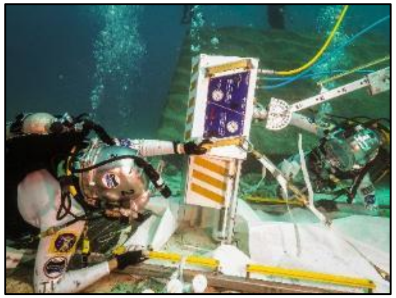
Labels

- Recommendations/Forward Design Work:
  - Add multiple labels on end effectors; on top facing out while in sample bag would help greatly
  - Sample color and scale indicators are best located on the surface via temp marker (rather than on the tool, but doesn't hurt to have on tool as well); overall these references need to be larger or scaled to best match image resolution
  - Require a method to indicate that the sample container has been used

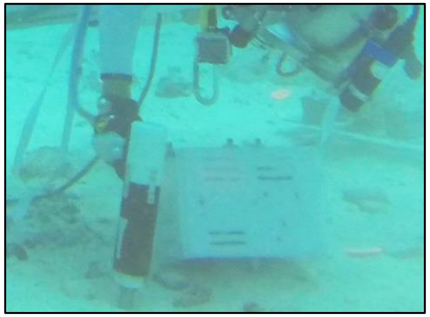
EVA Sample Collection Tools
Road To Flight

- Tool improvements for potential use on an asteroid will be incorporated into designs for the next generation of hardware
- EC7 is merging results from NEEMO18/19/20 with work done by Honeybee Robotics (HBR) through the Asteroid Redirect Mission (ARM) Broad Agency Announcement (BAA) Contracts for an EVA Core Drill concept
  - Key test data exchanged between these two efforts includes the timeline data of NEEMO 18/19/20 with the drilling power and duration/depth of HBR’s proven planetary drill designs
  - Together, these two efforts allow EVA to close the Architecture and EVA Ops Con and identify any fundamental design/technical issues such as power availability for core drilling operations
- The NEEMO 20 core drill focused on a hand held “shallow core” device more similar to the Honeybee concept.

Hand Core Drill
NEEMO 17



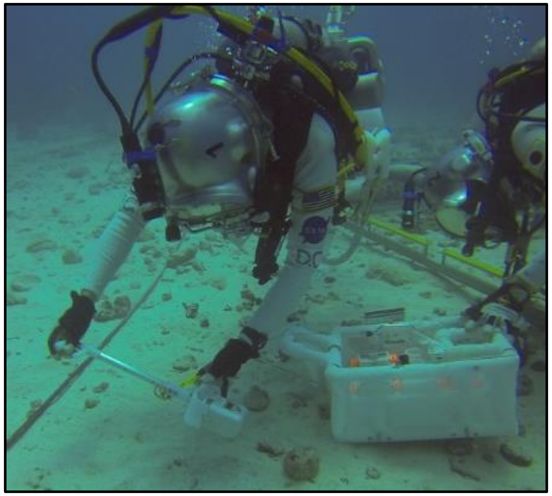
Deep Core Drill
NEEMO 18 & 19



Hand Core Drill
NEEMO 20

Representative photo (Publicly released by HBR, ARM concept designs in-work and will be released by ARM Mission Concept Review (MCR))

EVA Integrated Geology Sampling System Summary Take-Away



Objective
- Evaluate EVA hardware and operations for science sampling

Gap closures addressed with NEEMO 20 results
- 502: Micro-g tool for loosely adhered particles
- 503: Micro-g tool for chip samples
- 504: Micro-g tool for subsurface samples
- 505: Sample Storage and Curation
- 801: DRM maturity (further mature EVA model)
- 805: Scientific objectives (geology activities/samples and supporting tools)
- CAPTEM 5: Collection of 1000 g from two sites

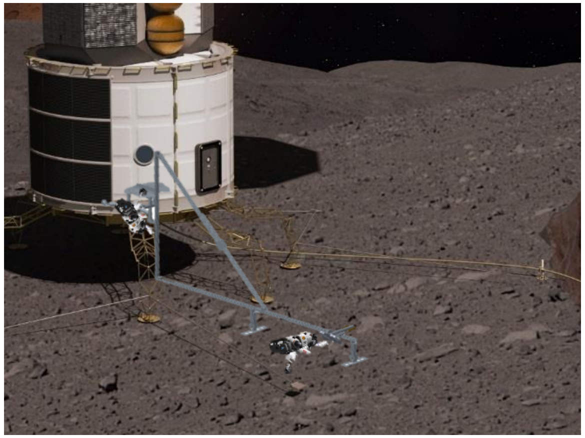
Summary Take-Away for EVA
- Concept proved feasible for EVA collection of geology and astrobiology (marine science) samples
- Provides a viable method for minimizing sample-to-sample and crew-to-sample contamination
- Keeps tools and samples organized, which improves deployment, stowage, and transportation
- It was difficult to not contaminate a site when taking samples (crew had to walk into an area/zone in order to reach a specific sample)

EVA Recommendations for Forward Work
- Concept largely solves the problem of sample contamination while being easy to employ, but its size and mass are rather large compared to the actual samples obtained - further work needs to be done to minimize the size/mass of the tools while maximizing return samples
- Have further discussions between the EVA Office, EVA Tools, and ARES to understand the acceptable level of cross contamination (and possible reuse of tools) at all destinations
- Work out methods or make modifications to tools in order to keep the EV crew from contaminating an area
- Incorporate recommendations for individual components (drivers, end effectors, and container) into the next version of prototype tools, including tools specifically for surface ops
- Test the next versions of the prototypes during NBL runs to examine tool operation in a pressurized suit and during future NEEMO missions for ops con iteration/refinement

Phobos Hab EVA Deployable Boom

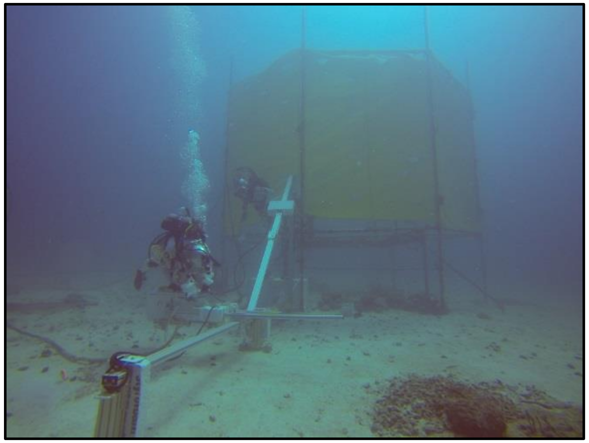
Purpose

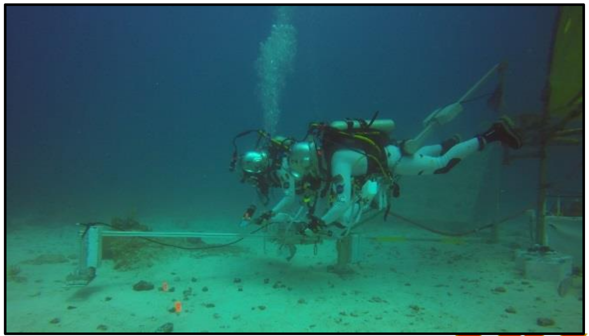
- Evaluate EVA tools/methods for translation and stabilization
- Research Questions: Are the operations concepts, task, and hardware designs for translation and stabilization while performing exploration tasks in Mars moons gravity acceptable? What improvements are desired, warranted or required?



Phobos Boom Overview

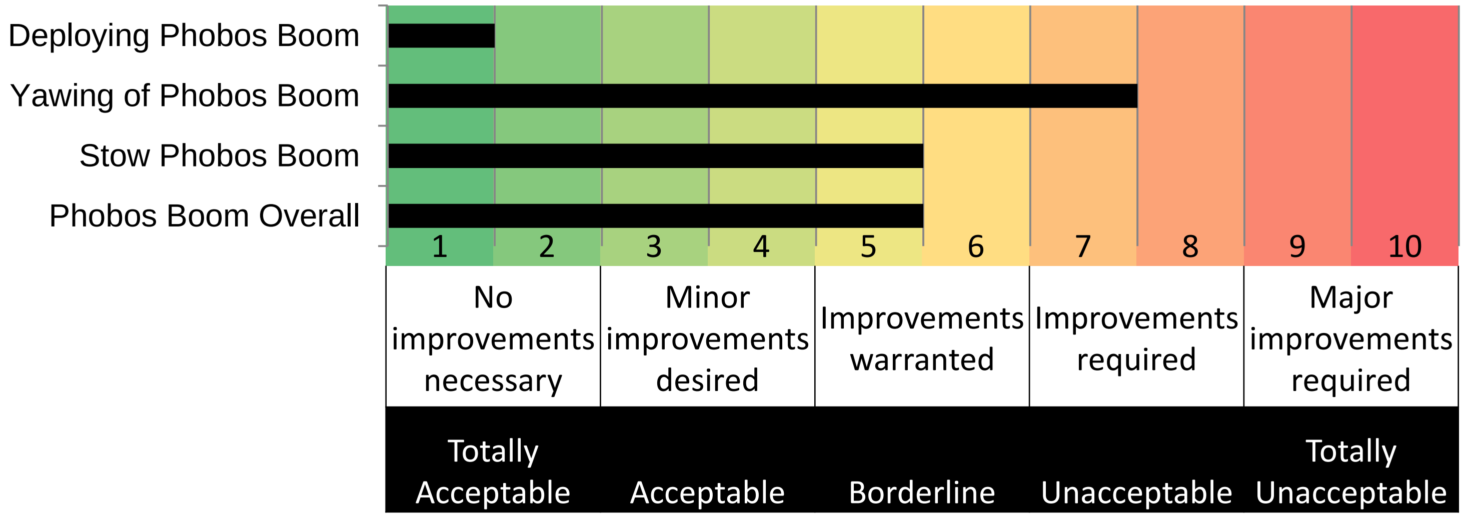
- NEEMO 20 investigated the concept of having a deployable structure on a Phobos Habitat
- This device would allow for translation and body-stabilized activities off a Phobos habitat, while providing access to a wide area to study from a single landing site
- A Foot Restraint, Handrails, and a Crew Lock Bag Stanchion allowed for crew operations
- NOTE: The boom as tested was 16 feet long, however the concept for flight would be a 25 ft. boom, with the possibility of putting two together to create a 50 ft. boom.





Phobos Hab EVA Deployable Boom
Post-EVA Crew Consensus Acceptability Ratings

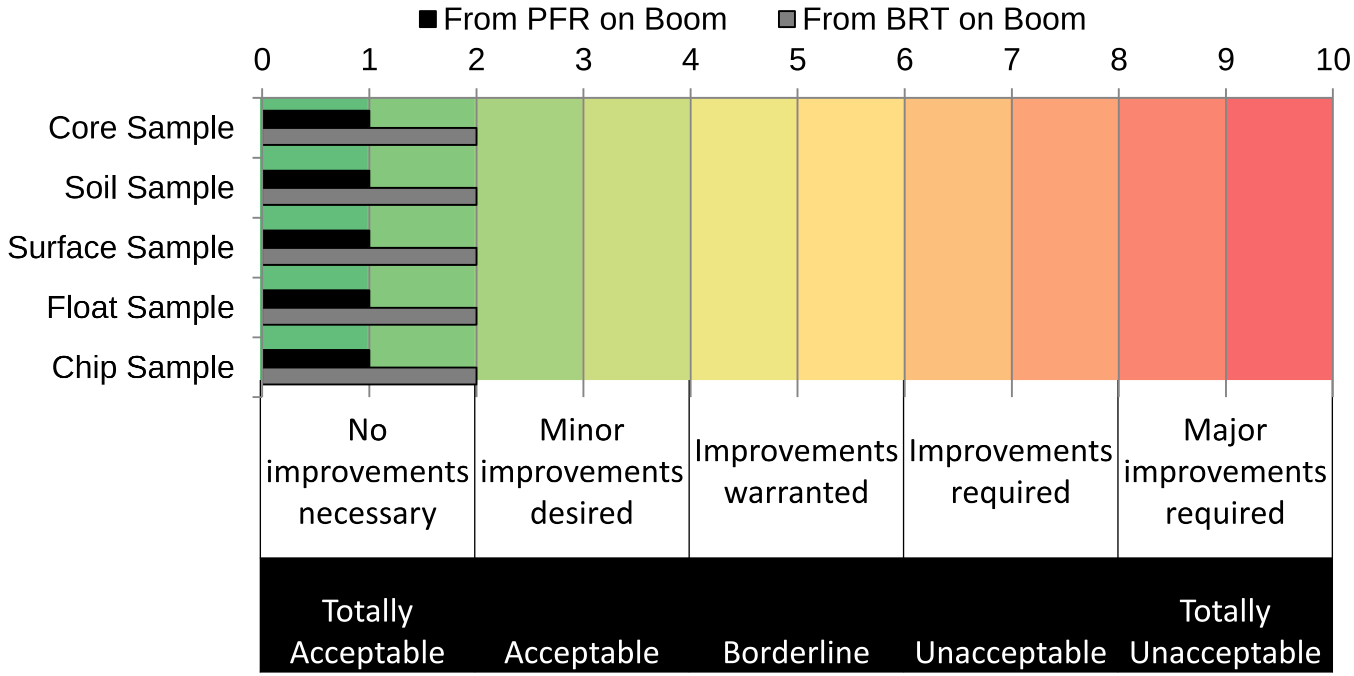
- <u>Deploying Phobos Boom</u>: totally acceptable; “good”
- <u>Yawing of Phobos Boom</u>: unacceptable; “required a tremendous amount of work”
- <u>Stow of Phobos Boom</u>: borderline; “heavy to stow, would be better to reel in with a cable”
- <u>Phobos Boom Overall</u>: borderline; no additional consensus comments provided



<u>Take Away:</u> manual methods for yawing and stowing the boom using a rope and leverage were not optimal and improvements are required

Phobos Hab EVA Deployable Boom Post-EVA Crew Consensus Acceptability Ratings

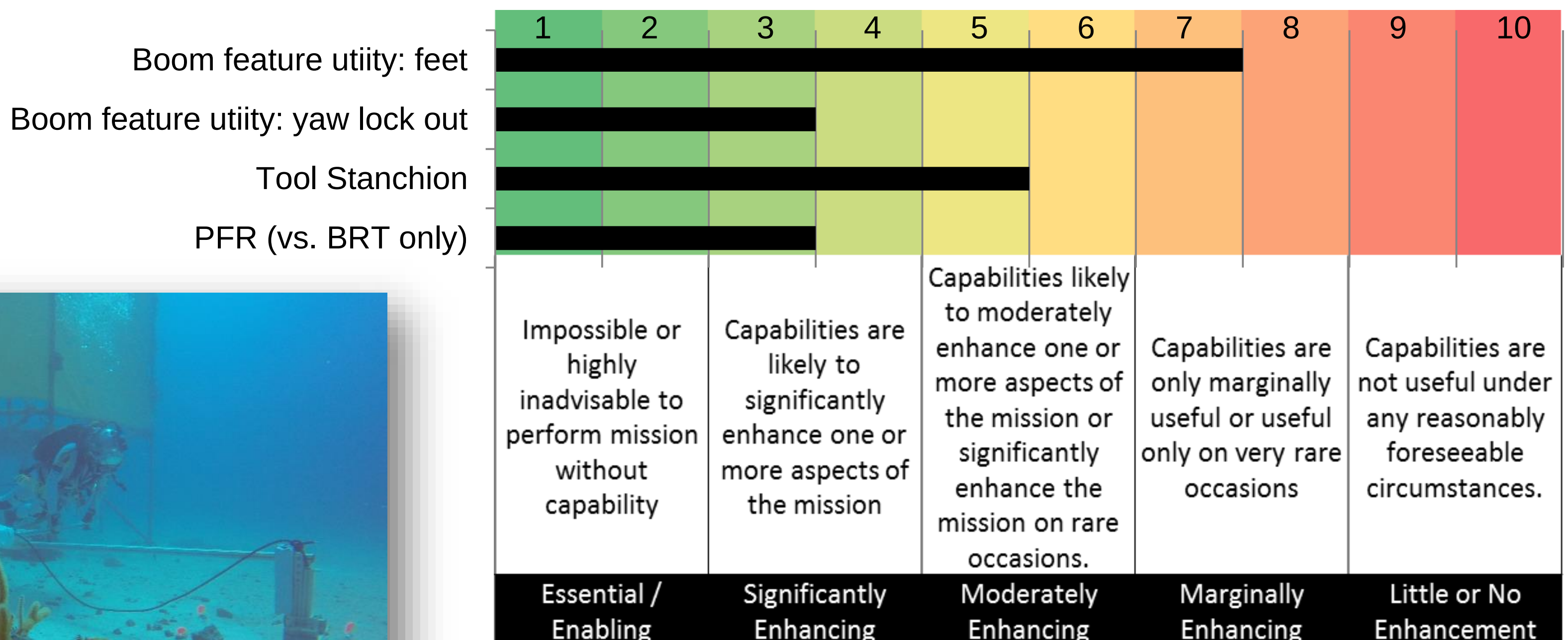
- Same ratings across all sampling types within a method (i.e. PFR or BRT); all totally acceptable
- General PFR comments: need "Better PFR with more pitch, yaw, roll"
- General BRT comments: "Constantly came undone and was difficult to latch at times." – However, feed back from previous missions indicated some liked this BRT better than the flight version.

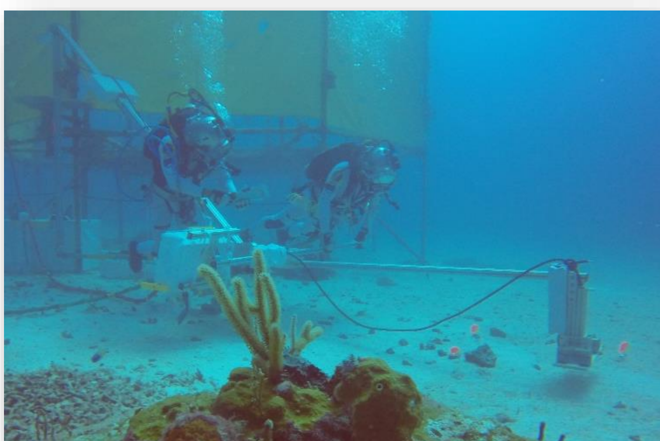


<u>Take Away:</u> standard sampling techniques using provided tools and stabilization techniques were totally acceptable

Phobos Hab EVA Deployable Boom Post-EVA Crew Consensus Capability Assessment

- Boom feet: intended to react loads and reduce instability at tip; "definitely depends on design"
- Boom yaw lock out: intended to react lateral loads; "yaw lock out was difficult to use at times"; in general, yaw lock out was not needed for the tasks performed
- Tool stanchion: "a tool stanchion should help but definitely depends on the design"
- Portable Foot Restraint (PFR) vs. Body Restraint Tether (BRT): "PFRs are definitely better than BRTs for stability"; "more capability for the PFR (pitch, yaw, roll)" desired





Phobos Habitat EVA Deployable Boom Results & Recommendations

Results

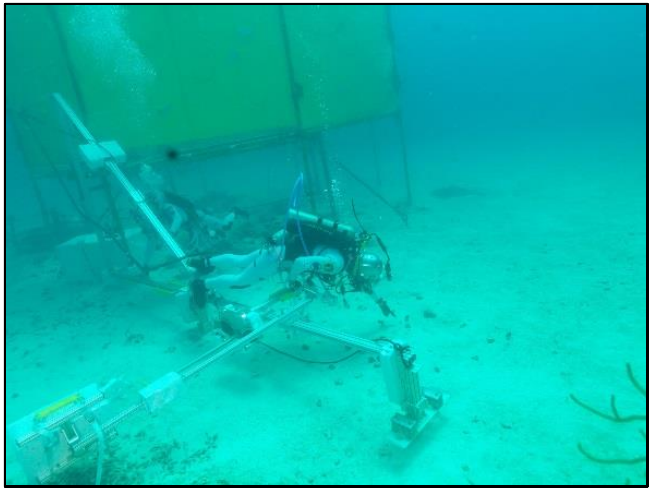
- A boom/arm deployed from a mobile habitat will work well for performing geology sampling
  - 16 ft. boom was stable enough for the tasks tested
  - Flight boom may be 25+ ft.
- Performance of a core set of science tasks was totally acceptable while using the boom for stabilization (PFR and BRT)
- Manual yawing was difficult due to lack of mechanical advantage, limited visibility in helmet, and water drag
- It will be critical to be able to know where the feet will land so that they don't end up on top of a good sample
- A movable foot restraint is important for operation
- Crew Lock Bag stanchion like device is important to prevent worksite contamination

Recommendations

- Develop a better way to yaw the boom rather than having crew pull on a line
  - Look into a powered system or mechanical advantage device
  - Make the lock easier to engage
- Improve the stow system so that not as much force is required, possibly with a reel system
- Improvements in equipment and methods for deploying, stowing, and using the boom should be made
- Look at the stabilization of a longer boom (25-50 feet concept for flight)

Phobos Habitat EVA Deployable Boom Summary Take-Away

Objective
- Examine a manually deployable truss structure for EVA translation and sampling ops



Gap closures addressed with NEEMO 20 results
- 501: Microgravity stability and anchoring tools
- 511: Microgravity translation aids for non-engineered surfaces
- 801: DRM maturity (further mature EVA model)
- CAPTEM 5: Collection of 1000 g from two sites

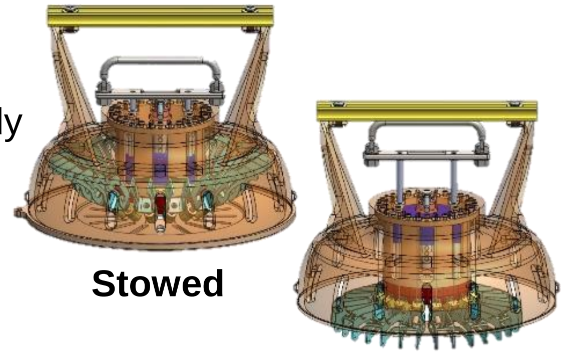
Summary Take-Away for EVA
- A boom/arm deployed from a Phobos mobile habitat will work for performing EVA geology sampling
  - 16 ft. boom was stable enough for the tasks tested
  - Flight boom may be 25 ft
  - Performance of a core set of science tasks was totally acceptable while using the boom for stabilization (PFR and BRT)
- Lack of mechanical advantage and control made use difficult, and ability to control exactly where the feet landed (so as not to land on top of a good sample) was sub-optimal
- The movable foot restraint and crewlock bag stanchion worked well for sampling operations and helping to minimize contamination of the worksite

EVA Recommendations for Forward Work
- Develop improvements in equipment and methods for deploying, stowing, and manipulating the boom
- Perform evaluations of a full length boom if this type of sampling continues to be a significant part of HAT's Moons of Mars reference mission
  - Look at the stabilization of a longer boom (25-50 feet concept for flight)

Microspine Stabilization Device Summary Take-Away

Supplementary Objective

- Evaluate microspine as an EVA stabilization device
  - NEEMO 20 evaluated the microspine grippers capability to be a body stabilization platform
  - Provided by JPL in a crew-operable package



Stowed **Engaged**

Gap closures addressed with NEEMO 20 results

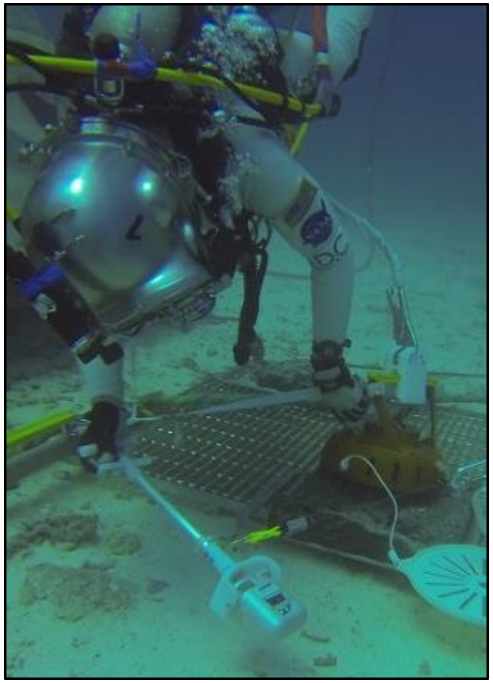
- 501: Microgravity stability and anchoring tools
- 801: DRM maturity (further mature EVA model)

Summary Take-Away for EVA

- Current as-tested version did not allow for good EVA body stabilization
- Crew induced torsional loads and the housing creating contact points with a moment arm caused the microspine to release from the rock

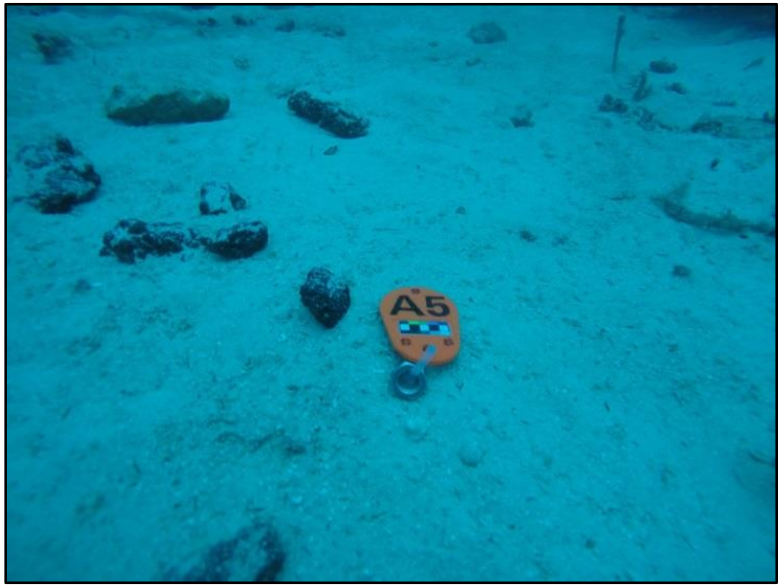
EVA Recommendations for Forward Work

- Examine utilizing the device as a deployable drill base for obtaining core samples during a future NEEMO mission
- Look at the possible use of a small microspine as an end effector for collecting float samples



Purpose

- Evaluate an EVA tool for identifying and high grading samples
- Crew used the temporary markers in two different scenarios
  - Geology sites: Crew placed the temp markers at locations identified on precursor maps in order to identify the samples for confirmation from the ST
  - Marine science sites: Crew located a site based on precursor data, and then deployed the temp markers at corals of interest for the ST to determine from which corals to take a sample
- The ST evaluated the EV crew helmet camera video to determine which samples to take by referencing the temp markers
- Markers gave some scale and color reference information



EVA Sample Marker/High Grading Tool Summary Take-Away

Objective

- Evaluate an EVA tool for identifying and high grading samples

Gap closures addressed with NEEMO 20 results

- 509: In-situ High Grading, EVA Tool
- 805: Scientific objectives (geology activities/samples and supporting tools)

Summary Take-Away for EVA

- Crew were able to use the temporary sample markers to identify potential corals to sample
- Temporary markers are critical when communicating with IV and ST/MCC
- The ST had difficulty reading the markers in the helmet cam video at times
  - Temp markers IDs were unreadable given the image quality at a few meter distance, especially over unstable video
  - Deploying markers in order is preferred; makes it easier to track progress (especially with bad coms)
- It was difficult to deploy the markers in the middle of a site without disturbing the area - it would be good to have a way to deploy markers further away
- It was challenging to remember where all of the temp markers were placed when returning to a worksite

EVA Recommendations for Forward Work

- Current version has color bars and scale markings - look further into what gives the ST the information needed to evaluate potential samples
- Continue iterating the design and test the next version during future NEEMO missions

Incapacitated Crew Rescue Hardware

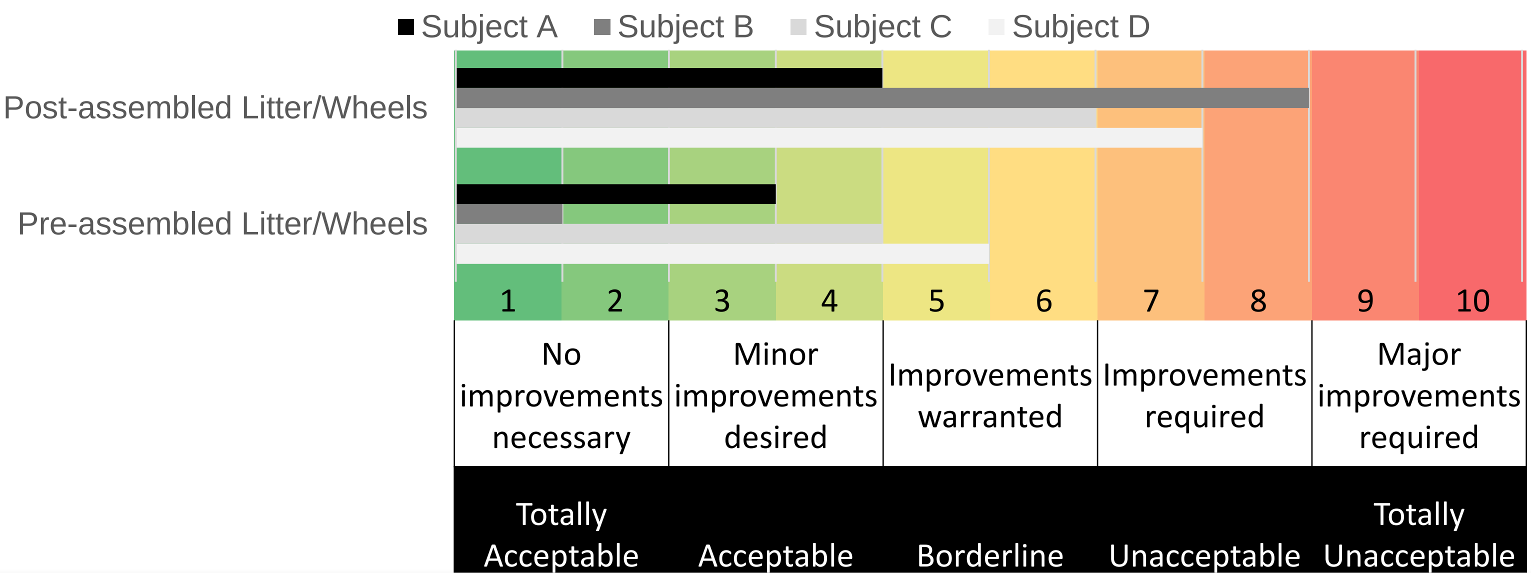
Purpose

- Assess hardware and techniques for incapacitated crew rescue
  - Goal was to investigate the ops con and hardware necessary for getting incapacitated crew back to the habitat over long distances and complex terrain
  - Are the operations concepts, task designs, and tool designs for incapacitated crew rescue in partial-g acceptable? What improvements are desired, warranted or required?
  - How does the acceptability of the operations concepts, task designs, and tool designs for incapacitated crew rescue vary between two different patient loading methods? How does the acceptability vary by simulated crewmember weight?
- Simulated reduced gravity (Moon or Mars) evacuation of incapacitated crewmember through level (or low-angle undulating) and/or rough terrain with obstacles not trafficable by rover
  - Requires the use of “litter” system for as few as one rescuer crewmember to load and transport incapacitated crew member to rover (at which time, previously tested haul systems and ingress methods can be used)
- A COTS litter assembly was purchased to provide a “first look”
- The crew was weighed out to 50 lbs. Actual Mars weight with current suit estimates would be closer to 150 lbs.

Incapacitated Crew Rescue Hardware Acceptability Ratings

- Results should be viewed as very early pilot study/evaluation data
- Crew was prompted to provide post-EVA consensus ratings but they were not provided; real-time individual ratings and comments used here to summarize results
- Post-assembled litter/wheels method rated borderline/unacceptable; “need a faster way to attach litter to wheel mechanism”; “litter kept sliding out of the spaces”; “it's a lot of work”
- Pre-assembled litter/wheels method rated mostly acceptable; “Would like a hoist to help bring them up the inclined litter”

Incapacitated Crew Rescue Individual Acceptability Ratings



Take Away: early evaluations show that loading patient on preassembled apparatus is less work and more efficient; design ideas generated for how to use the suit and minimal supplemental equipment for loading and evacuation

Incapacitated Crew Rescue Hardware Summary Take-Away

Objective

- Assess hardware and techniques for incapacitated crew rescue

Gap closures addressed with NEEMO 20 results

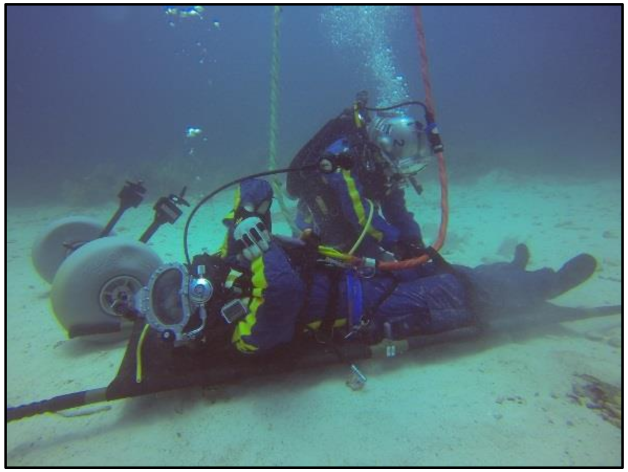
- 406: Rescue Incapacitated Crew Member
- 801: DRM maturity (further mature EVA model)

Summary Take-Away for EVA

- Crew were able to use the litter in both configurations to rescue each other
  - It was difficult to load a crewmember on a litter and then raise it to a set of wheels – need to have the whole unit stay as one
  - Need a way to hook the ICM onto the angled litter in order to let go and attach the straps.
  - A winch might work better to hoist an ICM onto the litter rather than deadlifting
  - Retractable straps would be more efficient

EVA Recommendations for Forward Work

- Look at ways to modify the litter to add in the suggested capabilities (minimize lifting and maximize efficiency)
- Further research and test improved equipment with heavier simulated crew weight during future NEEMO missions



Additional Backup Details

Ops Concept Maturation

EVA OPERATIONS CONCEPTS

Exploration EVA Objectives & Gaps Operations Concepts

EVA Objective	Applicable Mission	EVA SMT Gap Closure & ARCM CAPTEM	Hardware and Technique
Continue to enhance understanding of comm limitations by including MCC/ST response time and comm with IV, and continue to investigate practicality of directing EVA operations from MCC over a comm latency	Moons of Mars Mars surface	703: EVA use model 801: DRM Maturity	Science Team 5-min comm latency ops con 10-min comm latency ops con
Assess potential operations of a robotic asset for EVA and inform functional needs of a robot for EVA tool management	Mars surface	510: Tool management device 801: DRM Maturity	NPS ROV
Investigate crew driven multi-day planning of EVA operations utilizing scenarios with variables and a task list that must be planned and carried out over the course of multiple days	Mars surface	703: EVA use model 801: DRM Maturity	Playbook
Begin looking at types of hardware needed and techniques for navigating on a foreign body	Mars surface	214: Navigation Short Range 801: DRM Maturity	Navigator
Investigate building EVA hardware in situ	Mars surface	512: Common tools for vehicle maintenance 801: DRM Maturity	3D printer

EVA Ops Con
EVA Interaction with MCC/ST Over Comm Latency

Purpose

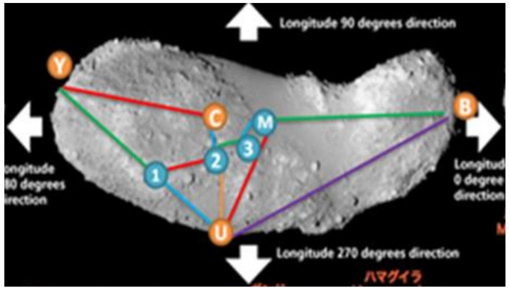
- Evaluate the effects of communications latencies on exploration EVAs
  - Are the mission operations concepts, science operations concepts, and communications protocols under consideration for exploration mission destinations acceptable?
  - Do mission operations concepts, science operations concepts, and communications protocols remain acceptable as communications latency increases up to 10 minutes one-way light time (OWLT)?
- **A primary mission objective was to understand the potential interaction between a Mars-based crew doing geology tasks and a Science Team (ST) on Earth (across a time latency) during an EVA**
  - All science sampling involved interaction with MCC/ST during the EVA
  - Initial tasks were performed based on precursor data
  - Follow-up tasks were conducted based on the direction of the ST
    - An ARES team member acted as the ST for geology sampling
    - A small team from the FIU Marine Science department acted as the marine science backroom
    - ERAU provided a team to provide backroom support for the CORAL tasks
  - IV1 directly communicated with the ST on their priorities, and relayed direction to the EV crewmembers
  - A typical surface EVA involved two marine sites and one geology site
- Pioneering tasks were conducted during some of the EVAs, along with science sampling

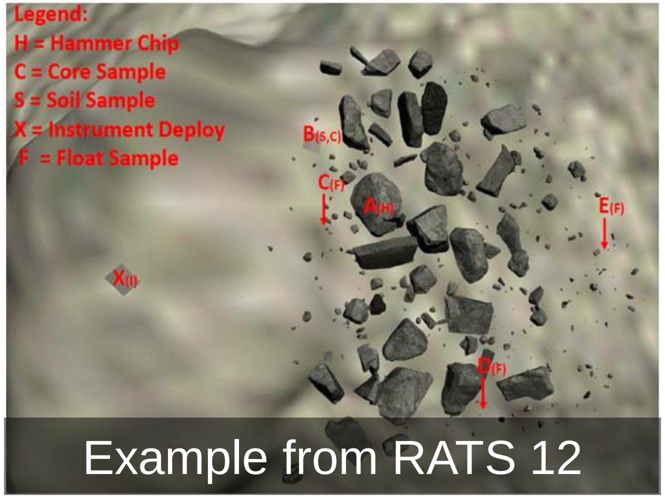
EVA Interaction with MCC/ST Over Comm Latency Science Traverse Ops Con

- There are varied operations concepts for executing exploration traverses that have different levels of autonomy and different methods for integration of ground input
  - Very low communication latency (i.e. as was the case for the Apollo missions) allows for interaction with ground on a regular basis without impacting efficiency or increasing crew idle time
  - As communication latency increases, it could be assumed that higher levels of crew autonomy will be required and that ground interaction cannot happen without efficiency losses (e.g. increasing of crew idle time while waiting for ground input)
    - One option would be to highly train the crew and have them autonomously execute science traverses with the ground only providing feedback and "go backs" across latency as best as they can to get the science that is desired
    - **A second option is to assume that there will always be a higher level of science expertise on the ground that can increase the value of the science being performed by the crew**
      - In this case, it is necessary to design EVA timelines in such a way that intentionally provides time for the ground to provide input to maximize science while still minimizing total EVA time and EVA idle time
      - It is this second option that the operations concept research has focused on across several analog missions and here at NEEMO 20

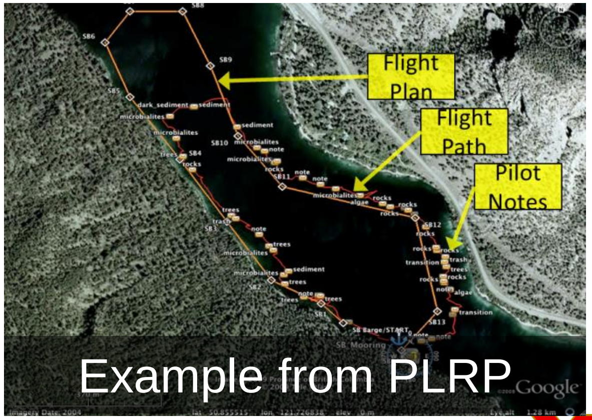
EVA Interaction with MCC/ST Over Comm Latency Exploration Traverse Ops Con Assumptions

- Assumptions:
  - For exploration destinations, robotic precursor missions will have collected sufficient high quality imagery and precursor data to plan detailed exploration traverses to be performed by human crews once they arrive.
  - Upon actual execution of the exploration traverses by the crew on EVA, additional levels of information may be obtained through pre-sampling surveys of each science site on the traverse that may modify traverse plans, science tasks, and/or science priorities.
  - Pre-sampling survey data will be used by a ground-based MCC and science team (ST) to provide input to the EVA crew to maximize the quality of the science achieved
  - A higher level of science expertise or analysis capabilities exists in the ST than with the crew
  - EVA timelines can be designed to allow for MCC/ST input



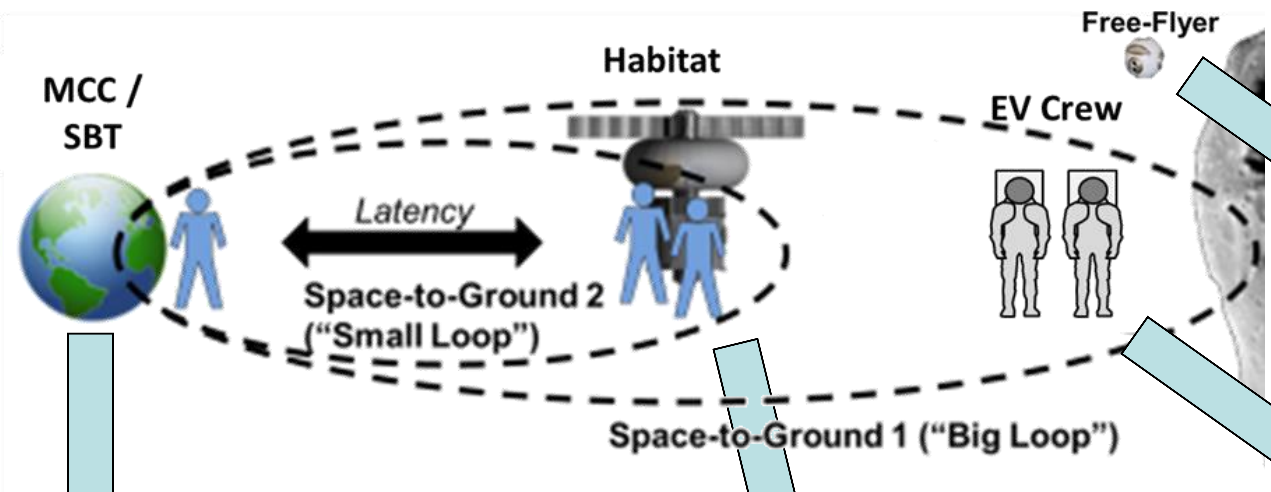


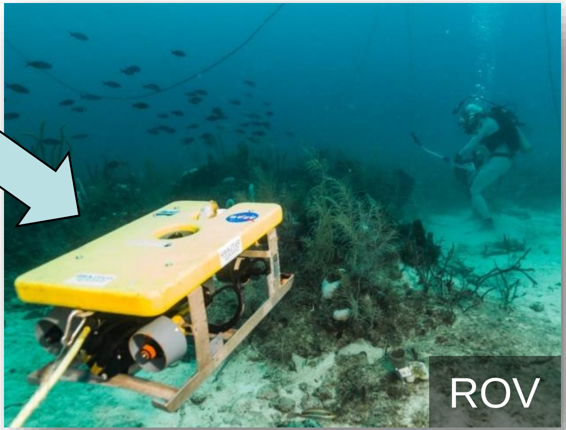
Example from RATS 12



Example from PLRP

EVA Interaction with MCC/ST Over Comm Latency Communication Architecture



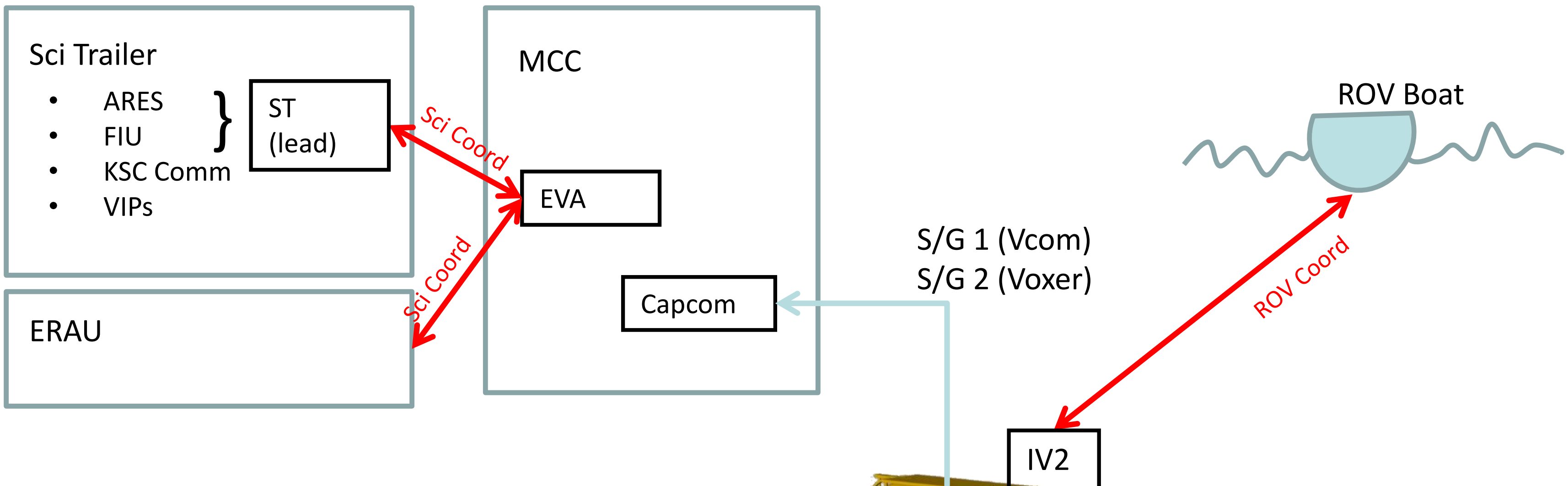

ROV


Aquarius Reef Base MCC

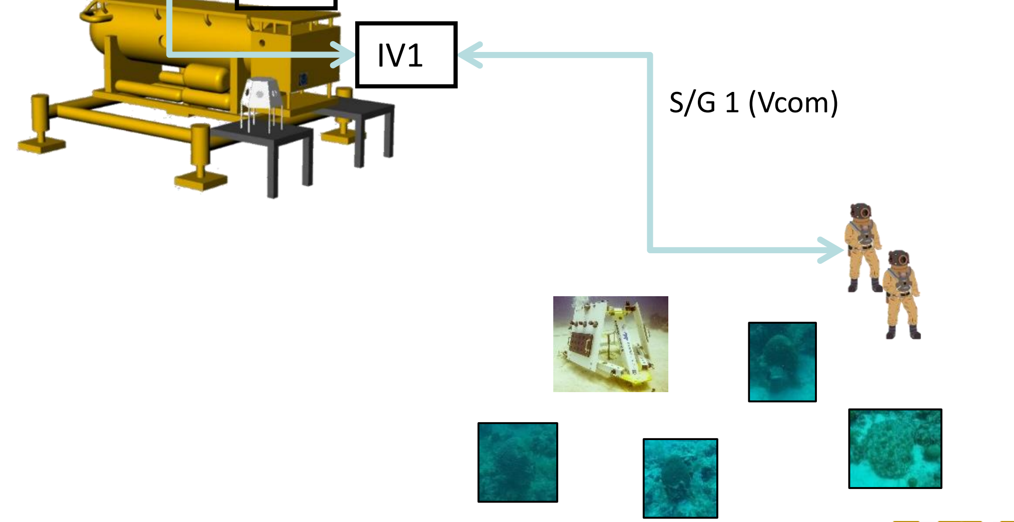

Aquarius Habitat IV


Aquarius EVA Crew

NEEMO 20 EVA Comm Loops



- S/G 1 used for big loop comm during EVA
  Uses Vcom software
- S/G 2 used for comm between MCC and IV1
  Uses Voxer software
- ROV COORD used for comm between IV2 and NPS ROV Pilot
  Uses Voxer software



EVA Interaction with MCC/ST Over Comm Latency Ground Assimilation Time Study Design

- Study was implemented during both Phobos (5 min OWLT) and Surface EVAs (10 min OWLT)
- ST was engaged and providing input based on information received
- Objective was to compare the effects of having fixed ground assimilation time vs. allowing it to dynamically vary within an EVA based on actual completion times; the intent was to show effects on idle time, ground assimilation time, total EVA time
- Ground assimilation time (GAT)
  - Calculated as time from beginning of first activity to beginning of subsequent activity within the same group
  - Time available for ground to discuss data/imagery after it has been collected, in addition to the time taken to watch imagery being collected in the first place (if data is streaming to the ground)
- For tasks dependent on science team input:
  - A fixed GAT equal to the first grouped task time + additional 5 minutes
    - 5 minutes chosen for additional GAT to attempt to minimize impacts to the EVA timeline design but still give adequate time for ST input
  - In the fixed GAT condition, the crew was asked to wait the entire planned GAT before performing a dependent task in the timeline
  - In the dynamic GAT condition, the crew was asked to proceed as soon as they reached a dependent task in the timeline
    - If ST input was received in time for the given GAT condition, the crew would proceed based on that input; otherwise the crew would proceed based on the precursor plan
- Under the dynamic GAT condition, the crew were to notify the MCC as soon as possible that a task will likely take shorter or longer than planned; MCC/ST would then attempt to adjust to a shorter time scale or take advantage of the additional time afforded to them to provide input

Definitions Related to Communication Latency

- Dependent task groups
  - Groups of two or more EVA tasks in which initial tasks are performed and subsequent tasks are dependent on ground input based on initial tasks
- Ground assimilation time (GAT)
  - Time available for ground to discuss data/imagery after it has been collected, in addition to the time taken to watch imagery being collected in the first place (if data is streaming to the ground)
- Idle time
  - Time spent waiting for ground input
- Total EVA time
  - Total available work time during EVA (“post-egress/ready” to pre-”ingress/clean-up”)
- Max possible GAT/EVA Time
  - Max possible GAT is limited by the fact that the final 2xOWLT min. is not actionable (i.e. not enough remaining time in the EVA for the ground to provide instructions back to the crew)

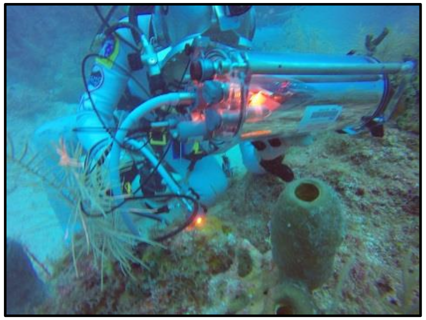
EVA Science Tasks

Geology Sampling

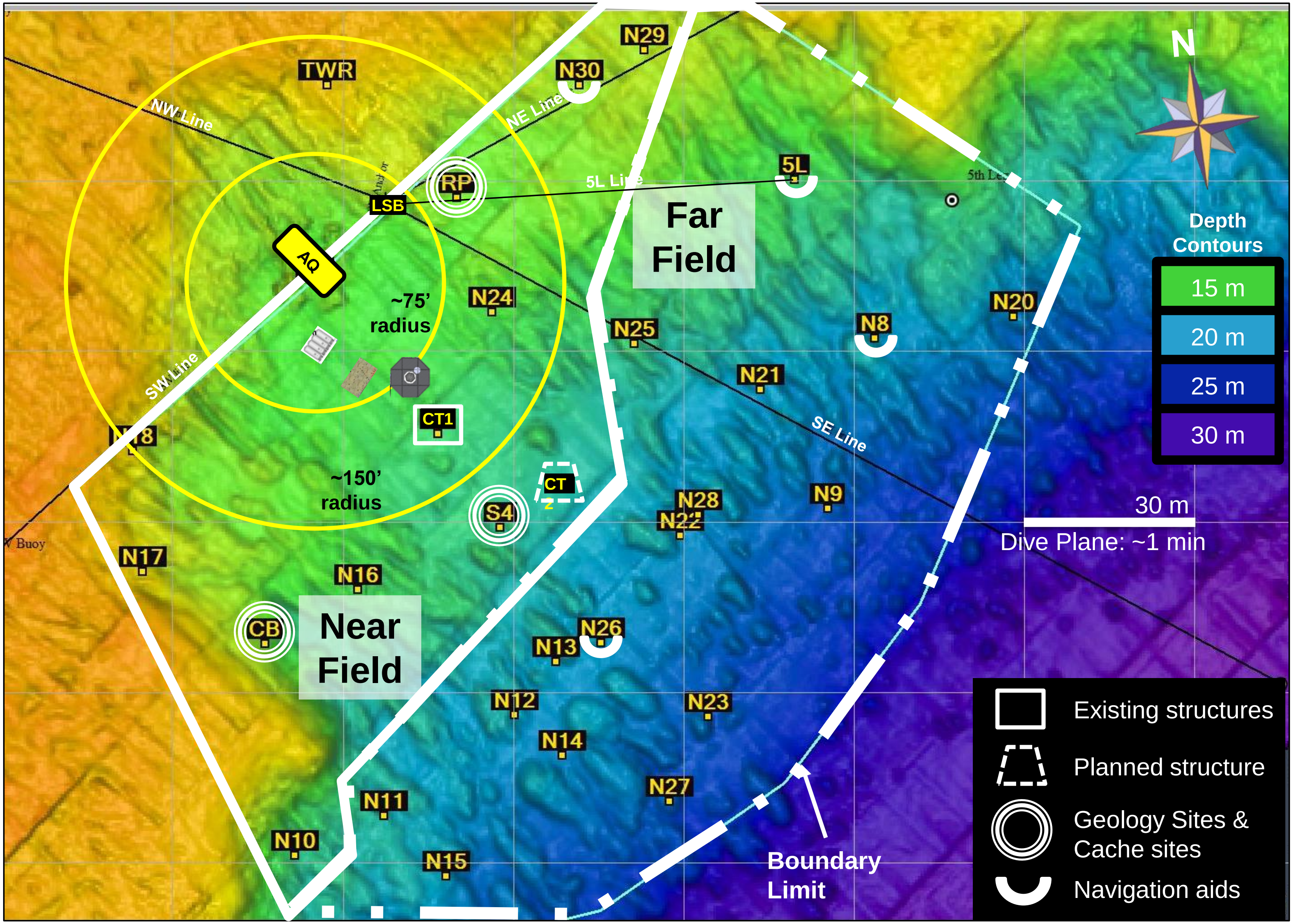
- Planetary geology tasks included
  - Collecting float, soil, surface, core, and rock chip samples
  - Deploying and using scientific instruments, such as a geophysical array
  - In situ analyses using scientific instruments
- Geological tool use and evaluations were included in crew tasks by developing geology sites with rocks deployed by the support team
- An Astromaterials Research and Exploration Science (ARES) scientist provided ST support for the geology tasks

Marine Science Sampling

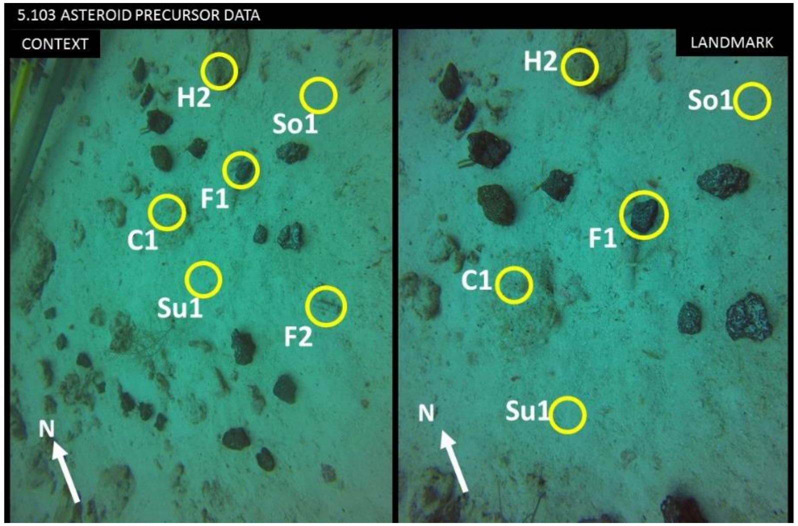
- Since no representative astrobiology/geology is naturally present on a NEEMO mission, a suitable proxy needed to be found instead to achieve these objectives
- The following marine science objectives were utilized to evaluate sampling
  - Tag colonies from three targeted coral species at 100 ft. and 60 ft. depth intervals. These long-term tags will also allow to monitor these colonies in future missions.
    Analogous to marking geological samples for communicating with the ST
  - Deploy a long-term temperature sensor (Hobo) in each sampling area.
    Analogous to deploying a scientific instrument such as a geophysical array
  - Acquire PAM fluorometry measurements for health assessment.
    Analogous to in situ analysis with scientific instruments
  - Obtain chip samples from selected coral species. These samples will be for DNA & RNA analysis.
    Analogous to geological sampling
- A team from the FIU Marine Science department provided ST support for the coral tasks

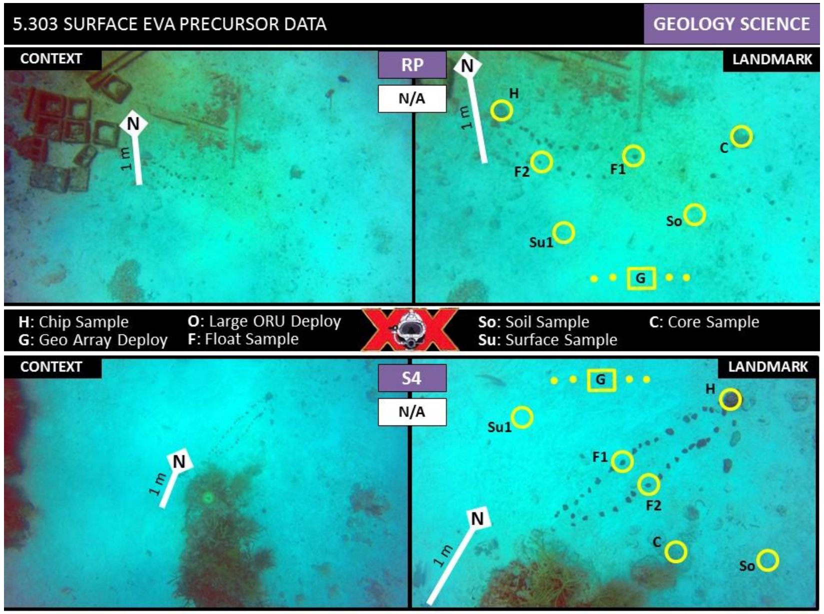


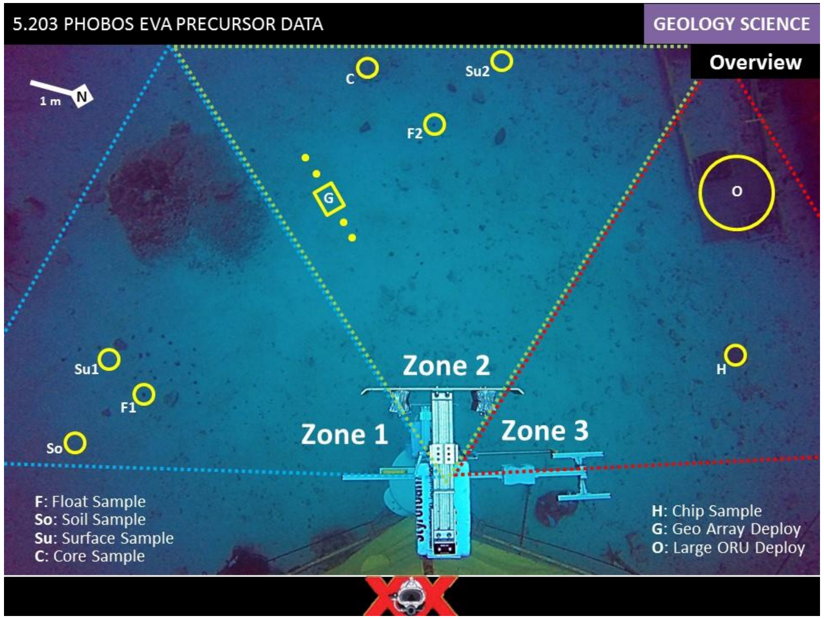
EVA Interaction with MCC/ST Over Comm Latency Science Site Map

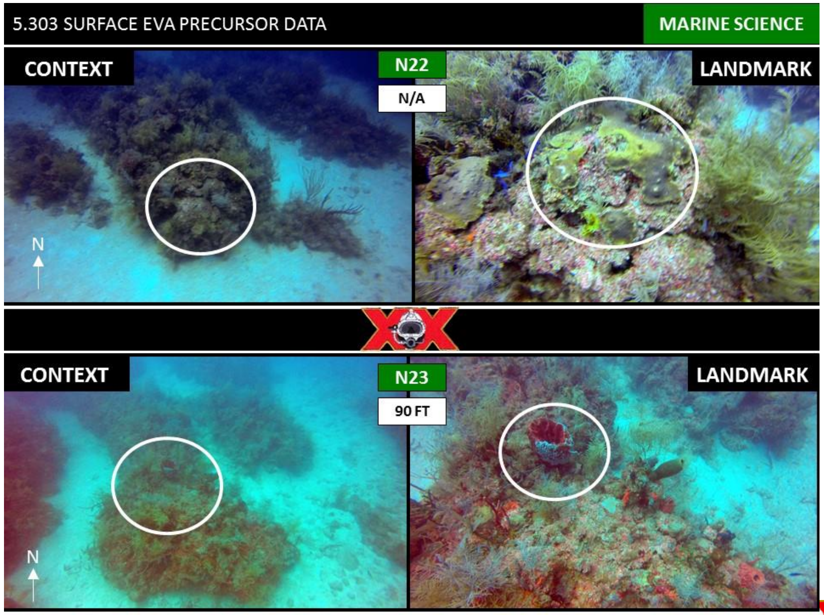


EVA Interaction with MCC/ST Over Comm Latency Science Precursor Data





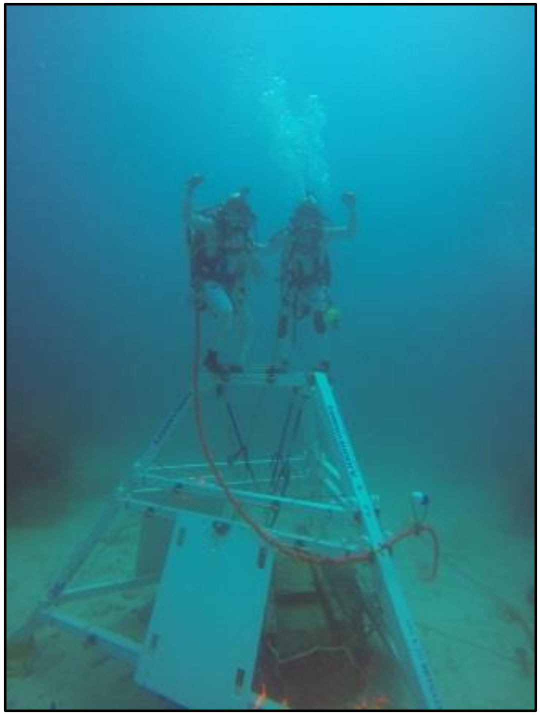




EVA Pioneering Tasks

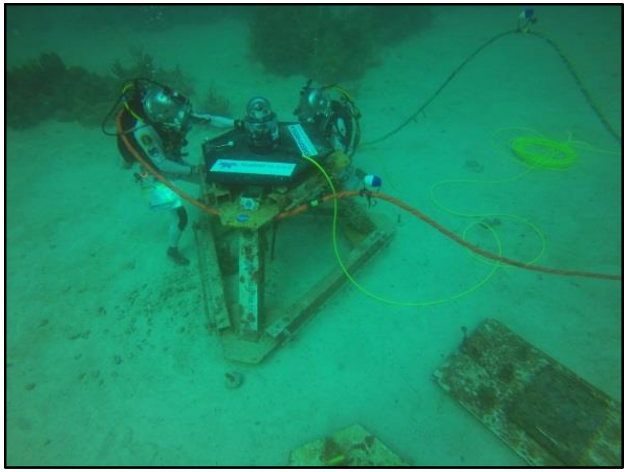
CORAL I

- Deployed during NEEMO 19
- Tasks involved removing the old panels for study by Teledyne Brown and installing a camera
- For ERAU, this is used for studies of long term exposure of hardware to the ocean
- **For NASA, this is analogous to working on building infrastructure on long duration surface missions**



CORAL II Tower

- Tasks involved assembling the tower and installing panels
- For ERAU, this is a 2nd structure to be assembled for long term hardware exposure study
- **For NASA, this is analogous to a pioneering task of building infrastructure, such as erecting a comm tower**
- ERAU provided a team to provide support for the CORAL tasks



EVA Interaction with MCC/ST Over Comm Latency Traverse & Science Flow

EV

Execute EVA
- Use Maps to Find Designated Sites
- Traverse between Sites

Pre-Sampling Survey
- Find Precursor-Defined Science
- Place Temporary Markers
- Marine/Geologic Description & Instrument Readings

Sampling
- Sample Based on Input from ST (via IV)
- Sample Based on Precursor Plan if no ST input received in time

IV

Guide EVA
- Use EVA Timeline to Direct EV to Designated Marine/Geologic Sites
- Provide Task Flow to EV
- Manage Time
- Provide Procedures

Pre-Sampling Survey
- Guide/Verify EV in Finding Precursor-Defined Science
- Verify Temporary Markers are Visible in Helmet Camera
- Record Descriptions and Instrument Readings

Sampling
- Receive input from ST in Mission Log Based on Imagery of Temporary Markers
- Provide input from ST to EV and Guide Sampling

Latency

MCC/ST

Monitor EVA
- Monitor Traverse
- Provide Input on Task Priorities & Time Management
- Clarify Procedures as Needed

Pre-Sampling Survey
- Analyze Incoming EV Video & Voice Into
- Manage & Adjust Science Priorities
- Snapshot and Annotate Images w/ ST Input
- Send ST Input to IV via Mission Log

Sampling
- Monitor Sampling
- Manage & Adjust Science Priorities
- Provide Further Science Input as Needed

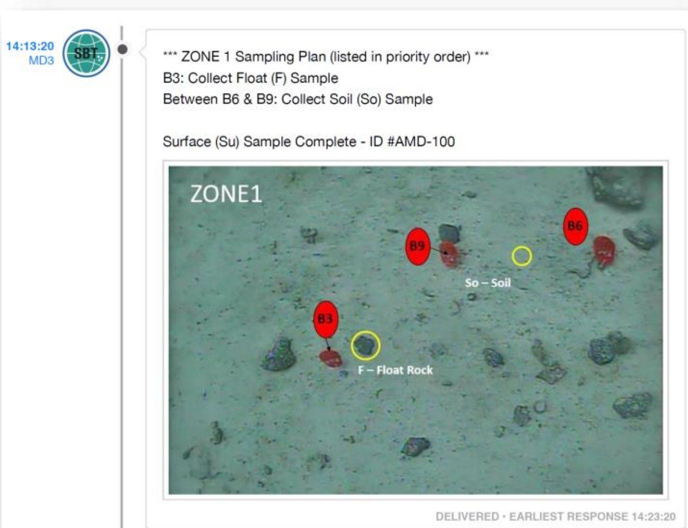
EVA Interaction with MCC/ST Over Comm Latency
Comm Between ST & IV During Mars System EVA

- EVA crew preformed preliminary tasks based on precursor data and training
- Data (video/audio) flowed back to MCC/ST
- ST evaluated data and provided direction to IV
- IV vectored EV crew for specific tasks to perform

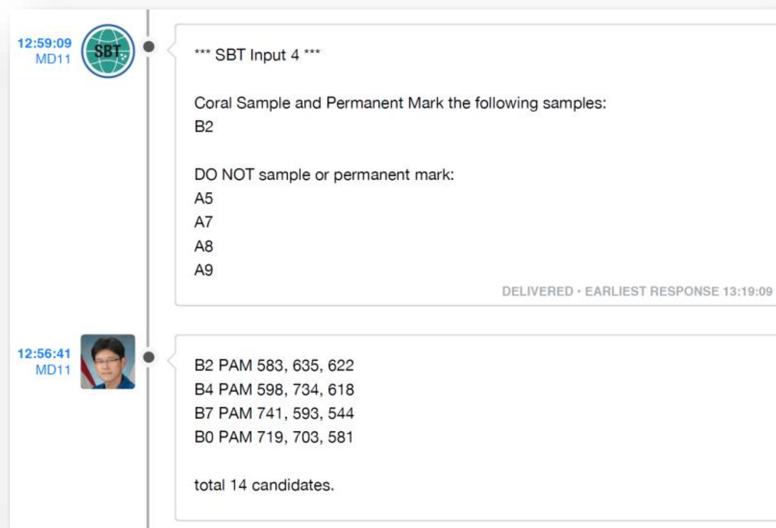
PET	EV1	EV2	IV1	IV2	MCC/SBT
0:05	Egress, Weighout, Don Crew-Worn Equipment		Assist w/ Egress		
0:10					
0:15	Translate to First Marine Science Site via Dive Planes				
0:20	Mark Center of Marine Science Site w/ HOBO Data Logger		Record Data Logger Number		
0:25	Recon Site and Place Temp Markers for Corals of Interest at First Site	Take PAM Readings from Corals of Interest at First Site	Record PAM Readings and Descriptions from Corals of Interest		
0:30					
0:35					Eval video of Corals of Interest for Identification of Samples at First Site
0:40					
0:45					
0:50					
0:55	Translate to Designated Geologic Site				
1:00	Perform Pre-Sampling Survey Based on Precursor Plan				
1:05					Ground Assimilation Time
1:10	Surface Sample 1	Soil Sample 1			Receive Pre-Sampling Survey from Geologic Site
1:15	Translate Back to First Marine Science Site via Dive Planes				
1:20	Perform Coral Sampling based on Plan from SBT (including placing permanent markers for samples selected by SBT)		IV receives SBT Input for First Site		Ground Assimilation Time
1:25			Record Sample Tubes Mapping to Corals of Interest and Direct Crew to next Sample Identified by SBT		Receive Float Sample 1 and Soil Sample 1 Data
1:30				Operate ROV to Support EV (use ROV to Translate w/ Samples, Tools, etc., to and from	Receive Coral Sampling Data for First Site
1:35					
1:40					
1:45					
1:50	Translate to Second Marine Science Site via Dive Planes				
1:55	Mark Center of Marine Science Site w/ HOBO Data Logger		Record Data Logger Number		

Information flow across latency indicated by color

Mars Surface EVA (Note: First 2 hours of 4-hour EVA shown here)



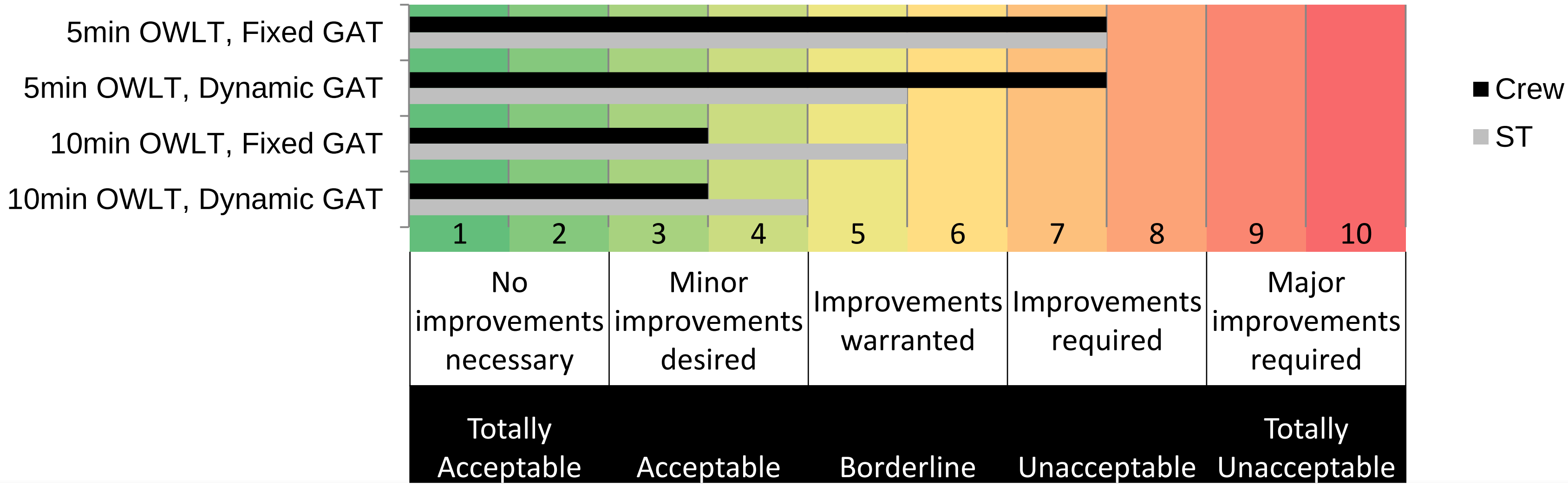
Geology Input from ST



Marine Science Input from ST

EVA Interaction with MCC/ST Over Comm Latency Post-EVA Crew Consensus Acceptability Ratings

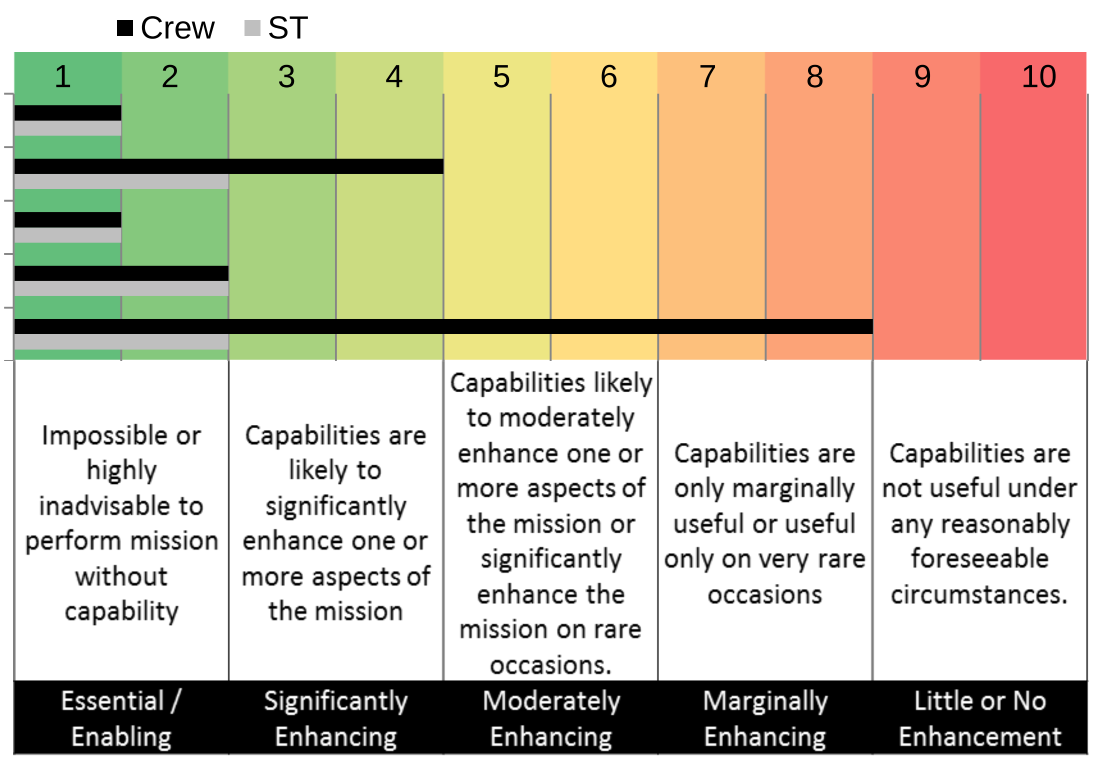
- The science team rated the dynamic condition more acceptable for both 5 min OWLT and 10 min OWLT
- The crew was not able to effectively discern the differences between fixed and dynamic GAT, mostly due to tasks taking longer than planned and never having to wait on input from the ground for either condition
  - The crews unacceptable ratings for 5 min OWLT were impacted by the need to execute on a tight timeline for both conditions & training effects due to being the first condition tested; ratings also impacted by a preference for a ops con they felt would be more efficient in which crew collects samples based on precursor data and training w/ follow-up directed by MCC/ST only as needed
  - The crews ratings for 10 min OWLT were impacted by more generous durations of tasks in the timeline and training effects associated with being the second condition tested

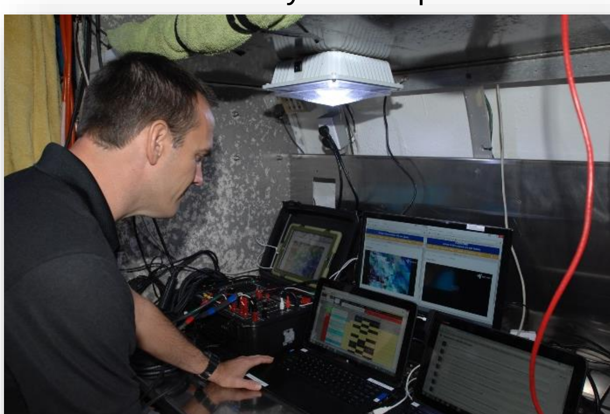


Take Away: Sufficient crew familiarization w/ tasks and a detailed understanding of the accuracy of designed time-lines are necessary to discern ops con changes; alternate ops cons w/ more crew control could be considered

EVA Interaction with MCC/ST Over Comm Latency Post-EVA Crew Consensus Capability Assessment

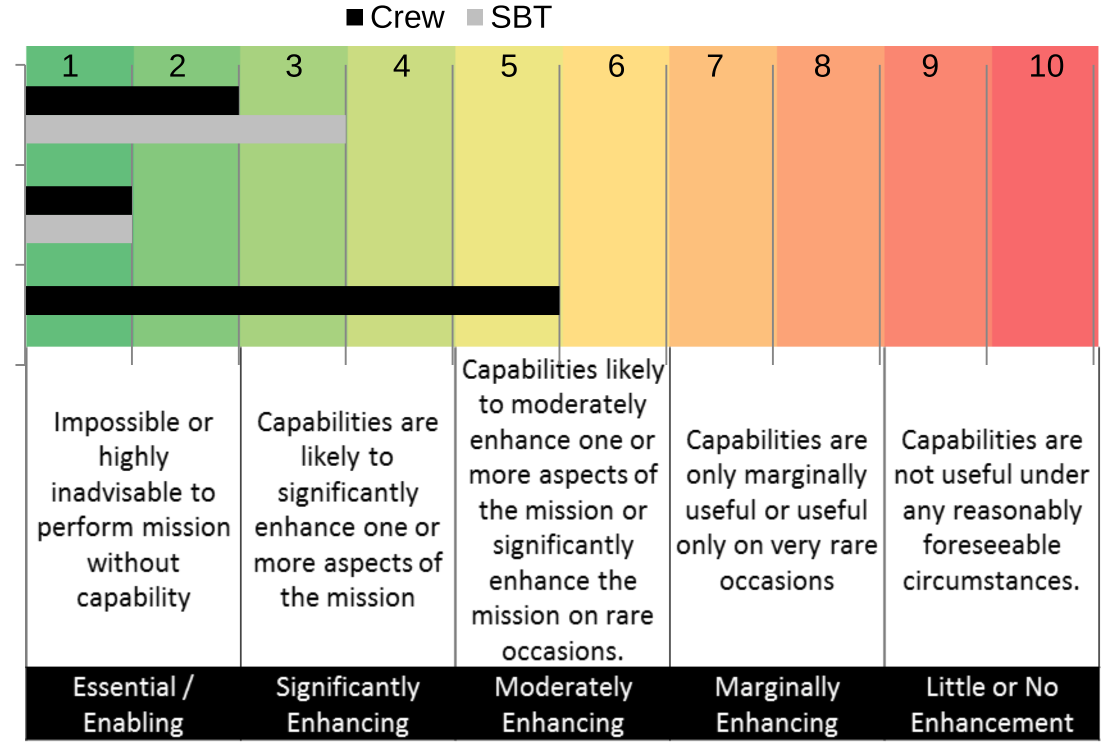
- **IV Support**, **Pre-sampling survey**, and **Playbook mission log** rated as **essential/enabling** to the operations concepts tested
- **Real-time (w/ latency) ground support** was rated **significantly enhancing**; “it is helpful to have real-time support to make sure the scientists get the samples they need”
- **Dynamic spreadsheet features** were rated as **marginally enhancing** by crew; “It's more information than an IV really needs. IV primarily needs to know how much time is left.”

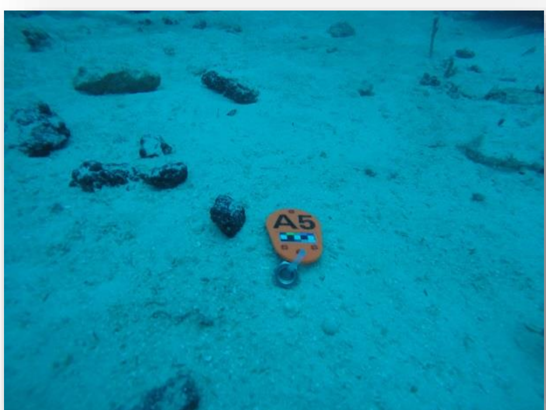




EVA Interaction with MCC/ST Over Comm Latency Post-EVA Crew Consensus Capability Assessment

- **Candidate sample labeling/identification** rated **essential/enabling** and **significantly enhancing**; “allowed the EV crew to communicate candidate samples to the SBT and keep them marked so they could be found again.”
- **Helmet cameras** rated **essential/enabling**; “Needed for the IV to know exactly what the EV crew are sampling.”
- **Situational awareness (ROV) camera views** rated **moderately enhancing**; “It helped at times to have the view from the ROV”; “was utilized on MD11 EVA to get an overview and review of the sites.”





EVA Interaction with MCC/ST Over Comm Latency Post-EVA Crew Consensus Capability Assessment

- **Voice** between ST/MCC and IV was not utilized even though the capability was available; voice between EV and IV (w/ MCC hearing) rated as **essential/enabling**
- **Text** between SMT/MCC and IV rated as **essential/enabling**
- **Annotated images** from ST/MCC to IV rated as **essential/enabling**; although not available and not rated, *annotated images and text from IV to EV seen as potentially valuable addition*
- MCC/ST/Crew ratings similar

5 MINUTE LATENCY

TRANSMITTING	RECEIVING: SBT / MCC		RECEIVING: IV		RECEIVING: EV	
MCC			Voice (with pre-alert)	NR		
			Text	1		
			Annotated Images	1		
IV	Voice	NR			Voice	1
	Text	1			Text (if possible)	NR
	Annotated Images	NR			Annotated Images (if possible)	NR
EV	Voice	1	Voice	1		
	Text	NR	Text	NR		
	Annotated Images	NR	Annotated Images	NR		

Essential / Enabling		Significantly Enhancing		Moderately Enhancing		Marginally Enhancing		Little or No Enhancement		No Rating
Impossible or highly inadvisable to perform mission without capability		Capabilities are likely to significantly enhance one or more aspects of the mission		Capabilities likely to moderately enhance one or more aspects of the mission or significantly enhance the mission on rare occasions.		Capabilities are only marginally useful or useful only on very rare occasions		Capabilities are not useful under any reasonably foreseeable circumstances.		Unable to assess capability
1	2	3	4	5	6	7	8	9	10	NR

EVA Interaction with MCC/ST Over Comm Latency Results and Observations

Summary

- Successful execution of 10 EVAs (32 hours) of operations concept-oriented research using precursor-based science plans and incorporating ground science team input on science being performed
  - 4 EVAs (8 hours) w/ 5 min OWLT; half of time spent in each of fixed and dynamic GAT
  - 6 EVAs (24 hours) w/ 10 min OWLT; half of time spent in each of fixed and dynamic GAT
  - Video, voice, and data from crew received in MCC and by science team across latency
  - Science team captured provided input back to crew based on fixed and dynamic GAT constraints

Results and Observations

- It's possible to have a Science Team on Earth influence the plan/tasks during an EVA, provided that the EVA is timelined such as to allow the transmission of data back and forth
  - Incorporation of ground input during EVAs seen as at least significantly enhancing to a mission by both crew and science team
  - It might be better, to have well trained crew that operate autonomously from a plan, and only have the ST call for deltas/go-backs
  - Tasks not requiring MCC input can be added into the EVA to accommodate the time required for round trip comm
- A good video camera is critical when it comes to communicating with IV and MCC/ST about geology
- Texting was shown to be a very effective way to transmit info between ST and IV
  - At times items in the running mission log got lost, however
  - Improvements to the portion of the Playbook tool used for texted were sent to the Ames team
- Some sort of IV support system will be critical due to the amount of information and tasking the IV crewmember must contend with (essentially performs the roles of IV, Flight Director, partial EVA Officer, and partial BME)
- The dynamic GAT condition was preferred over the fixed condition
  - The dynamic condition provided the flexibility for the science team to take more time to provide input when the crew was running behind on the timeline, thus increasing potential value of science team input
- For all fixed GAT conditions, more time was available to the science team to provide input than was allowed by the condition (5 minutes + time to receive all data)
  - This was due to nearly all tasks on the EVA timeline taking more time than planned such that more time was available for round trip communication

Recommendations

- Continue to enhance our understanding of comm delay by doing ops under very different latencies (5 min, 10 min, 20 min)
- Continue to perform science traverses that focus on realistic analogous tasks (marine coral science)
- Further evaluate support systems needed by MCC/ST and IV that help mitigate the comm latency, or example:
  - Use of software, such as the mission log in Playbook, for file/image upload
  - Improve texting capability to more clearly show incoming, read, unread, and important messages
  - Camera views needed to understand the details of the site being seen by the EVA crew
  - MCC screen capture and image editing capabilities needed to communicate direction to the IV crewmember
  - EVA sample/target markers that give true scale and color information to the ST
- Continue to use an ST populated by planetary and marine scientists
- Hybrid approaches that incorporate both crew autonomy based on precursor plans and science team input where value can be added should be considered

EVA Interaction with MCC/ST Over Comm Latency Summary Take-Away

Objective

- Continue to enhance understanding of comm limitations by including MCC/ST response time and comm with IV, and continue to investigate practicality of directing EVA operations from MCC over a comm latency

Gap closures addressed with NEEMO 20 results

- 703: EVA use model
- 801: DRM maturity (further mature EVA model)

Summary Take-Away for EVA

- Science ops can be constructed such that a Science Team on Earth can provide relevant, timely feedback to influence the plan and sampling tasks during an EVA, provided that the EVA is timelined such as to allow the transmission of data back and forth (i.e., having multiple sites to move between and having some tasks that don't require MCC input)
- The ability to communicate between the crew and MCC using text, voice, video, and annotated images during time-latent operations were all rated as essential/enabling by both crew and ground teams
  - Voice comm that is automatically recorded and could be played back at-will was instrumental for clear communication
  - Texting and annotated imagery allowed for clear comm between MCC and the IV
  - Clear video back to MCC is highly enabling for conducting science operations
- The addition of scientific realism (rocks deployed by topside and local marine science) allowed for successful evaluations of interaction over a comm latency during an integrated mission
- A dynamic approach to incorporating ground science team input allows for maximum flexibility and time to provide that input, thus increasing the potential quality of science achieved
- Some sort of IV support system will be critical due to the amount of information and tasking the IV crewmember must contend with (essentially performs the roles of IV, Flight Director, partial EVA Officer, and partial BME)

EVA Recommendations for Forward Work

- Continue to enhance our understanding of comm latency by doing ops with realistic science and pioneering tasks and using EVA tools under different latencies during future NEEMO missions
- Further examine the interaction between a Science Team and IV crew to evaluate the assets needed to mitigate the comm latency and to allow for feedback that can influence an EVA during future NEEMO missions

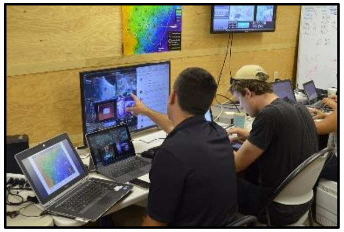
Science Team Engagement with EVA Summary Take-Away

Supplementary Objective

- Investigate how a Science Team engages with the crew in order to influence an EVA

Gap closures addressed with NEEMO 20 results

- 703: EVA use model
- 801: DRM maturity (further mature EVA model)



Summary Take-Away for EVA

- Incorporation of ground input during EVAs was seen as at least significantly enhancing to a mission by both crew and science team
- Though it’s possible to have a Science Team on Earth influence the plan/tasks during an EVA – provided that the EVA is timelined such as to allow the transmission of data back and forth – it may be better to have well trained crew that can operate autonomously from a plan, and only have the ST call for deltas/go-backs.
- During EVAs, the science team needs to be a focal point of the primary MCC team (not a “backroom”), and be fully integrated with all other operations taking place
- The geology tasks and the coral science tasks (used as a proxy to astrobiology), provided planetary science geological tasks that were realistic enough to effectively test and evaluate the ops concepts associated with the ST

EVA Recommendations for Forward Work

- Further examine the role of a Science Team as a primary MCC team and how that team can influence an EVA during future NEEMO missions
- Engage planetary protection personnel during NEEMO to begin looking closely at how ops cons will effect the planet

EVA Ops Con
Robotics for EVA (Man-Machine Work System)

Purpose

- Assess potential operations of a robotic asset for EVA and inform functional needs of a robot for EVA tool management
- NPS ROV was used to assist the EV crew
- ROV provided situational awareness for the IV and MCC/ST
- ROV took coral samples from the EV crew and transported them to the habitat
- Flown by both surface support and crew from the habitat

Results and Conclusions

- The ROV was successfully flown by an IV crewmember at two of the sites for EVA situational awareness
- It will be critical to have the latency low enough and controls such that's it's possible to fly/drive a robot near the EV crew

Recommendations

- Continue to explore the ops con associated with making the man-machine work system more efficient
  - Utilize the ROV to gather precursor data
  - Have crew recon the sites before the EVA, and utilize that info for planning
  - Place markers with ROV to identify landmarks
  - Guide the EVA crew to worksites
  - Hand the EVA crew tools and/or sample bags
  - Receive samples from the EV crew and return them to the habitat to maximize efficiency
  - Use the ROV to down-select high priority samples at one worksite while the EV crew works at another
- Increase crew training to allow crew to perform more of the flying

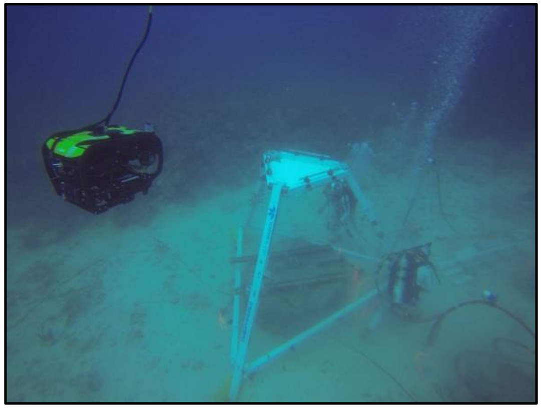
Robotics for EVA (Man-Machine Work System) Summary Take-Away

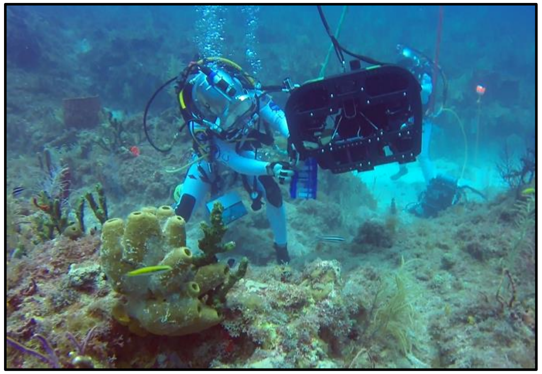
Objective
- Assess potential operations of a robotic asset for EVA and inform functional needs of a robot for EVA tool management

Gap closures addressed with NEEMO 20 results
- 510: Tool management device
- 801: DRM maturity (further mature EVA model)

Summary Take-Away for EVA
- The ROV was successfully flown by an IV crewmember at two of the sites for EVA situational awareness
- Low latency robotics (in this case the ROV controlled from the Aquarius) are able to offload EV workload for tasks like transporting samples, tools, etc. when the robotic element is working alongside the EV crew
- Stabilizing features (like autopilot, or ability to “park”) are necessary to offload the pilot and allow him to concentrate on other tasks (e.g., science, timeline/ops, and safety)

EVA Recommendations for Forward Work
- Continue to explore the ops con associated with making the man-machine work system more efficient in the end-to-end environment enabled by NEEMO
  - Utilize the ROV to gather precursor data, have crew recon the sites before the EVA for planning, place markers with ROV to identify landmarks, guide the EVA crew to worksites, hand the EVA crew tools and/or sample bags, receive samples from the EV crew and return them to the habitat to maximize efficiency, use the ROV to down-select high priority samples at one worksite while the EV crew works at another
- Evaluate different variations of ops concepts for ROV use during an EVA (e.g., working the same site side-by-side, working different sites in parallel) to understand how to gain the highest efficiencies possible in the man-machine work system during future NEEMO missions

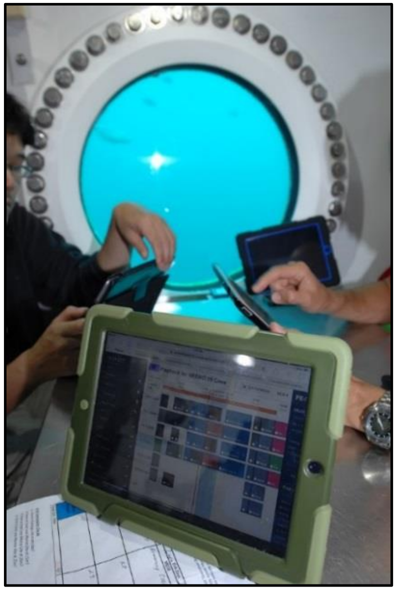




Multi-day Crew Self-Scheduling of EVAs

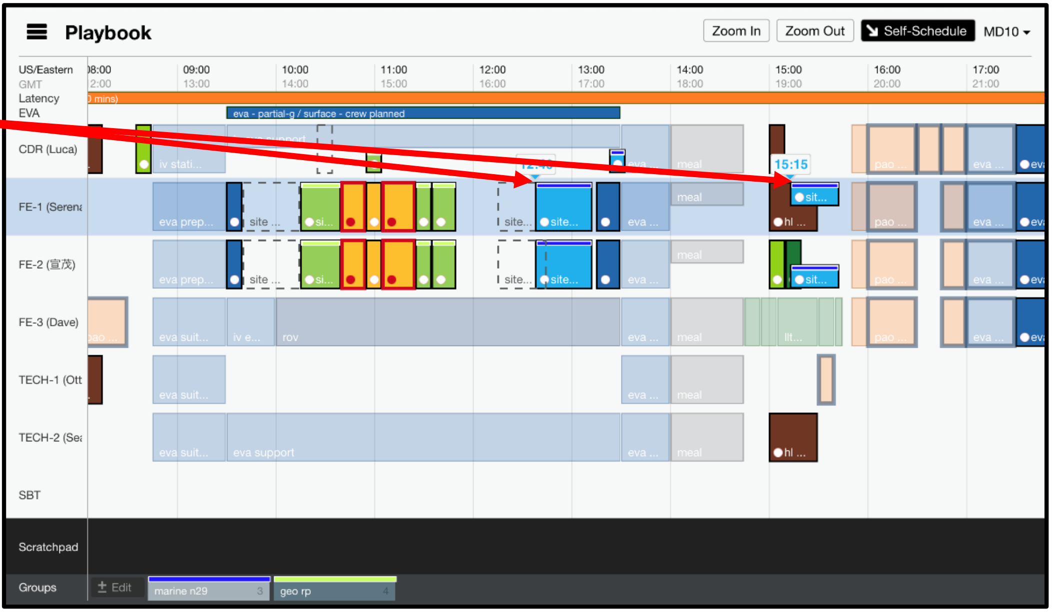
Purpose

- Investigate crew driven multi-day planning of EVA operations utilizing scenarios with variables and a task list that must be planned and carried out over the course of multiple days
- For the surface EVAs, the team evaluated having MCC plan 3 of the EVAs and then having the crew plan 3 of the EVAs
- Playbook was used as the planning tool
- Individual EVA tasks were put into Playbook, along with any associated constraints (such as a task not being able to be done until 25 min after another)
- For the self-scheduled EVAs, crew took the task blocks and arranged them as preferred to develop the entire timeline



Tool Features for Self-Scheduling

- Groups support allows multiple activities to be grouped and moved at once with a single drag and drop
- Used during the mission to assist with EVA self scheduling
- Helps preserve relative timing between activities when moving activities



Multi-day Crew Self-Scheduling of EVAs Results and Recommendations

Results

(for self-scheduling, not Playbook tool)

- The crew was able to successfully self-schedule EVAs utilizing task activity list, constraints, and Playbook
- Crew preferred determining what task got done on each EVA, but it was a lot of overhead and crew time for the crew to actually put the timelines together (prefer "self-determination" to "self-scheduling")
- The crew time it took to create the timeline was not worth the advantage of having the crew do it themselves

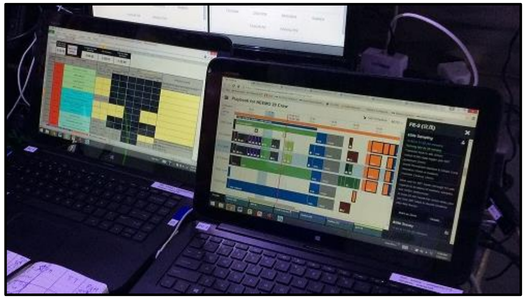
Recommendations

- The advantage of having the crew self-schedule is that they understand the immediate environment better than MCC
- Further test the concept of having the crew determine the tasks and order for each EVA, while having the MCC team actually put the plan into Playbook
  - In situ crew creates the plan based on their local observations
  - Crew determines the tasks and order for a particular EVA
  - MCC incorporates the tasks into Playbook to formulate the timeline
- Provide a wider range of tasks and constraints to the crew in order to drive the scheduling
- Incorporate recommendations into the next version of Playbook

Multi-day Crew Self-Scheduling of EVAs Summary Take-Away

Objective

- Investigate crew driven multi-day planning of EVA operations utilizing scenarios with variables and a task list that must be planned and carried out over the course of multiple days



Gap closures addressed with NEEMO 20 results

- 703: EVA use model
- 801: DRM maturity (further mature EVA model)

Summary Take-Away for EVA

- The crew was able to successfully self-schedule EVAs utilizing a task activity list, constraints, and Playbook
  - The constraints were clearly communicated, the Playbook tool was sufficiently capable, and the crew was able to develop successful, executable EVA timelines.
  - However, the time penalty was large (~4 man-hours/day) and the advantages did not outweigh the costs
- A better ops concept than crew self-scheduling would be crew “self-determination”, meaning that they determine what tasks get done on which EVA, but the actual scheduling is done by professional planners who are more adept at manipulating plans and more intimately familiar with all the myriad of constraints
  - In this way, the advantages of unique knowledge the crew brings from their high familiarity with the exotic environment is best incorporated without the high cost in crew time of turning them into planners

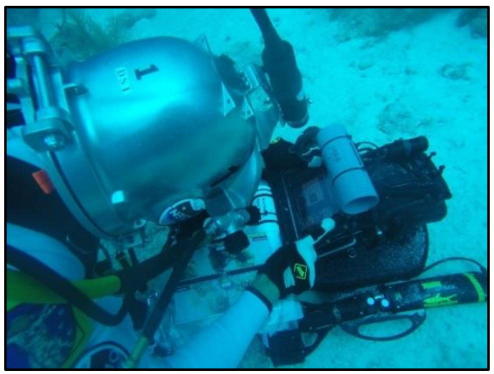
EVA Recommendations for Forward Work

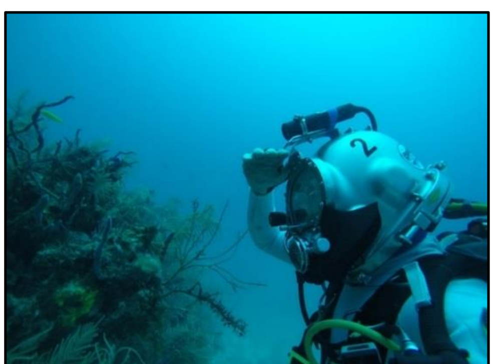
- Test concepts for optimizing EVA multi-day planning that incorporates crew input based on the unique in-situ knowledge they’ve acquired, while taking advantage of the skills and efficiencies that ground based planners bring
- Provide a wider range of tasks and constraints to the crew in order to stress the planning tools and concepts with flight-like fidelity

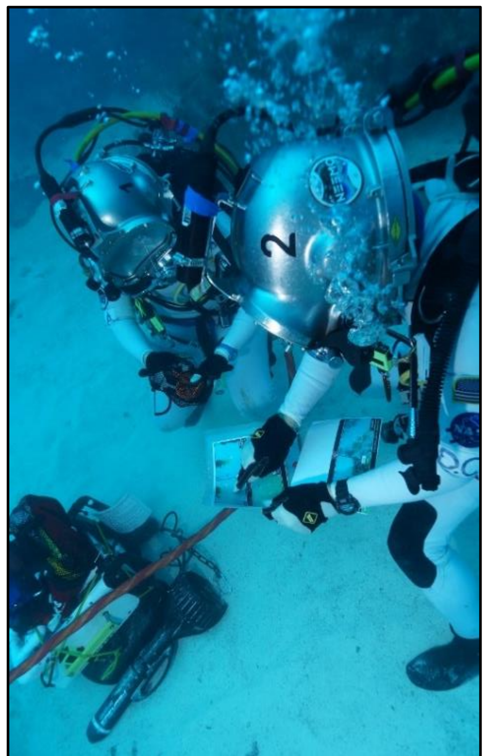
EVA Navigation

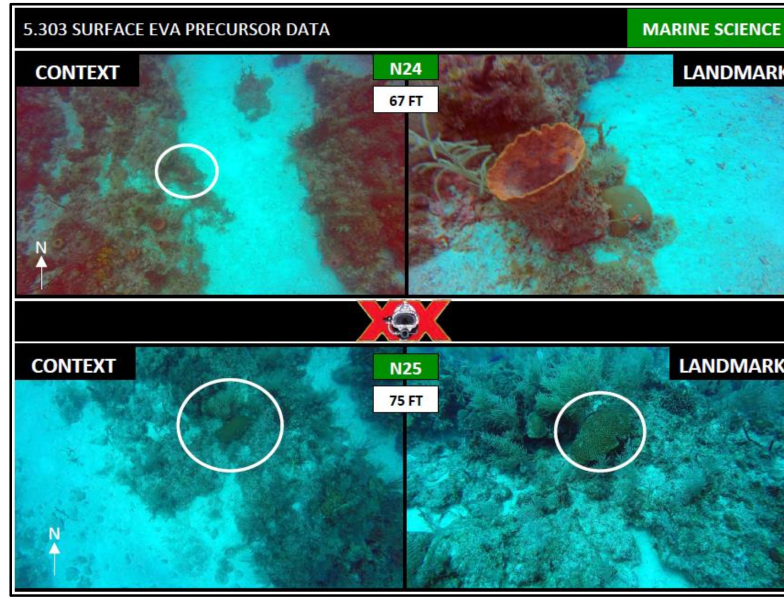
Purpose

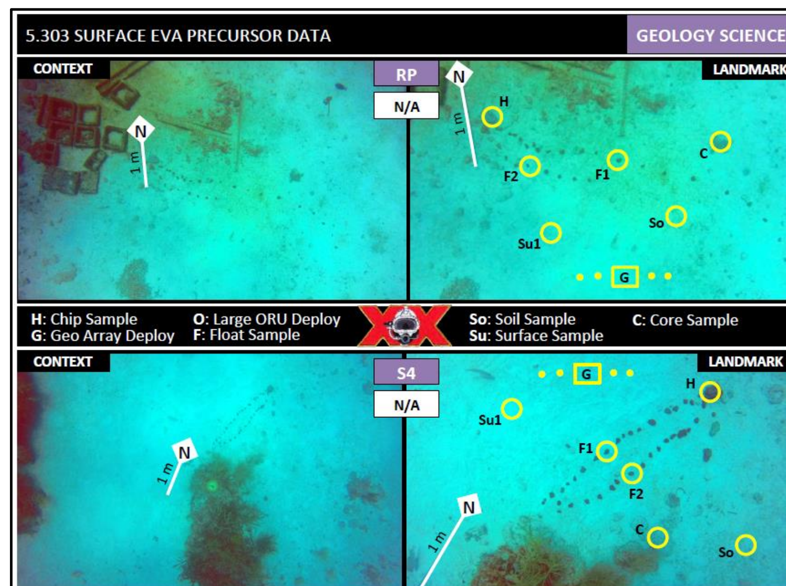
- Begin looking at types of hardware needed and techniques for navigating on a foreign body
- The Navigator system was used by EV crew as the primary means of navigating to landmarks that set the science sites
- EV crew had copies of the maps to assist in navigation to sites
- At the sites, EV crew used a set of cue cards to identify the primary landmark











EVA Navigation Summary Take-Away

Objective

- Begin looking at types of hardware needed and techniques for navigating on a foreign body

Gap closures addressed with NEEMO 20 results

- 214: Navigation Short Range
- 801: DRM maturity (further mature EVA model)

Summary Take-Away for EVA

- It was difficult locating an exact precursor landmark utilizing the Navigator
- The cue cards were critical to finding the landmarks once near the area
- Since the planetary science goal of an Exploration mission is to characterize an area more than pick up a specific rock, a navigation system more needs to get the crew close to a target that landmarks an area rather than locate a specific sample
- Electronic navigation will be critical in areas where the terrain looks similar, especially when marking new locations and returning to a site
- Maps worked well for planning and for helping with navigation during the EVAs

EVA Recommendations for Forward Work

- Continue investigating electronic navigation that allows the crew to locate a specific area to characterize, mark new locations, and return to sites
- Refine the cue cards and evaluate them on future NEEMO missions

Building EVA Hardware In Situ (3D Printer) Summary Take-Away

Objective

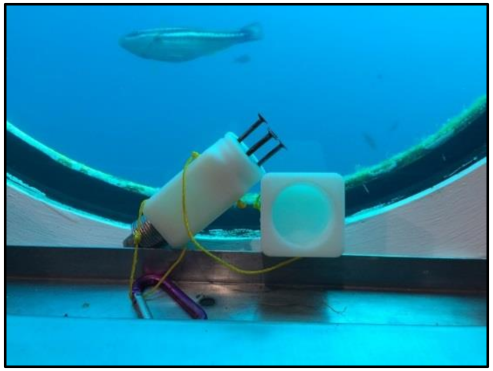
- Investigate building EVA hardware in situ
  - NEEMO 20 investigated the potential benefit to integrating a 3D printer into an exploration mission.
  - The team posed the question: “If a 3D printer was available for use, what could you print and how would you convey requirements real-time?”

Gap closures addressed with NEEMO 20 results

- 512: Common tools for vehicle maintenance
- 801: DRM maturity (further mature EVA model)

Summary Take-Away for EVA

- The 3D printer proved useful numerous times during the course of the mission for:
  - Designing and printing broken end effectors
  - Printing a missing part (an alignment pin)
  - The design from scratch and rapid delivery of a part whose need hadn’t been anticipated pre-mission (nail holder)
    - One unique crew requested item was a nail holder to help transport and dispense nails that were used to secure permanent marine science markers.
    - The nail holder was designed, modeled, printed, assembled and delivered to the crew in under 48 hours
- The speed with which pieces can be fabricated proves its promise as a rapid turnaround parts solution



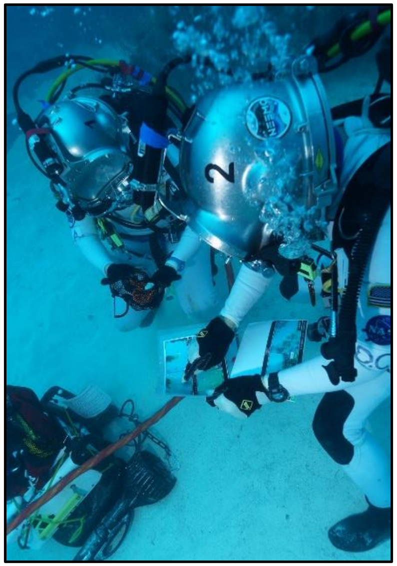
EVA Recommendations for Forward Work

- Continue utilizing the 3D printer during the next NEEMO missions for creating unforeseen items that the crew needs

General EVA Observations & Recommendations

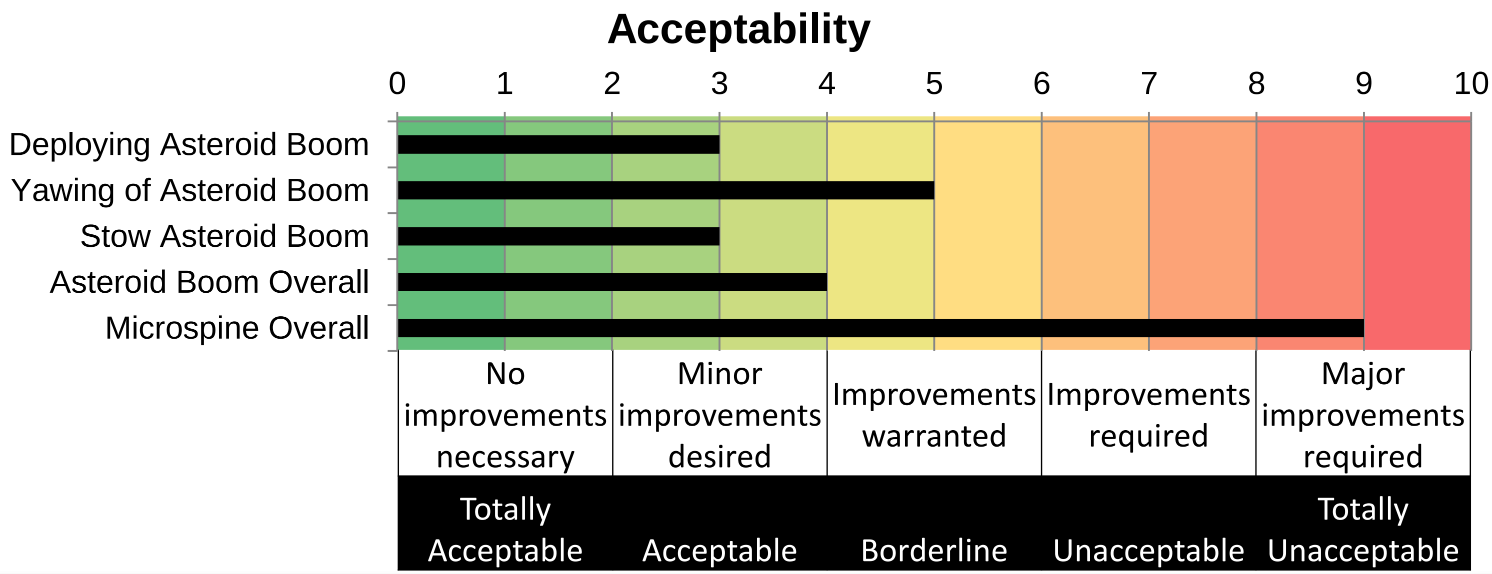
General Observations

- It was challenging to move around a geology site where there were several potential samples without contaminating the surface
- Telementoring technologies inside of a spacesuit would be useful
- It's always good to carry backup tools, like a hammer
- For future NEEMO missions, find a better way to organize and carry things like the marine science tools
- Embedded EVA Operations Engineer
  - Embedding the lead EVA operations engineer that was fully engaged throughout the entire process - developing the detailed objectives, guiding tool development, and formulating the complex EVA plan - was valuable for obtaining pertinent results
  - Focused all of the EVA stakeholders and enabled a more flight-like, thorough, credible, and meaningful mission for EVA that evaluated key gaps and operations concepts
  - EVA plan was complicate with not enough time for crew training, so the XX crewmembers was able to more thoroughly explain the purpose, metrics, ops, and tools during the mission, which focused the crew on the priorities and objectives
  - XX crewmember had enough vested in the mission and results to spend personal time capturing thoughts and lessons learned during the mission (before they're forgotten)
  - With minimal time to collect data from the crew before leaving after splashup, the XX crewmember with firsthand experience was able to stay engaged in post mission activities in order to formulate results
  - Per the crew report, "Having a non-astronaut crew member added extra value to the mission, especially for unflown astronaut crewmembers. For future missions, Flight Directors, CapComs, Flight Surgeons and Support Engineers from the crew office could be valuable candidates, together with EVA instructors and personnel involved with exploration projects."



Asteroid Boom & Microspine Post-EVA Test Subject Consensus Acceptability Ratings & Comments

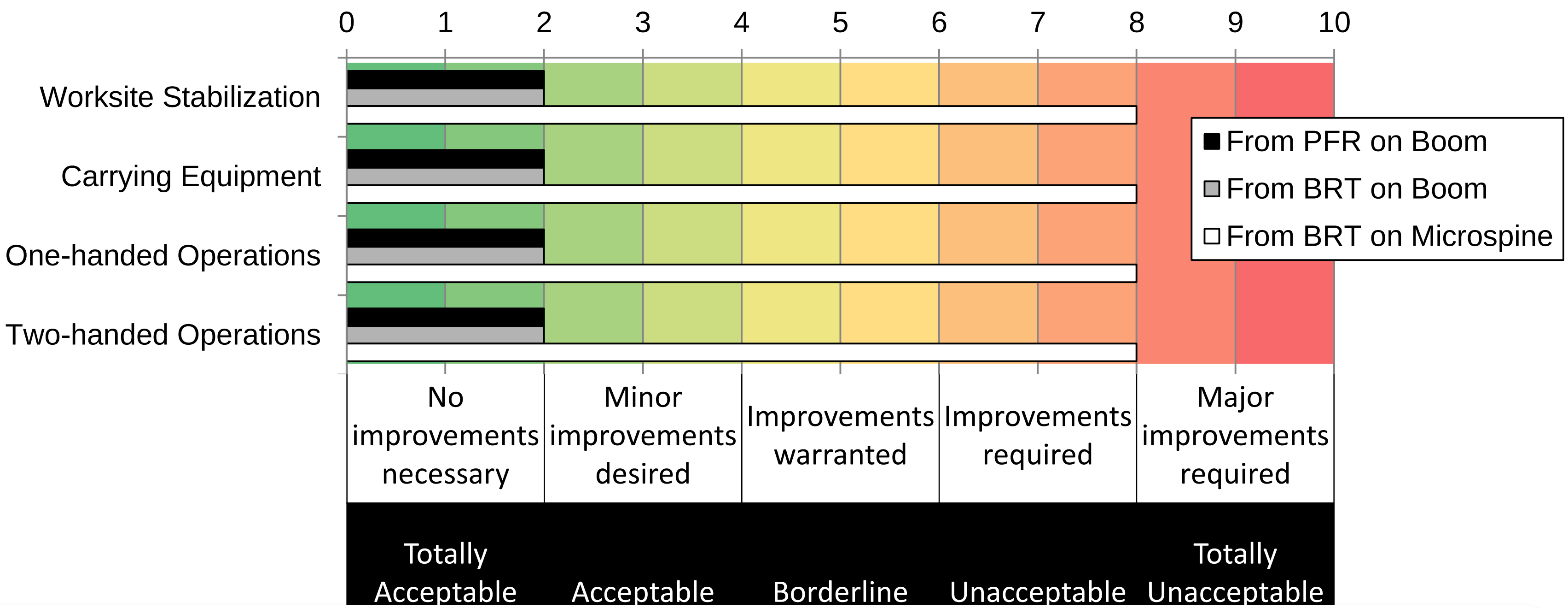
- Deploying Asteroid Boom: "the boom is heavy and the PIP pins kept sticking"
- Yawing of Asteroid Boom: "there is very little leverage when positioned in the base PFR to yaw the boom"
- Stow of Asteroid Boom: "the boom is heavy and the PIP pins kept sticking"
- Asteroid Boom Overall: "There are movements for which more leverage is required than can easily be achieved with this boom design."
- Microspine Overall: "would not hold onto a "good" rock even w/ limited BRT loads induced."



Take Away: Asteroid boom is acceptable w/ improvements desired/warranted in weigh out (to improve simulation), adjustment, and yawing; microspine has major improvements required to react necessary loads

Asteroid Boom General <u>Post-EVA Test Subject</u> Consensus Acceptability Ratings & Comments

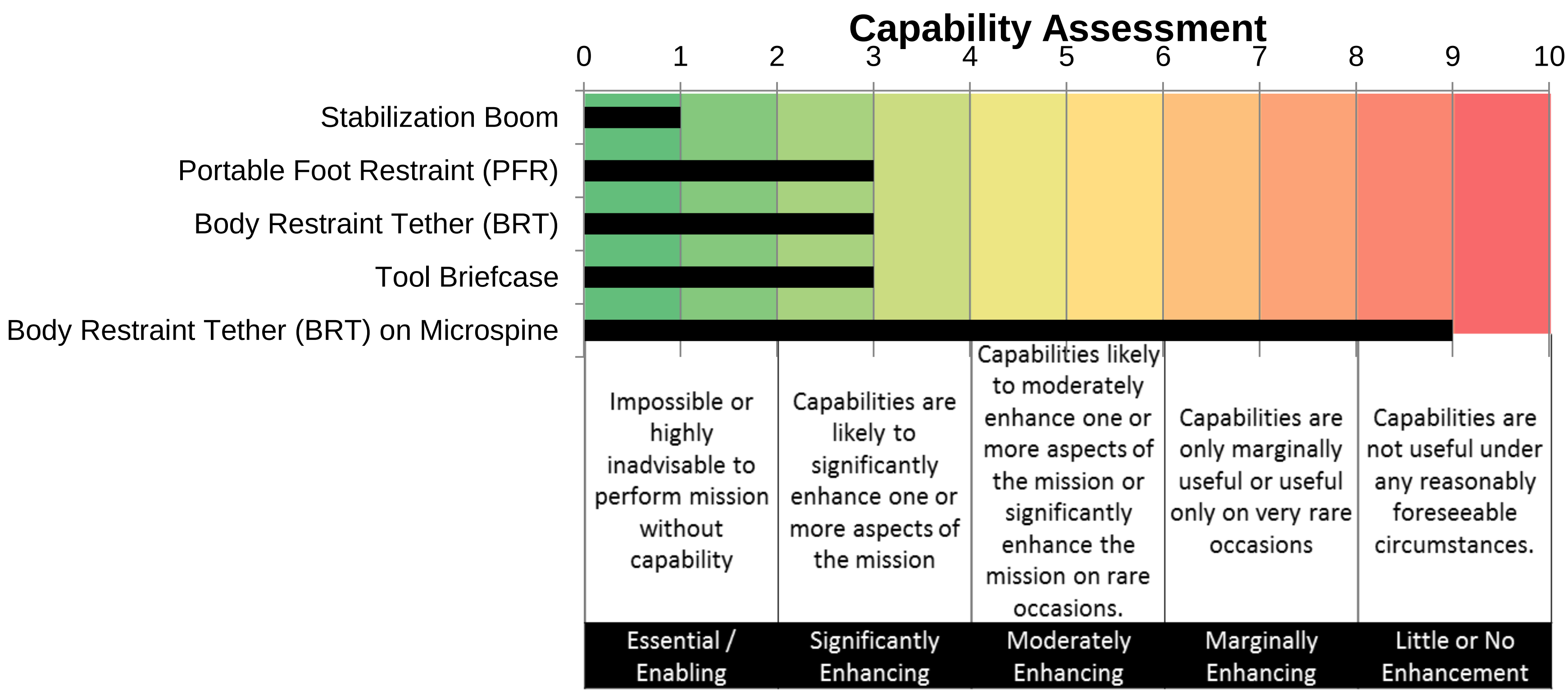
- <u>Worksite Stabilization</u>: acceptable except for microspine; "microspine slipping off rock under BRT-level loads"
- <u>Carrying Equipment</u>: sim quality 4 (crew lock bags not neutral)
- <u>One-Handed & Two-Handed Operations</u>: acceptable except for microspine; "microspine slipping off rock under BRT-level loads"



<u>Take Away:</u> Stabilization and operations acceptable from asteroid boom; microspine improvements are required to react BRT-level loads; weigh-out improvements are necessary to improve simulation quality

Asteroid Boom Features & Microspine Post-EVA Test Subject Consensus Capability Assessment Ratings & Comments

- Stabilization Boom: essential/enabling
- PFR: “a PFR is useful, but a boom with places to BRT all along it would work well”
- BRT: “either a BRT or PFR are needed, but not necessarily both”
- Tool Briefcase: is “needed to ensure that samples are contaminated as little as possible”
- BRT on Microspine: “The microspine kept slipping. It will also be difficult to find rocks in a micro or milli-g environment that will take any sort of EVA loads.”



Additional Backup Information

SCIENCE OBSERVATIONS FOR EVA

Science Realism

- Comment: Incorporating both geology and marine science tasks, coupled into the larger simulation, added a realistic science component for the crew and overall analog mission
- Recommendation 1: This integrated model was successful in adding a level of scientific realism to the mission that should be sustained and expanded upon in the future. Particularly, the real time re-scoping of the marine science to fit within the operational constrains allowed for a realistic dynamic interaction between science and operations. The geology sites were particularly important for testing tools and sample collection strategies.
- Recommendation 2: With additional pre-mission coordination the overall science scenario could be further established. For example, we could further incorporate remote sensing, on-the-ground imagery, science results, terrain naming schemes, etc. of the current Mars rovers into a more realistic surface scenario for a human operations. Using real data from the Martian surface will help to further immerse the crew into the simulation.

IV Position

- Comment/Opinion: EVA support should be the highest priority for all IV crew
- Recommendation: If two IV crew are in the habitat both should be supporting EV crew members; one would track EVA basics (consumables, timeline, communications, systems, etc.), while the other IV member would concentrate on the science (executing the plan, achieving intent/objectives, capturing data, dealing with Science Team inner-EVA deltas, etc.). The crew split the IV responsibilities a few times during some EVAs (when ROV ops were not being conducted) which seemed to work well and was mentioned as an efficiency in their debrief comments.
- Note: If robotic assistance is available – autonomy of these systems would be critical (i.e. the ROV or surface rover would need to be able to station-keep, track crew, and perform certain tasks on its own with limited IV input; allowing the crew to concentrate on the science, timeline/ops, and safety)

Science representation in MCC during Science EVAs

- Comment: During a nominal science EVA the majority of communication, reprioritization, etc. is coming from the Science Team; in some analog surface mission configurations there is no Science representation in MCC (strictly following the Science "Backroom" connotation). This does not allow for a dynamic integration between the Science Team, EVA Team, Mission Director, etc. The Science Team could essentially send anything to crew without operational integration or review.
- Recommendation: A science representative should be present in MCC (as Science Liaison or SciCom), this position would interface/communicate with the larger Science Team that would be located in another location(s). This MCC science role would communicate both ways 1) the science planning consensus ultimately sent back to the crew and 2) the constrains of the other MCC components (ex. consumables, communication or power limitations, etc.) back to the science team that may impact the plan going forward. See image as one possible configuration.

Science Operations

- Video is great for situational awareness, but high-resolution still imagery is largely preferred for most science requirements. Future analogs should develop a method to capture and send real-time (or over the given time delay) still imagery for optimal science planning and integration. For example, find a way to “real-time stream” giga-pan like imagery taken during the pre-site survey and/or close up GoPro images of the samples of interest.
- For the Phobos mission, it would be interesting to explore the addition of a Science Team controllable camera located on the hab/upper-boom (with PTZ capability); providing both surface and crew context. It would be interesting to test if a Science Team controlled camera is useful and/or manageable over time delay.
- The ability to further delay video (i.e. delaying video beyond the time delay) is a greatly useful real-time function to have incorporated into the software tool package used by the Science Team. It was used in two ways 1) to delay the video a few seconds behind the voice to help hear and distinguish the comm before actually seeing the video and 2) to rewind, find, and screen capture images from the video feed to annotate and send back to the IV.
- Similar to the current instrument operation of the Mars rovers, separate science Uplink Lead and Downlink Lead roles are required to rapidly provide inner-EVA Science input, but also to ensure capture of the downlink (sample IDs, images, descriptions, comments).
- EVA timeline needed to reflect more time for translation, umbilical management, etc.

EVA Science Operations
Science Team Observations & Recommendations

Fixed GAT

- Overall, the fixed GAT allowed little time to absorb, process, and create meaningful science products to push back to the crew in a 5 min fixed time frame (i.e. we could not conduct a full or even semi re-plan of the site based on the crew descriptions during the pre-site survey).
  - Note: For this test the size of the Science team was small, the overall size of the Science team will likely be a contributing factor.
- The only science decision that could likely be conducted under fixed GAT is to select from predetermined collection options (e.g. precursor imagery indicates 3 potential float rocks of interest (A,B, or C); pre-sample images now reveal only B is preferred)
- Training the crew to make the "on the ground" science call would likely be the most efficient method of sample collection (if pressed under this type of time constraint). Note: With this the science intent/objects need to be clearly stated and understood before the start of the EVA.
- Tool enhancements are required to efficiently capture and quickly process imagery to return to the crew; this is also relevant for dynamic GAT if the crew is operating ahead of timeline

Dynamic GAT

- Overall the dynamic GAT was preferred by the ST and resulted in more time to absorb, process, and create meaningful science products to push back to the crew
- With the dynamic GAT there is a possible compounding effect – if crew gets behind, science has more time to add to the plan, thus putting the crew further behind. This emphasizes the need to prioritizes samples so that IV can make the real-time call.
- Good examples of EVAs under dynamic GAT:
  - MD4 am - overall EVA was behind timeline, the dynamic case allowed for much more Science processing time
  - MD9 – another good example of where dynamic timing was largely beneficial. Due to CORAL tower issues, Science made the call that they had additional time to refine marine site (N9) sampling. Also allowed for Science to make a more informed decision on the next science site knowing how many samples were already requested prior (ex: 10 marine sites were selected for sampling which provided more "known" time for the planning of the geo site)
  - MD11 – Site N29 rapid dynamic example (crew stayed at site rather than intentionally designing gaps between dependent tasks). This was not optimized for science, and was prone to errors given the task load on one IV. It might help if the Mission Log was optimized to better communicate rapid plan updates. This is an example of how dynamic GAT may negatively impact ST input

Site Diversity and Extent

- Comment: More samples are required for additional analog realism (More Rocks!)
- Recommendation: Develop/construct a few sites with very realistic geologic layout. This would likely require a few pallets of landscape rocks laid out in a manner that would allow the crew and Science Team to plan, explore, and collect in a more realistic matter. A mixture of rock sizes (from smaller boulder to gravel) and diversity would be optimal. From an initial search, there are a few local companies that look like they would deliver pallets to the FIU facility/dock. For any asteroid scenario on the rock wall, additional rocks affixed on the wall would be desired for tool testing and science sampling.

Site Disturbance

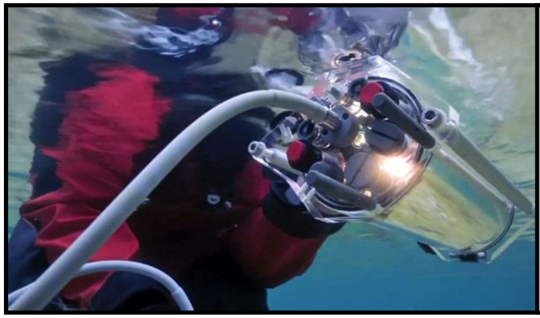
- Observation: Numerous times support divers disturbed the precursor area either by pre-staging tools directly on top of the geology samples or while taking photographs. The sites also were also likely disturbed by current over the course of the mission.
- Recommendation: Mark off geologic sampling area so support divers don't disrupt precursor plan. Make all support divers aware of the site boundaries. Most of this was a result of the limited extent of the rock field.

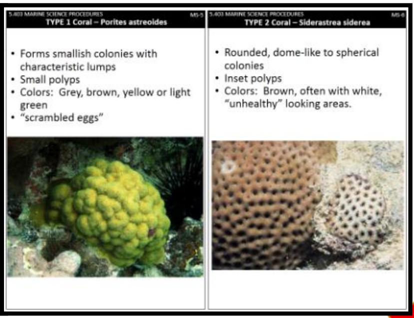
Precursor Image/Data

- Comment: Scale and orientation was critical for developing precursor plan. For any given scenario (asteroid, Mars moons, Mars/Lunar surface) we need to further consider the most realistic precursor imagery that would applicable.
- Recommendation: Continue to develop more realistic precursor plans that include scientific input for the given mission scenario(s)
- Lesson Learned: For the surface days the precursor plan likely did not reflect a good sim; rather, I should have identified regions of interest (i.e. outcrop or site scale intent). Precursor planned collection targets became the focus of crew rather than good site characterization and executing Science Team inner-EVA input.

Partnership with Florida International University (FIU) Marine Science

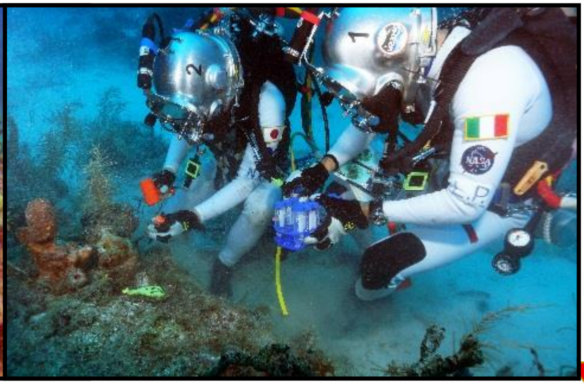
- **FIU Objectives for the NEEMO 20 mission**
  - Determine the migratory connectivity between shallow and deep reefs
  - Determine the implications of this migration in future coral recovery
    - Determine natural migration patterns among depths through genetic fingerprinting analyses
    - Assess the photosynthetic efficiency of corals from different depths
    - Determine the composition of microbial symbionts associated with the corals using DNA sequencing analysis
      - Tag colonies from three targeted coral species at approximately 100 ft and 60 ft depth intervals. These long-term tags will also allow for monitoring these colonies in future missions.
      - Deploy a long-term temperature sensor (Hobo) in each sampling area
      - Acquire PAM fluorometry measurements for health assessment for the same corals at point #1 and also for other coral species found within the area of sampling
      - Obtain 2-cm cores from 3-5 colonies of three targeted coral species indicated at #1. These samples will be for DNA & RNA analysis.
- **Why NEEMO?**
  - Real crew operators in a spaceflight operational analog environment gathering relevant marine science to help improve the health of our coral reefs
  - Increased bottom time afforded the crews as a result of saturation diving allows for uninterrupted coral tagging, sensor deployment, fluorescence measurement and core sampling at multiple sites during a single "EVA"
  - Activity would be time consuming and difficult to accomplish using divers from the surface on standard SCUBA
  - Opportunity to mentor students and enable their participation in operations during a NASA mission



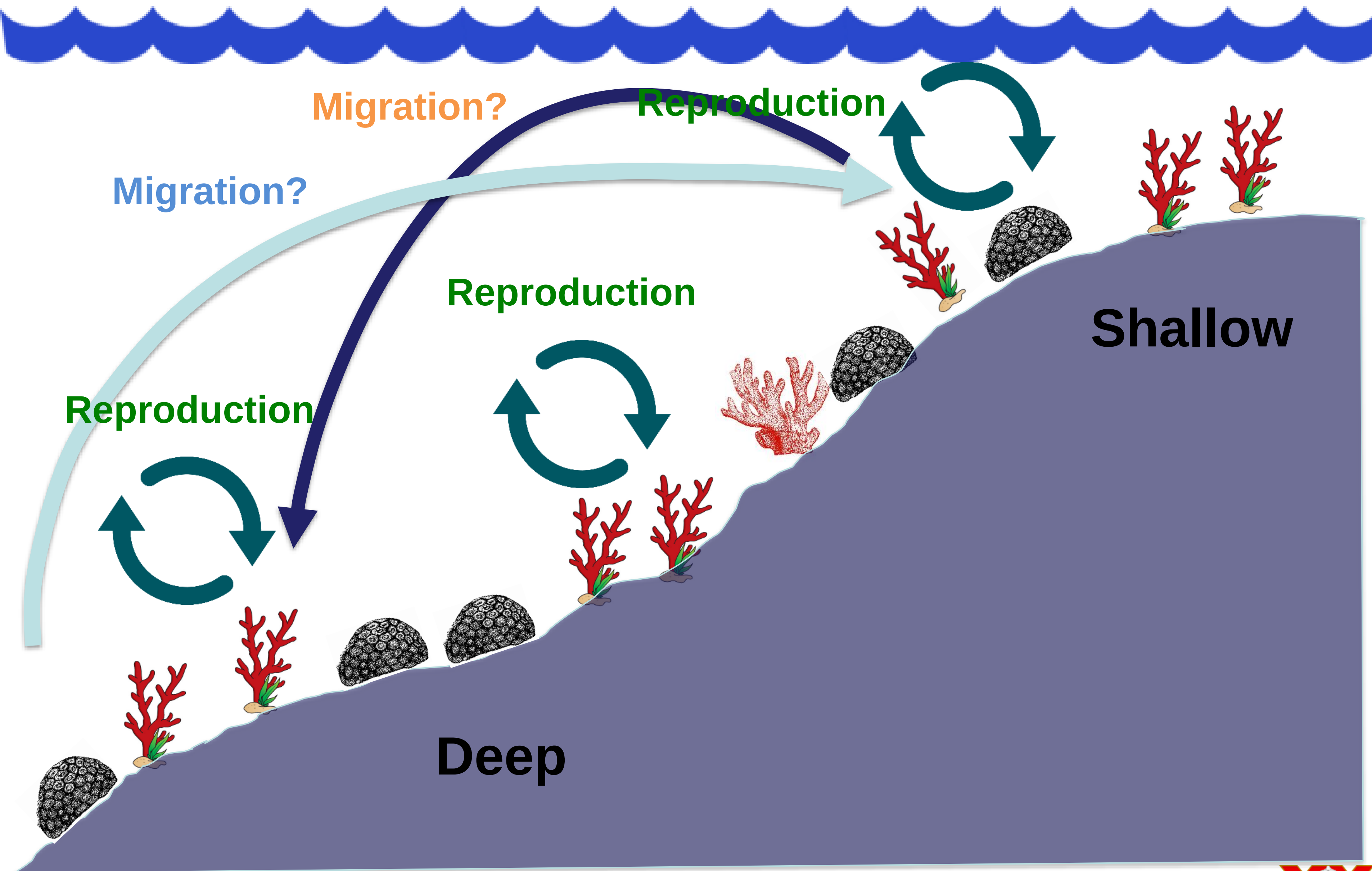


- **Results**
  - Physical sampling update
    - Initial trial DNA extractions have yielded large quantities of high quality DNA from the samples collected by the astronauts that are suitable for downstream applications
    - With this DNA it should be possible to determine the extent of connectivity between shallow and deep water coral populations
    - Excitement about the quality of DNA extracted from these samples warrants expanding the scientific goals with this biological material. Forward work includes identifying the bacteria and symbiotic dinoflagellates associated with these deep corals using genetic analyses and conducting a full genome sequence analysis for the targeted coral species.
  - Photo-physiological measurements
    - The raw photosynthetic yield data of PAM measurements show no apparent difference as a function of depth
- **Lessons Learned**
  - Improve teaching to astronauts about identifying coral species
  - Incorporate further dry training prior to saturation mission start and wet training in Aquarius





Marine Science for EVA Ops
"Deep Reef Refugia" Hypothesis



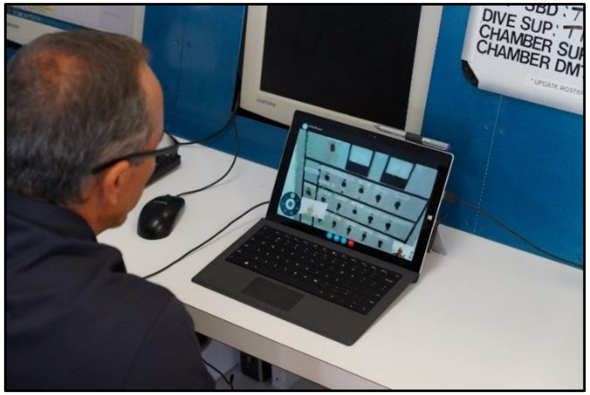
Ops Tools Maturation

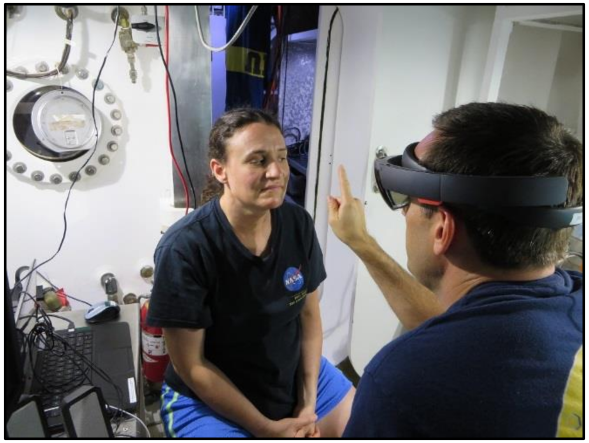
Ops Concept Maturation

ISS & IVA OBJECTIVES

Project Sidekick with Hololens

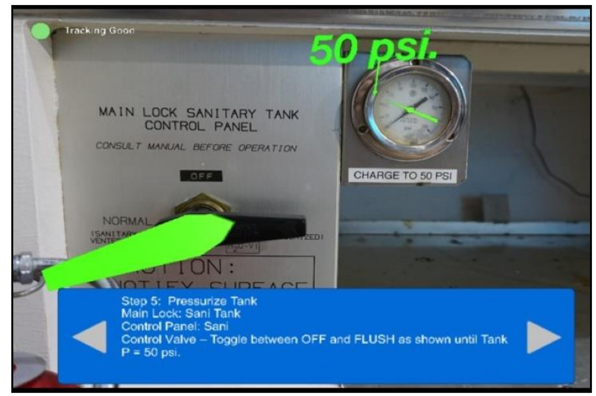
- NEEMO 20 crew evaluated the NASA JPL project "Sidekick", which uses the HoloLens mixed-reality headset for remote assistance of crew members on ISS
  - Hololens was utilized for habitat maintenance and a simulated medical scenario
  - Ground based experts (at the ARB watch desk) were able to use the Skype capability to remotely see what the aquanauts saw in first-person
  - Ground experts could virtually place 3D markings and drawings in the crew's field of view to assist with performing various procedures
- **Take-away for EVA**: Inclusion of this type of technology in a spacesuit could allow an IV crewmember to more easily guide an EV crewmember through both pioneering and science tasks

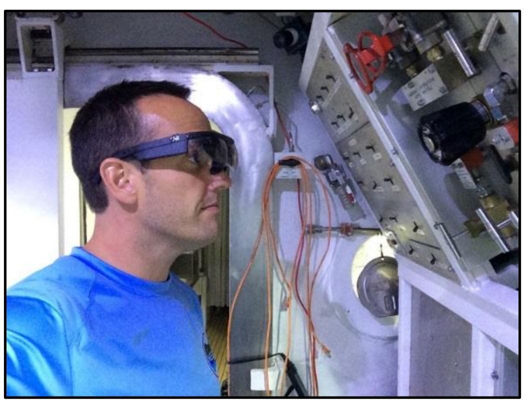


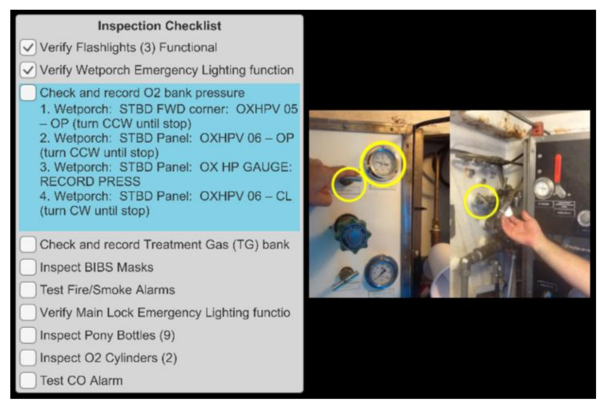


ODG R6 Headset and Augmented Reality

- NEEMO 20 crew evaluated the Osterhout Design Group (ODG) R6 Augmented Reality Headset to conduct maintenance tasks within the Aquarius habitat
  - The platform delivers enhanced procedures that provide a more intuitive understanding of the task, enabling greater autonomy
  - The crew tested different delivery methods of procedure content, including both augmented reality enhanced and “pinnable” procedures
- **Take-away for EVA**: This type of procedure delivery and augmented reality, if incorporated into a spacesuit, could help EVA crew perform construction and maintenance tasks for which they haven’t been trained or for which it’s been a long time since training







MobiPV

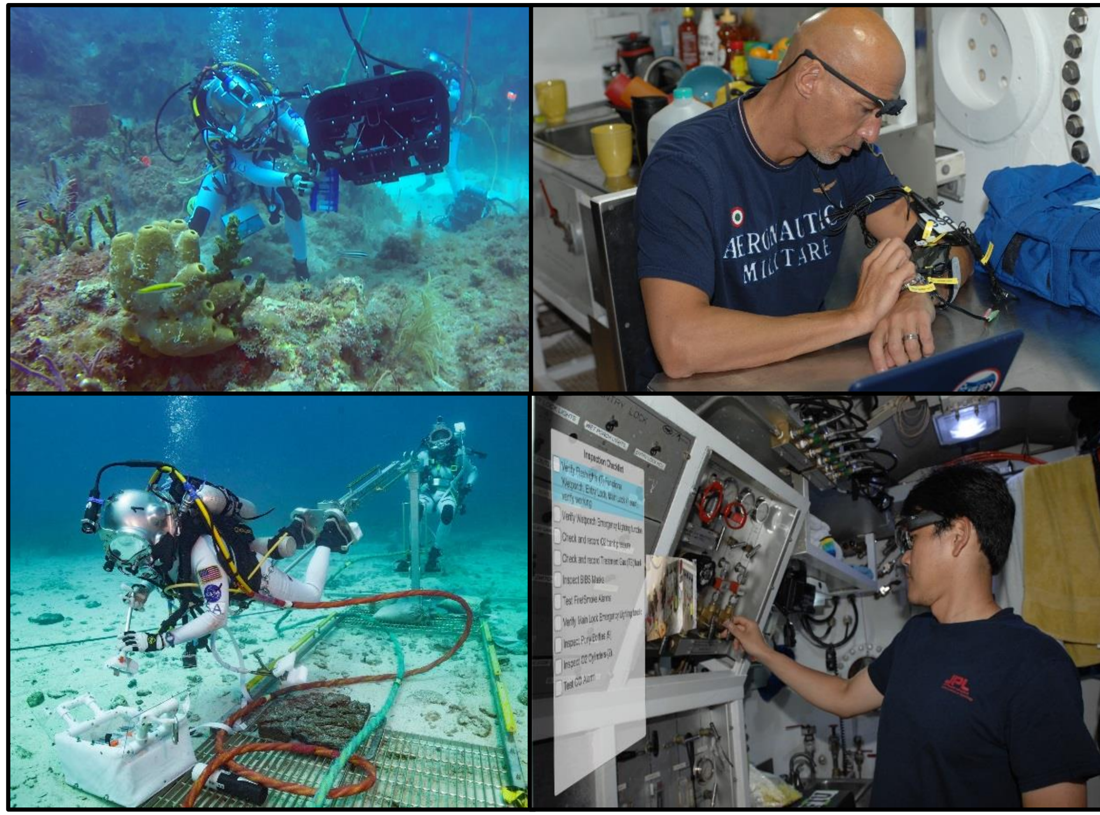
- MobiPV is an ESA developed set of assistive communication tools and displays enhancing Crew–MCC interaction for hands-busy crew activities
  - The NEEMO crew used mobiPV to execute the SKIN-B experiment, which was also studied on ISS
  - ESA Capcoms in MCC supported the MobiPV execution in direct connection with the MobiPV operators inside Aquarius
  - SKIN-B experts followed along with the experiment execution from the European Astronaut Centre of ESA in Cologne, Germany
- **Take-away for EVA**: This type of technology could be useful in talking crew through non-standard procedures, such as the R&R of an FPS

Additional Backup Information

NEEMO 20 HIGH LEVEL INFO

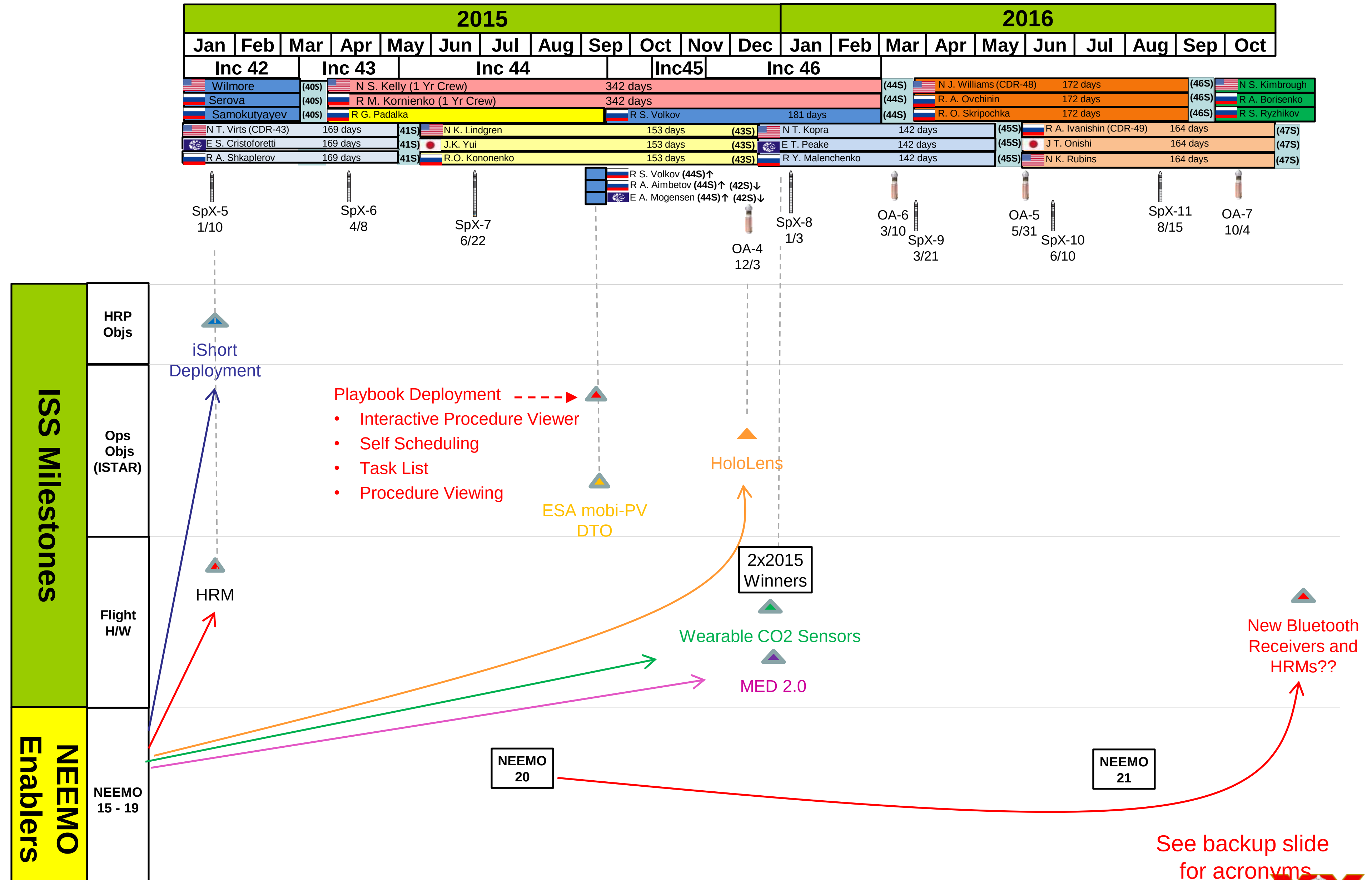
Primary Uses of NEEMO Missions

- Technology Maturation for Ops
  - Hardware
  - Procedures
  - Processes (e.g., IRB, TRRs, etc.)
- Ops Tools Maturation
  - Useful now
  - Critical for Exploration
- Ops Concept Maturation
  - Useful now
  - Critical for Exploration
- Pure Science
  - Generally human research
- Crew Preparation
  - Expeditionary training
- Outreach Opportunities



A strong blend of near term (ISS, Orion) and exploration objectives

NEEMO-Enabled Near-Term ISS Objectives



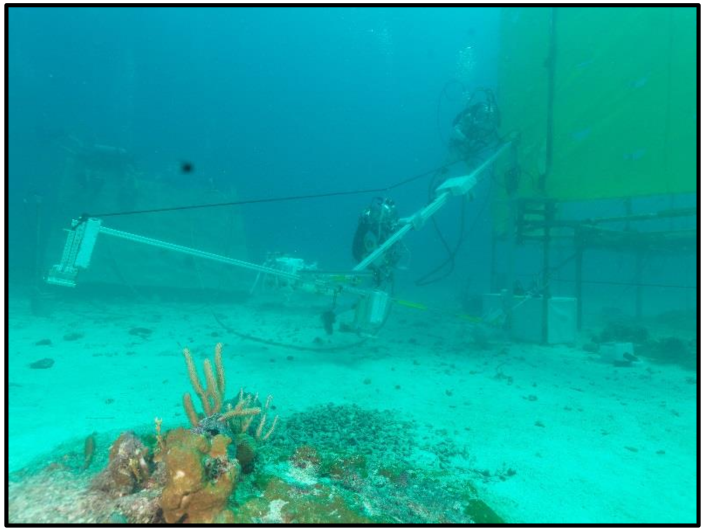
	Technology Maturation for Ops				Ops Tools Maturation			
	GeoSamp Kit	ARCM Boom	Micro-spines	Phobos Boom	Playbook	MobiPV	HL-TM	iSHORT
Environmental Factors								
RF reflection/multi-path issues (tin can effect)								
Electronically noisy from multitude of devices					√	√	√	√
Controlled CO2 environment with general module sensors								
Ambient noise level similar to ISS							√	
Dependence on ECLS systems								
ICE environment, e.g.								
Isolated								
Confined (small habitation space)								√
Extreme (percentage of attention always on safety)								
Immersive Operational environment, including								
multi-day mission	√	√	√	√	√	√	√	√
interaction with MCC	√	√	√	√	√	√	√	√
robust comm infrastructure					√	√	√	√
daily re-planning					√	√	√	
timeline pressures	√	√	√	√	√	√	√	
use of ops products (e.g. procedures, messages, etc.)	√	√	√	√	√	√	√	
pace and activity level	√	√	√	√	√	√	√	√
Crew size similar to that of ISS or DRM					√			
Meaningful consequences (e.g., LS eqpmt, PAO events, etc.)					√		√	
Inherently interesting to public								
Flexibility in conditions (e.g., time delay, off-nom scenarios)					√		√	
Subjects								
Spaceflight certified operators								
astronaut crewmembers								
trained to perform procedures under ops constraints	√	√	√	√	√	√	√	
high quality critical feedback	√	√	√	√	√	√	√	√
Varied size and background								
range of spaceflight experience					√	√	√	√
range of cultural and language backgrounds					√	√	√	√
mixed gender								√
physiology (size, body chemistry, harness fit, etc.)						√	√	√
Crew size statistically meaningful (N)	√	√	√	√	√	√	√	√

	Ops Con Maturation									Crew Preparation	Outreach Opportunities
	AR Proc's	Pinnable Proc's	Time Delay	Self Sched	Science Team	Man-Machine	LLT	3D Printers	Incap Crew	Exp Trng	PAO/EPO
Environmental Factors											
RF reflection/multi-path issues (tin can effect)											
Electronically noisy from multitude of devices	√	√									
Controlled CO2 environment with general module sensors											
Ambient noise level similar to ISS	√	√								√	
Dependence on ECLS systems										√	
ICE environment, e.g.											
Isolated										√	
Confined (small habitation space)				√						√	
Extreme (percentage of attention always on safety)						√			√	√	
Immersive Operational environment, including											
multi-day mission	√	√	√	√	√	√		√		√	
interaction with MCC	√	√	√	√	√	√		√		√	
robust comm infrastructure	√	√	√	√	√	√		√		√	√
daily re-planning	√	√	√	√	√	√		√		√	
timeline pressures	√	√	√	√	√	√		√		√	
use of ops products (e.g. procedures, messages, etc.)	√	√	√	√	√	√		√	√	√	
pace and activity level	√	√	√	√	√	√		√	√	√	
Crew size similar to that of ISS or DRM				√	√	√				√	
Meaningful consequences (e.g., LS eqpmt, PAO events, etc.)	√	√		√	√	√				√	
Inherently interesting to public										√	√
Flexibility in conditions (e.g., time delay, off-nom scenarios)			√	√	√			√	√	√	
Subjects											
Spaceflight certified operators											
astronaut crewmembers										√	√
trained to perform procedures under ops constraints	√	√	√	√	√	√	√		√	√	√
high quality critical feedback	√	√	√	√	√	√	√	√	√		
Varied size and background											
range of spaceflight experience	√	√	√	√	√	√	√		√	√	√
range of cultural and language backgrounds	√	√	√	√	√	√				√	√
mixed gender									√	√	√
physiology (size, body chemistry, harness fit, etc.)	√	√							√		
Crew size statistically meaningful (N)	√	√	√	√	√	√	√	√	√		

Key Summary Points – Technology Maturation

- Phobos Boom
  - A boom/arm (of the type and length tested) deployed from a mobile habitat provides good stabilization for performing geology sampling.
  - Better methods for boom deployment and positioning need to be developed. Lack of mechanical advantage and control made use difficult, and ability to control exactly where the feet landed (so as not to land on top of a good sample) sub-optimal.

- Bluetooth Receiver Software
  - Custom Bluetooth Receiver Software successfully received and parsed data from all transmitters simultaneously.
  - Successfully commanded custom software 100% of time from topside MCC (and without impact to the crew). This included start up and shut down of software, retrieving data, and uplinking new config files to add/replace sensors. That is a promising result for future ISS ops because it represents a 15 min/download time savings over current methods.
  - Evaluation of custom Bluetooth Receiver Software and a downselected group of Bluetooth transmitter hardware solutions for Heart Rate and other physiological monitoring provided a clear recommendation for moving forward with implementation of the custom Bluetooth Receiver Software on ISS utilizing a newer Cheststrap based solution for heart rate monitoring.



Key Summary Points – Ops Tools Maturation

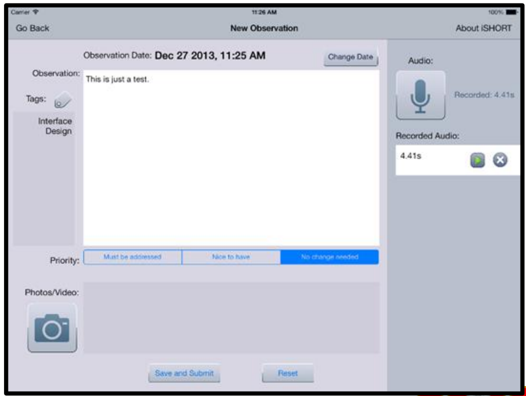
- Playbook
  - Both previously existing and new features (multi-day self scheduling, task list, scratch pad) proved mature and operationally robust
  - Crew feedback
    - Love the ease and portability offered by having an iPad based ops tool
    - Features easy to use and crew feedback very positive
  - Captured numerous suggestions for further improvement from both crew and ground users

- mobiPV
  - All functions were successfully tested except the procedure commanding by voice recognition, and both crew and Capcom feedback was captured for enhancement of the next version of mobiPV
  - Being able to operate the flight version of mobiPV in a space analog operational environment, as a precursor test before its use on board the ISS, was very valuable in contributing to improvements for the in-flight test execution on ISS (during Soyuz 44S)

Key Summary Points – Ops Tools Maturation (cont'd)

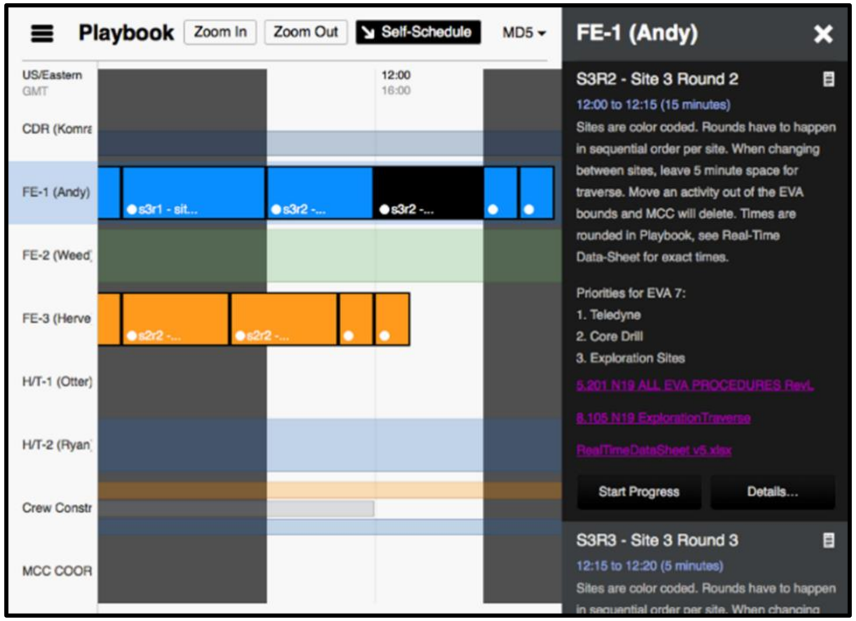
- HoloLens Telementoring
  - HoloLens with telementoring proved highly effective for
    - 1st time operations with no prior training or exposure
    - Systems maintenance tasks
    - Complex assembly and checkout task, including cable routing
    - Medical scenarios (both real and simulated)
  - HoloLens with telementoring will prove its capability to increase crew efficiency for a wide variety of ISS tasks when 2 devices arrive at ISS in Dec. 2015 (OA-4)

- iSHORT
  - Matured in part through feedback from numerous NEEMO missions (15-20)
  - Currently being used onboard ISS as a tool in an HRP-sponsored spaceflight study, "Vehicle NHV and Habitability Assessment"
    - Manifested and flew on flight SpX-6, March 2015
    - 6 crewmembers (including US 1-year mission crewmember) will be using iSHORT to collect data for the study, which aims to characterize habitability onboard ISS
    - ISS testing to take place March 2015 through 2017 (or when 6 participants are completed)



- Augmented Reality and Pinnable Procedures
  - Augmented Reality Enhanced Procedures proved highly intuitive and easy to use, and good for complex tasks
  - Numerous lessons learned related to hardware performance, controls, user interactions were collected for future improvements

- Crew self-scheduling
  - The time penalty for crew self-scheduling was large (~4 man-hours/day) and the advantages did not outweigh the costs
  - A better ops concept than crew self-scheduling would be crew "self-determination", meaning that they determine what tasks get done on which EVA, but the actual scheduling be done by professional planners who are more adept at manipulating plans, and more intimately familiar with all the myriad constraints



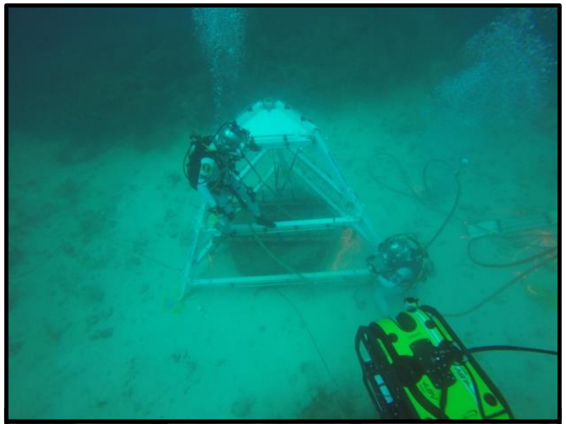
Key Summary Points – Crew Preparation and Outreach Opportunities

- Crew Preparation
  - Crewmembers trained for upcoming ISS assignments
    - Command experience for 1 previously flown with potential as ISS CDR
    - Mission experience for 2 potential ISS rookies
      - N. Kanai assignment to Exp 54/55 announced shortly after NEEMO 20 ended
    - Crew complement similar to USOS crew on ISS with representatives from NASA, ESA, and JAXA

- Outreach Opportunities
  - NEEMO 20 crew generated widespread international media interest and discussed mission objectives
    - New technologies, ops concepts and tools being investigated for use on ISS
    - Challenges for deep space Exploration
  - Audiences reached through a variety of live and interactive events
    - TV/Radio station features in 3 countries
    - Print/On-line features with worldwide readership
    - Educational outreach events
    - # of social media followers increased compared to pre-mission levels
      - 71k+ people reached in peak Facebook post

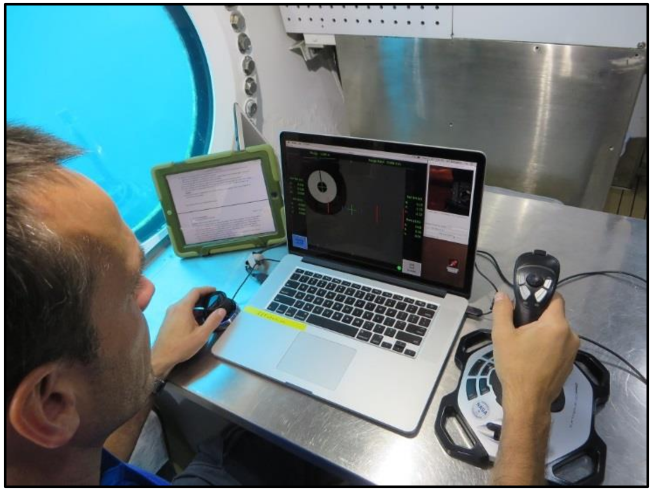
Key Summary Points – Partnerships

- ERAU & Teledyne
  - Exposed aerospace engineering and human factors students to an operational spaceflight analog mission and the need to be prepared with contingency plans
  - CORAL
    - Provided a “pioneering” EVA construction task to further NASA objectives
    - Structure successfully deployed and collecting data for use by Teledyne
- NPS
  - Experience and operations maturation to be applied to future technology development by the Navy for joint robot-human exploration
- AFRL
  - Experience and operations maturation to be applied to future technology development by the Air Force in the area of multi-robot control conditions
- FIU
  - Exposed marine science students to an operational spaceflight analog mission
  - Furthered ongoing studies on migratory connectivity between shallow and deep reef coral, and the implications of this migration in future coral recovery



Low Latency Teleoperations (LLT) Simulation

- LLT is a method by which humans remotely control robotic systems with a time delay between when commands are issued and when they are performed
- Short latencies (< 1 second) exist between Phobos and Deimos (moons of Mars) and the surface of Mars
- NASA has been studying the feasibility of human exploration missions to the moons of Mars as an intermediate step toward the eventual Mars surface missions
- The benefits of potential low latency teleoperation of systems on the surface of Mars from orbit or its moons, particularly associated with preparation of pre-deployed support systems on the surface of Mars prior to a human landing, are being studied
- The NEEMO 20 crew evaluated several different latencies while flying a simulated robotic vehicle



NEEMO Crew Members

Key
* Repeater
Blue – CDR upgrade
Green – IP
RED – Rookie
Gray – non-Astro

NEEMO 1 - 06 Days, Oct. 2001	**DT/B. Todd, CB/M. Lopez-Alegria, M. Gernhardt*, CSA/D. Williams***
NEEMO 2 - 09 Days, May 2002	**CB/M. Fincke, D. Tani, S. Williams, DT/M. Reagan**
NEEMO 3 - 09 Days, July 2002	**CB/J. Williams, D. Olivas*, G. Chamitoff, SLSD/J. Dory**
NEEMO 4 - 05 Days, Sept. 2002	**CB/S. Kelly*, R. Walheim, DA8/P. Hill, SLSD/J. Meir**
NEEMO 5 - 14 Days, June 2003	**CB/P. Whitson, C. Anderson, G. Reisman, SLSD/E. Hwang**
NEEMO 6 - 10 Days, July 2004	**CB/J. Herrington, D. Wheelock, N. Patrick*, EB/T. Ruttley**
NEEMO 7 - 11 Days, Oct. 2004	**CSA/B. Thirsk, C. Coleman, M. Barratt, CMAS/C. Mckinley, M.D.**
NEEMO 8 - 03 Days, April 2005	**CB/M. Gernhardt*, S. Kelly*, D. Olivas*, M. Schultz**
NEEMO 9 – 18 days, April 2006	**CSA/D. Williams*, CB/N. Stott, R. Garan, TATRC/T. Broderick*, M.D.**
NEEMO 10 – 07 days, July 2006	**JAXA/K. Wakata, CB/D. Feustel, K. Nyberg, NOAA/K. Kohanowich**

NEEMO Crew Members

Key
* Repeater
Blue – CDR upgrade
Green – IP
RED – Rookie
Gray – non-Astro

NEEMO 11 – 7 days, Sept. 2006	**CB/S. Magnus, T. Kopra, B. Behnken, T.J. Creamer**
NEEMO 12 – 12 days, May 2007	**CB/H. Piper, J. Hernandez, SD/J. Schmidt, TATRC/T. Broderick*, M.D.**
NEEMO 13 – 10 days, August 2007	**CB/N. Patrick*, R. Arnold, JAXA/S. Furukawa, Cx/C. Gerty**
NEEMO 14 – 12 days, June 2010	**CSA/C. Hadfield, CB/T. Marshburn, EAMD/A. Abercromby, S. Chappell**
NEEMO 15 – 7 days, October 2011	**CB/S. Walker, JAXA/T. Onishi, CSA/D. Saint-Jacques, NAC/ S. Squyres***
NEEMO 16 – 12 days, June 2012	**CB/D. Metcalf- Lindenburger, JAXA/K. Yui, ESA/T. Peake, NAC/S. Squyres***
NEEMO 17 – 7 days, Sept. 2013	**CB/J. Acaba, K. Rubins, JAXA/S. Noguchi, ESA/A. Mogensen***
NEEMO 18 – 9 days, July 2014	**JAXA/A. Hoshide, CB/M. Vande Hei, Jeanette Epps, ESA/Thomas Pesquet**
NEEMO 19 – 7 days, Sept. 2014	**CB/R. Bresnik, ESA/A. Mogensen*, CSA/J. Hansen, ESA/ H. Stevenin**
NEEMO 20 – 14 days, July 2015	**ESA/L. Parmitano, CB/S. Aunon, JAXA/N. Kanai, XX/D. Coan**