Scientific analogs and the development of human mission architectures for the exploration of the Moon, deep space and Mars.

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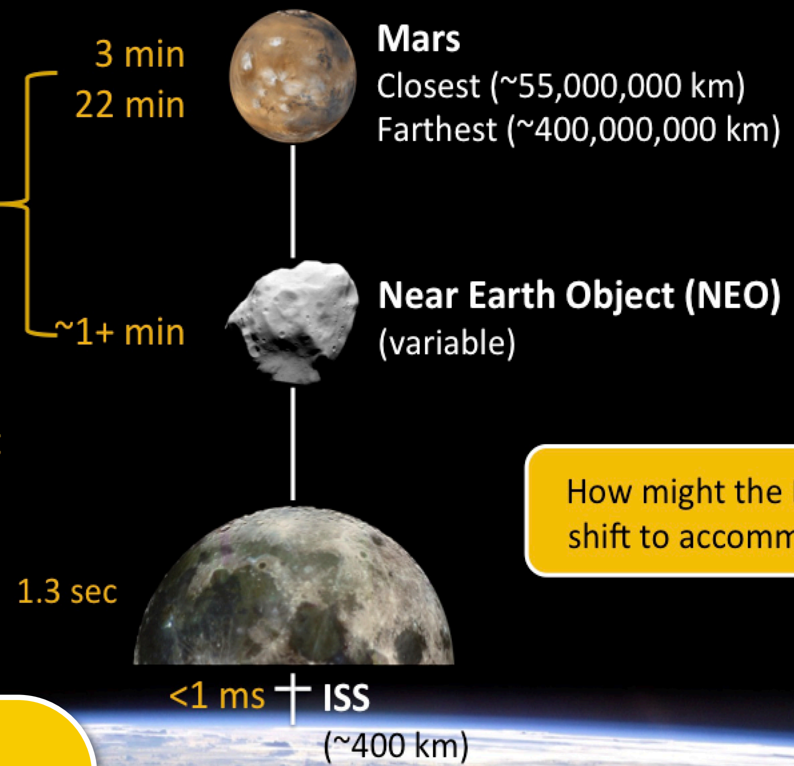
NASA
EXPLORE MOON to MARS
MOON LIGHTS THE WAY

Moon, Deep Space and Mars present new operational paradigms for Human Space Flight

Time Delay of interest



One-Way Time Delay Implications

- Impaired ability to provide relevant information
- Slow response to events
- Reduced situation awareness

How might the EVA work domain need to shift to accommodate future operations?

M.Miller et al. 2016

Future EVA Expectations

- ↑ Frequency
- ↑ Efficiency
- ↑ Productivity
- ↑ Flexibility

How might we design EVAs that are in service of scientific exploration and discovery?

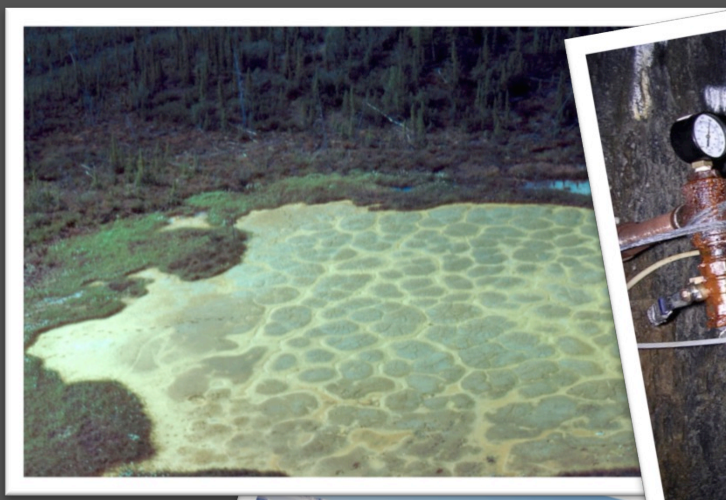
Research Analogs

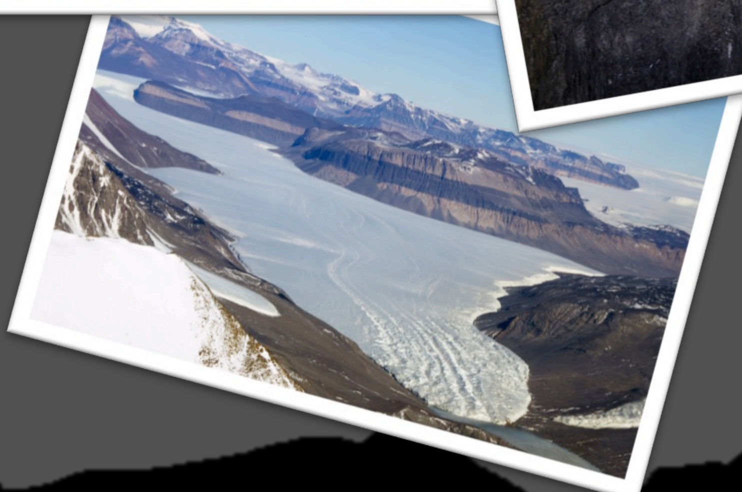
Places on Earth that allow us to approximate operational or physical conditions on other planetary bodies and within deep space

Analog research is a lower cost, lower risk means of preparing for our journey to the Moon, Deep Space and Mars.

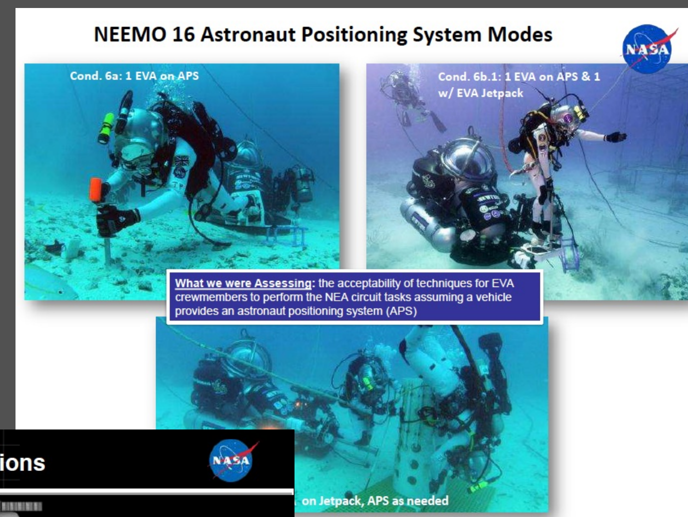
Through analog missions, NASA can identify operational and engineering designs that support human-robotic science and exploration.

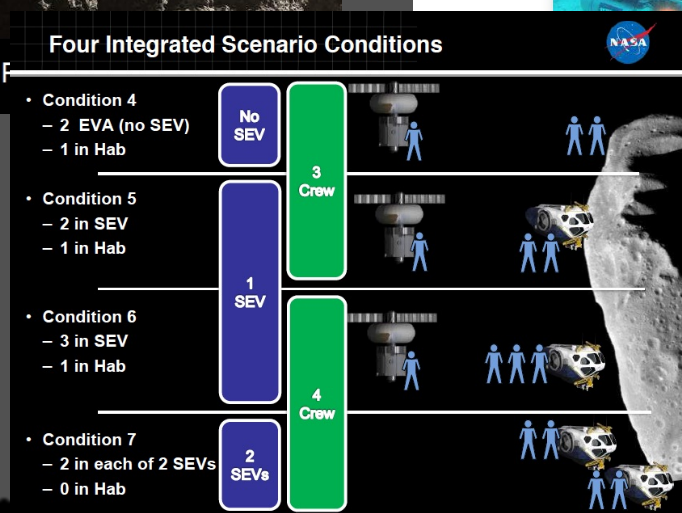
Scientific Analogs that explore life at extremes as a means to understand the habitability potential of our solar system





Operational Analogs that study ops concepts and related technologies for future human-robotic missions





This talk focuses on two on-going NASA-funded Analog Missions

BASALT:
Biologic Analog Science of Basaltic Terrains
https://spacescience.arc.nasa.gov/BASALT/

SUBSEA:
Systematic Underwater Biogeochemical Science and Exploration Analog
https://spacescience.arc.nasa.gov/SUBSEA/

BASALT

Biologic Analog Science Associated with Lava Terrains

Website: http://spacescience.arc.nasa.gov/basalt/

Twitter: @BASALT_research

NASA SMD PSTAR Grant
NASA SSERVI Grant (FINESSE)

BASALT Project Background

Investigate habitability of terrestrial volcanic terrains as analog environments for early and present-day Mars

SCIENCE

Seek, identify, & characterize life & life-related chemistry in basaltic environments representing these two epochs of Martian history.

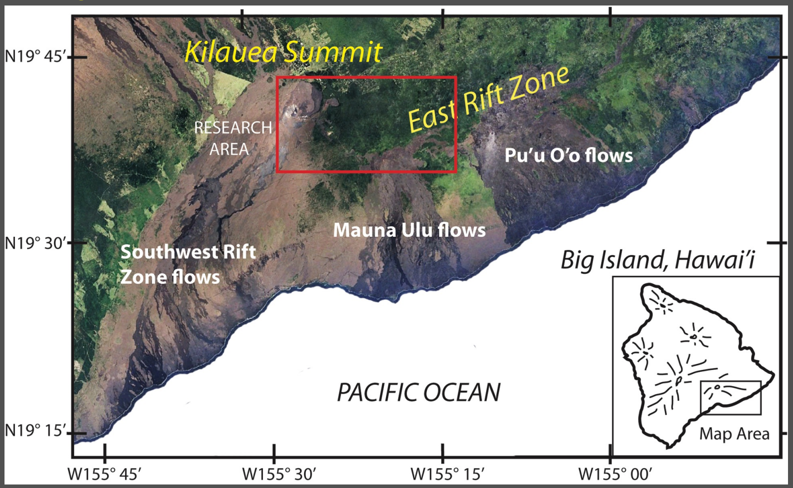
SCIENCE OPERATIONS

Conduct science within simulated Mars exploration conditions based on current architectural assumptions. Identify which human-robotic ConOps & capabilities enable scientific return & discovery.

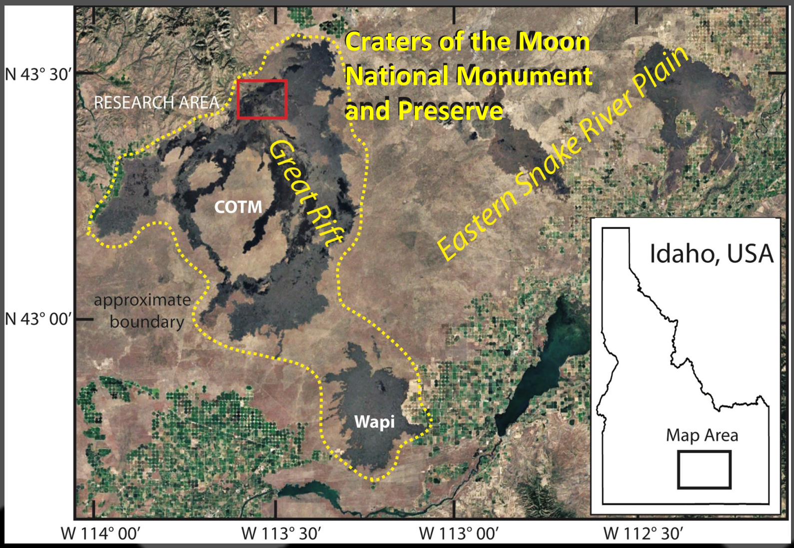
TECHNOLOGY

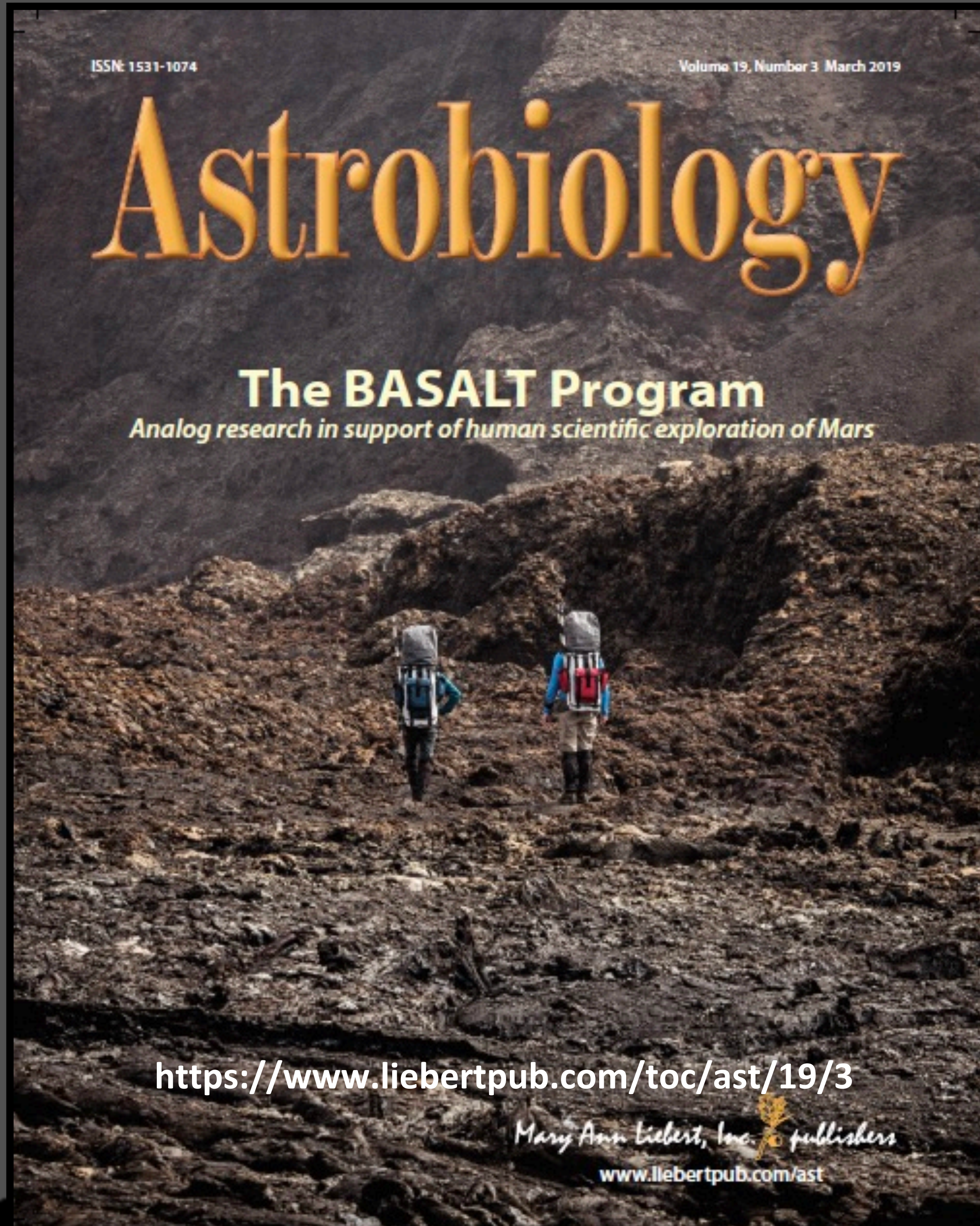
Incorporate & evaluate technologies directly relevant to conducting science, including mobile science platforms, EVA informatics, display technologies, comm and nav packages, remote sensing, science mission planning tools, and scientifically relevant instrument packages.

Early Mars



Present Mars



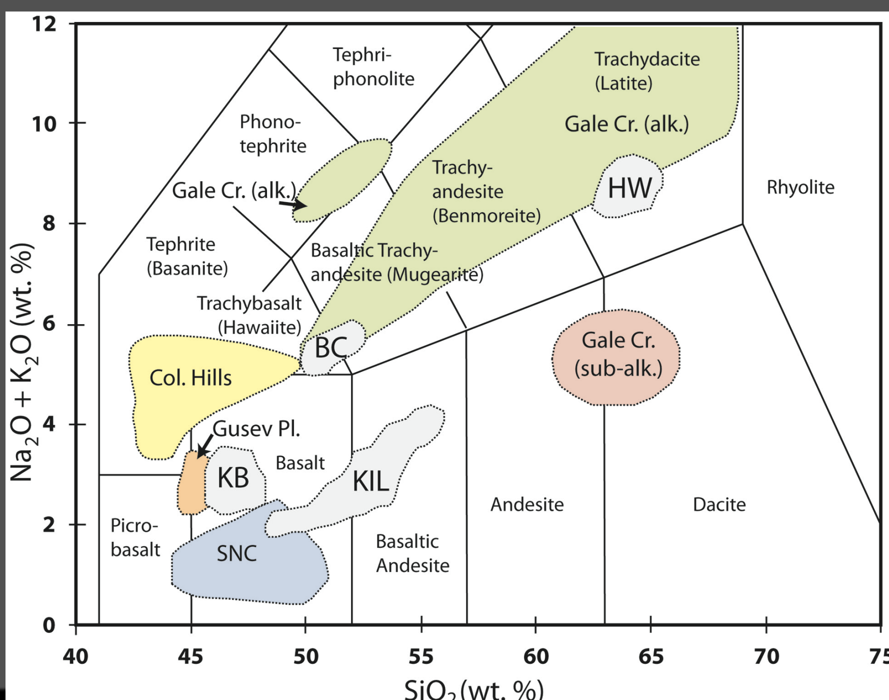


https://www.liebertpub.com/toc/ast/19/3

13 research papers, 1 commentary (Astronaut Stan Love)

BASALT Science

Science		How do microbial communities and habitability correlate with the physical and geochemical characteristics of chemically-altered basalt environments?
	Geology	**1A.** What are the geochemical, mineralogical, and textural properties associated with basalts affected by liquid water, intrinsic volatiles, and fumarolic gases at complementary Mars analog sites? **1B.** What geochemical and geological conditions provide appropriate energy sources, major biogenic elements (CHNOPS), liquid water, and micro-habitats for microbial growth?
	Biology	**2A.** What is the relationship between the physical characteristics and geochemistry of Mars analog basalts and the biomass that they can support? **2B.** What are the upper bounds on the biomass that could have been supported on Mars? **2C.** How does this upper bound inform future requirements to detect extinct life on Mars?



Hughes et.al., Astrobiology 19(3): 260-283

Scientific Lessons for Exploration

Cockell et al. Astrobiology 19(3): 284-299

- Volcanic rocks can support a diverse community of organisms. Most are adapted to low organic carbon availability.
- On Mars, many dry/intermittently wet volcanic rocks are theoretically habitable (they have the requisites to support life), but the elements such as reduced iron, are generally kinetically inaccessible. In the low carbon regime of Mars, they may be poor locations for life or support very low biomass.
- **Bulk composition does not predict habitability**
- **Thermodynamics does not necessarily predict habitability**
- Robotic and human exploration: Need to go after hydrologically active volcanic regions, fumaroles, rivers etc where kinetic limits are overcome and organisms can feed more directly off elements from the rocks

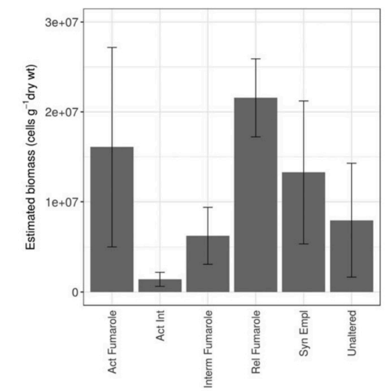


FIG. 1. Biomass estimates for each material type for the four samples used for diversity analysis. The data are shown as means ± standard error.

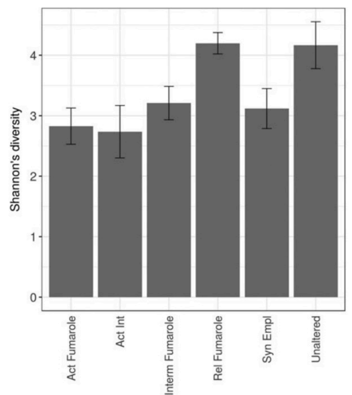


FIG. 2. Alpha diversity (Shannon) analysis of the six materials studied. The data are shown as means ± standard error.

BASALT Science Operations

Brady et al Astrobiology 19(3): 347-368

Field Deployment 3

Field Deployment 2

Field Deployment 1

STRATEGIC PLANNING

Science Traceability Matrix

- Questions of Interest
- Hypotheses
- Detailed Objectives
- Precursor Data

↓

Baseline Field Deployment Plan

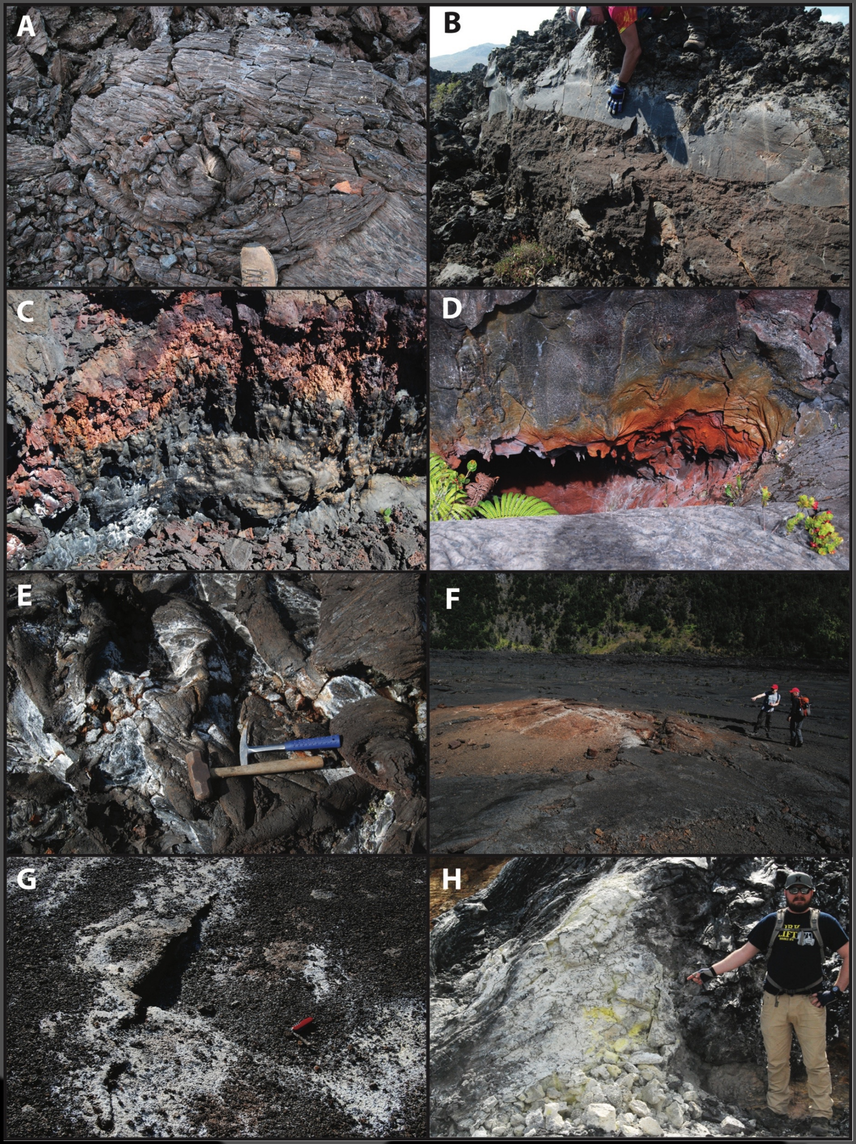
EVA 1 | EVA 2 | …

↓

TACTICAL PLANNING

Daily Sample Type Matrix

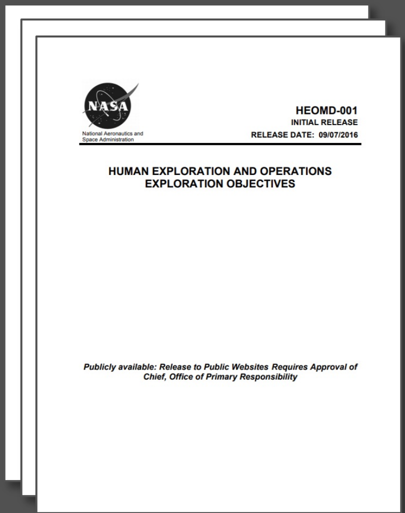
Updated inter- & intra- EVA



Hughes et.al., *Astrobiology* (2019)

BASALT Science Ops & Technology

Beaton et al A. Astrobiology 19(3): 300-320


HEOMD-001
INITIAL RELEASE
RELEASE DATE: 09/07/2016

National Aeronautics and Space Administration

HUMAN EXPLORATION AND OPERATIONS
EXPLORATION OBJECTIVES

Publicly available: Release to Public Websites Requires Approval of Chief, Office of Primary Responsibility

EVA SMT Gap#	Gap Name
EVA-GAP-099	Comm Latency
EVA-GAP-100	Comm Latency Tools
EVA-GAP-112	Flexible Execution Methodology for EVA Science Operations in Undefined Environments
EVA-GAP-113	IV Support System for EVA Operations

Development of baseline ConOps, comm protocol, capabilities

SciOps & Technology

Which exploration ConOps and capabilities enable and enhance scientific return during human-robotic exploration under Mars mission constraints?

3A: Do the baselined Mars mission ConOps, comm protocols, and capabilities developed and tested during previous NASA analogs work acceptably during real scientific field exploration? What improvements are desired, warranted, or required?
3B: Do these ConOps, comm protocols, and capabilities remain acceptable as comm latency increases from 5 to 15 min OWLT? What improvements are desired, warranted, or required?
3C: Which capabilities are enabling and significantly enhancing for Mars scientific exploration?
3D: Do these capabilities remain enabling and significantly enhancing as comm latency increases from 5 to 15 min OWLT? As comm bandwidth decreases?

BASALT Baseline ConOps

Assumptions

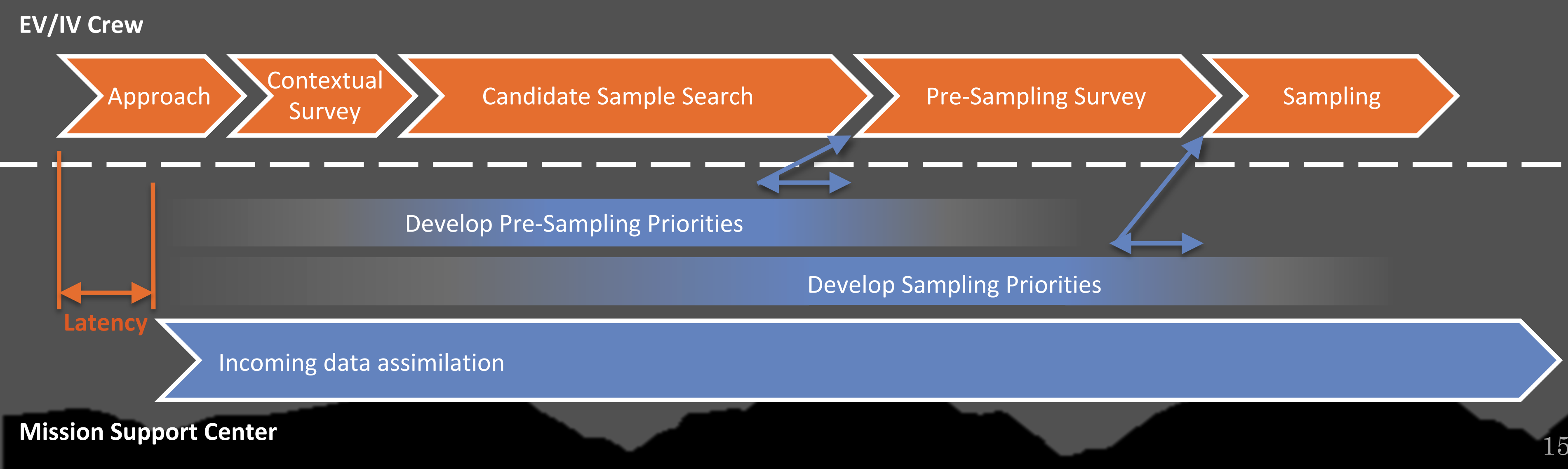
Precursor data → baseline exploration traverses

Boots-on-ground → modified science tasks, priorities, plans

Higher level of scientific expertise & analytical capabilities on Earth

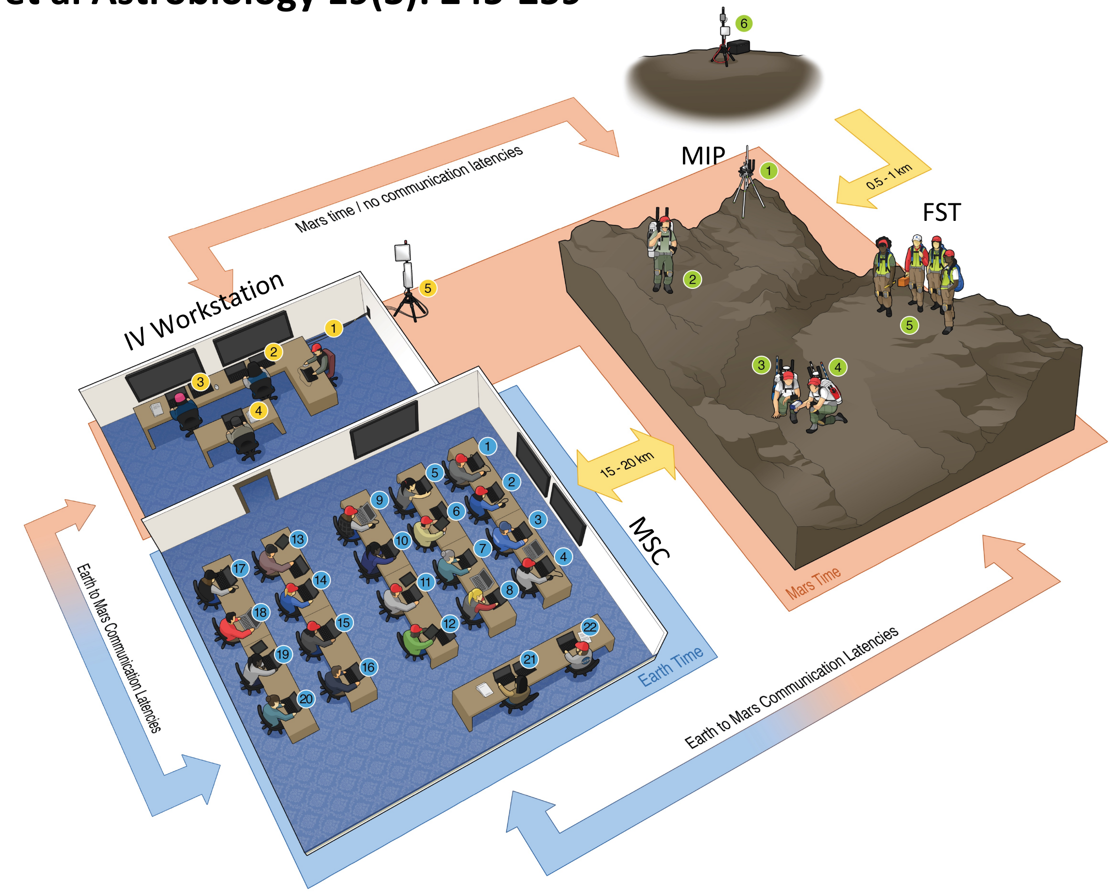
If we have opportunity for Earth-based science expertise throughout EVA:

- **What EV, IV, and MSC tasks and capabilities are needed? What are the necessary features and interfaces to achieve them?**
- **How do we integrate the tasks and capabilities into timelines that enable meaningful interactions without crew idle time?**



Science-Driven EVA Execution

Lim et al Astrobiology 19(3): 245-259



A IntraVehicular Crew

1. Stenographer
2. IV Crewmember - Science
3. IV Crewmember - Operations
4. XSIM Playbook
5. Base Camp Relay Node

B Mission Support Center

1. Leaderboard Lead
2. Science Lead
3. Sci-Comm
4. CapCom/EV
5. Situational Awareness
6. Image Tagging
7. Instrument Lead
8. Science Tactical (Geo)
9 &10. Situational Awareness/ Image Management/ Science Tactical
11. Ethnographer
12. Science Tactical (Bio)
13 & 14. xGDS Members
15. SEXTANT
16. VR/AR Support
17 & 18. Additional Support
19 & 20. Communications/Networking Support
21. Bio Lead
22. Geo Lead

C Field

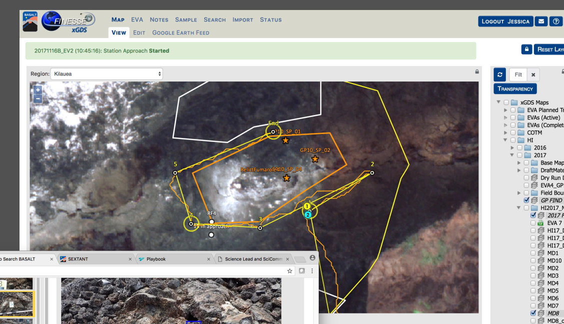
1. Situational Awareness Camera / Mobile Instrument Platform (MIP)
2. In-Field Communications Leader / MIP
3. EV Crewmember - Operations
4. EV Crewmember - Science
5. Field Support Team (FST) / MIP
6. Central Relay Node

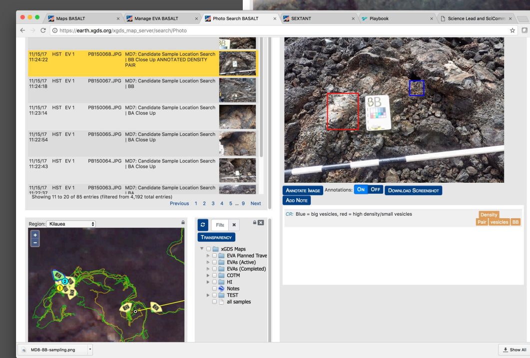
Science-Driven EVA Execution: EV Ops

Science-Driven EVA Execution: IV and MSC Ops

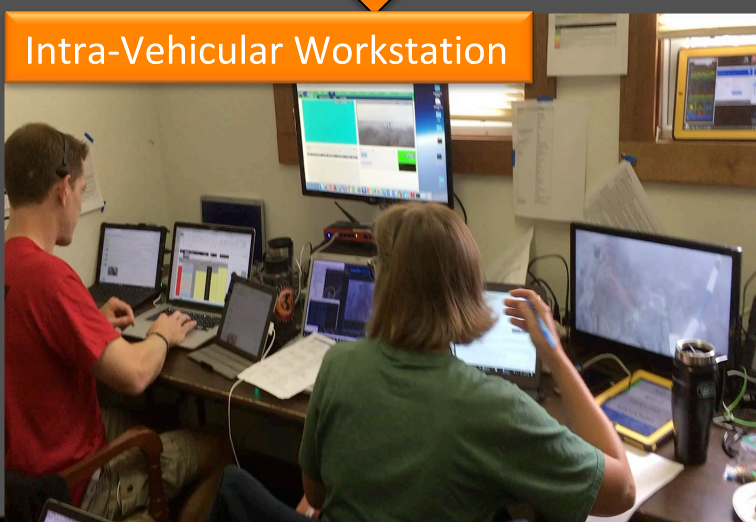
Bi-directional communications under time-delayed conditions to simulate data transmission latencies between the Earth and Mars.

EARTH





MARS



Station ID	Marker	Description (via EV/IV)	Survey Priority	Survey Rationale	FLIR	XRF?	ASD?	LIBS?	Alteration Type	Sample Priority	Sample Priority Rationale (via ST)	Sample Number (Bio)	Sample Number (Geo)	Sample Number (Org)	Sample Number (Porosity)	Container IDs (Archive)
1	BA	Friable white and yellow fumarolic deposit on black pahoehoe lobe. Small needle-like crystals. white mineralization under lobe, 60% mm-scale vesicles. no visible phenocrysts. Orange discoloration in lobe. 21.5 C FLIR.	6	Visible alteration crystals, small deposit	X				Relict							
	BB	Large deposit on fissure of spatter rampart. White, yellow and orange mineralization. Orange pervasive alteration under white deposit. 50% mm scale vesicles. Friable, no xtals. wall is 20.3 C FLIR	4	Good alteration gradient, pervasive orange alteration, large deposit. no sulfur	X				Relict	4	No reason to bump up based on scans; good alteration gradient, pervasive orange alteration, large deposit, no sulfur					
	BC	Yellow coated hole in spatter rampart. 80% mm vesicles. Dark unaltered with yellow deposit on surface, minimal white deposits in vesicles. Good for density pair 20.8 C FLIR	3	Diversity of alteration, unaltered under sulfur, white deposit in vesicles, good for density pair	X	X	X		Relict	2	Easier sampling than BD and EV prefers. Worse scans than BD and BE for relict. Diversity of alteration, unaltered under sulfur, white deposit in vesicles					
	BD	Huge sulfur deposit mixed with white mineralization in fissure of spatter rampart. very friable and light. <mm to mm heterogeneous vesicles. unaltered interior, no phenocrysts. 22.9 C FLIR	2	Huge sulfur deposit, friable. Good for density pair	X	X	X		Relict	3	Scans are worse than BE, still looks good for relict. Lots of sulfur, friable					
	BE	Pahoehoe lobe cracked open with white and yellow mineralization in cracks. Denser than others, 30% mm scale homogenous vesicles. Entire host rock is grey-tan. No phenocrysts. Good for density pair. 29.3 C and on surface. 25.6 C inside. 20.4 C on high density knock	1	Variable, pervasive alteration. Good for density pair	X	X	X		Relict	1	Scans look good for relict. Variable, pervasive alteration. Good for density pair	326, 331, 409	377, 391 (L), 392 (H)	382, 383	384, 379 (L), 387 (H)	378, 386 (L), 393 (H)

Science Ops Assessments

Beaton et al B. Astrobiology 19(3): 321-346

ConOps | **Comm Protocol** | **Capabilities**

Situational Awareness
- Environmental
- Temporal
- Tactical

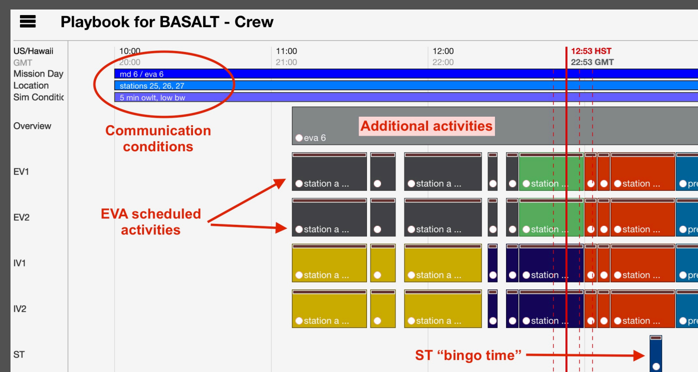
Tactical Interactions & Prioritization
- Btw EV & IV
- Btw IV & MSC

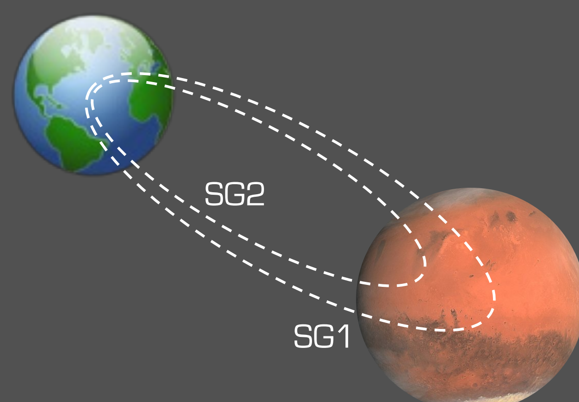
Strategic Assessment & Prioritization

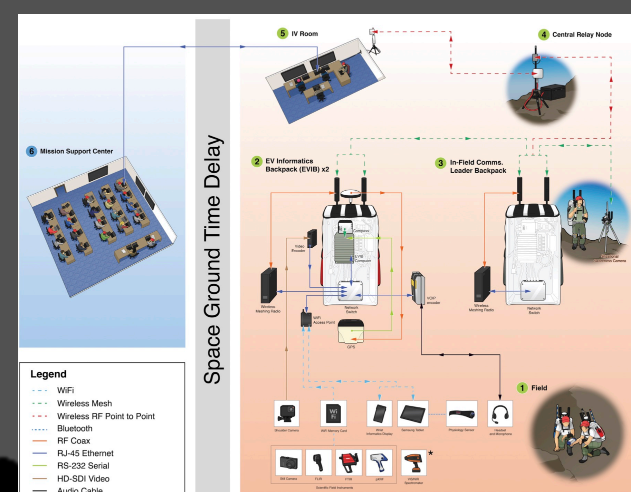
Navigation & Translation

In-situ Science
- Observations
- Measurements
- Physical samples
- Archiving/curation

Re-planning







Summary SciOps Results

Beaton et al A, B; Payler et al; Stevens et al; Kobs Nawotniak et al; Brady et al – Astrobiology 19(3) March 2019
Beaton et al. in progress (submission to PSS)

Continuous, meaningful input from remote science experts is achievable during exploration EVAs, even under long comm latencies and bandwidth limitations. *Desired*, *warranted*, and *required* improvements have been identified to enhance the BASALT ConOps.

Totally Acceptable		Acceptable		Borderline		Unacceptable		Totally Unacceptable		No Rating
No improvements necessary and/or no deficiencies		Minor improvements desired and/or Minor deficiencies		Improvements warranted and/or Moderate deficiencies		Improvements required and/or Unacceptable deficiencies		Major improvements required and/or Totally unacceptable deficiencies		Unable to assess
1	2	3	4	5	6	7	8	9	10	NR

9 new capabilities were envisioned during BASALT field testing. 8 were rated *significantly enhancing*. 4 were integrated, tested, and evaluated during final field deployment.

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
1	2	3	4	5	6	7	8	9	10	NR

New Capabilities Evaluated

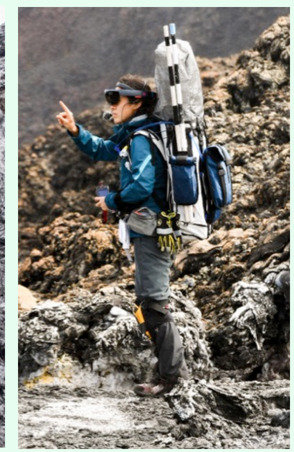
Pre-EVA

Virtual Reality and Telepresence for EV/IV Training
(JPL Onsight)

Virtual Reality and Telepresence for MSC Planning
(Onsight)

Intra-EVA

EV Augmented Reality
(MIT HoloSEXTANT, Microsoft HoloSkype)



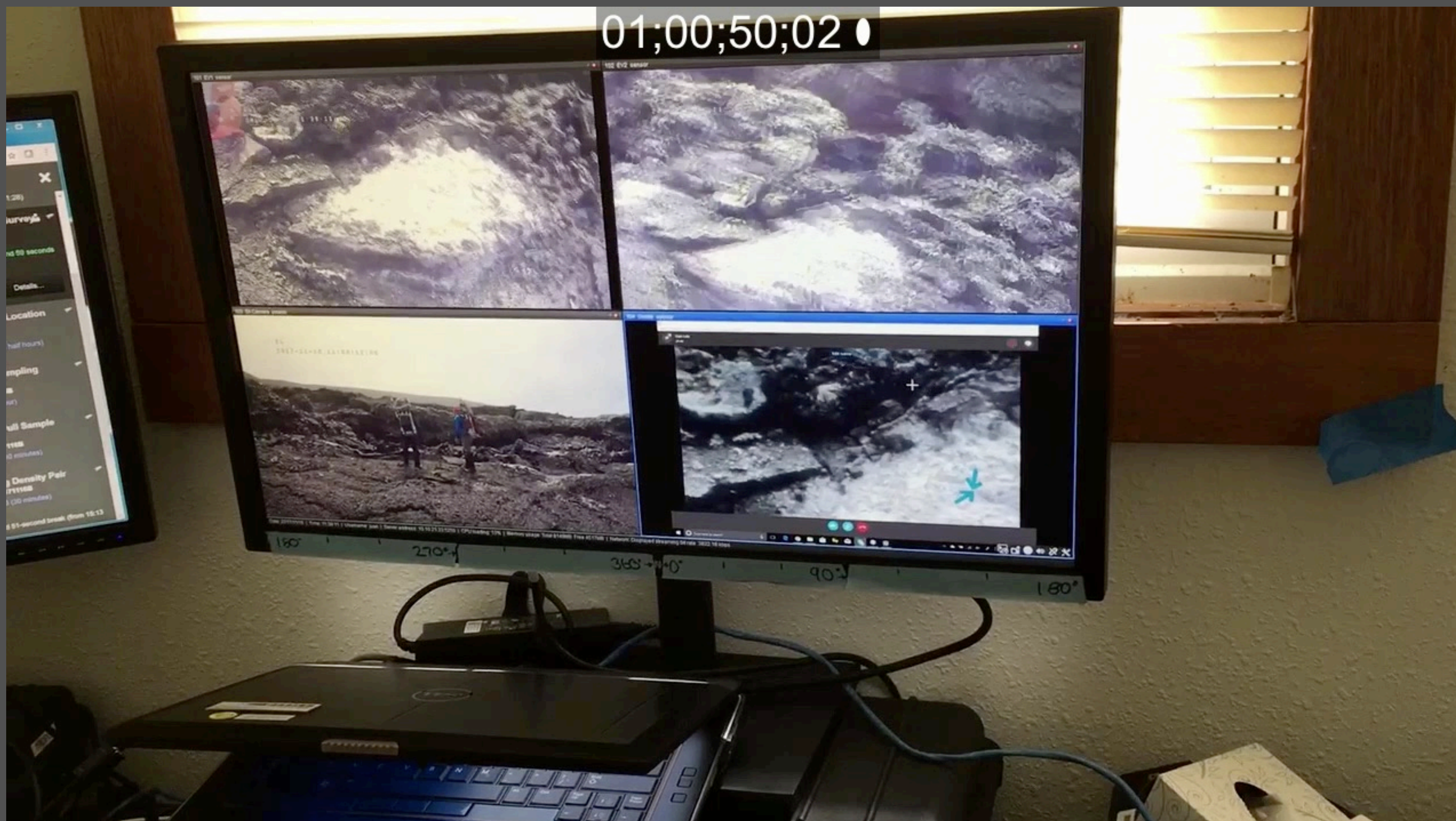
IV Augmented Reality and Virtual Telepresence
(Onsight, Holoskype)

MSC Virtual Telepresence
(Onsight)

Onsight: VR Training and Planning

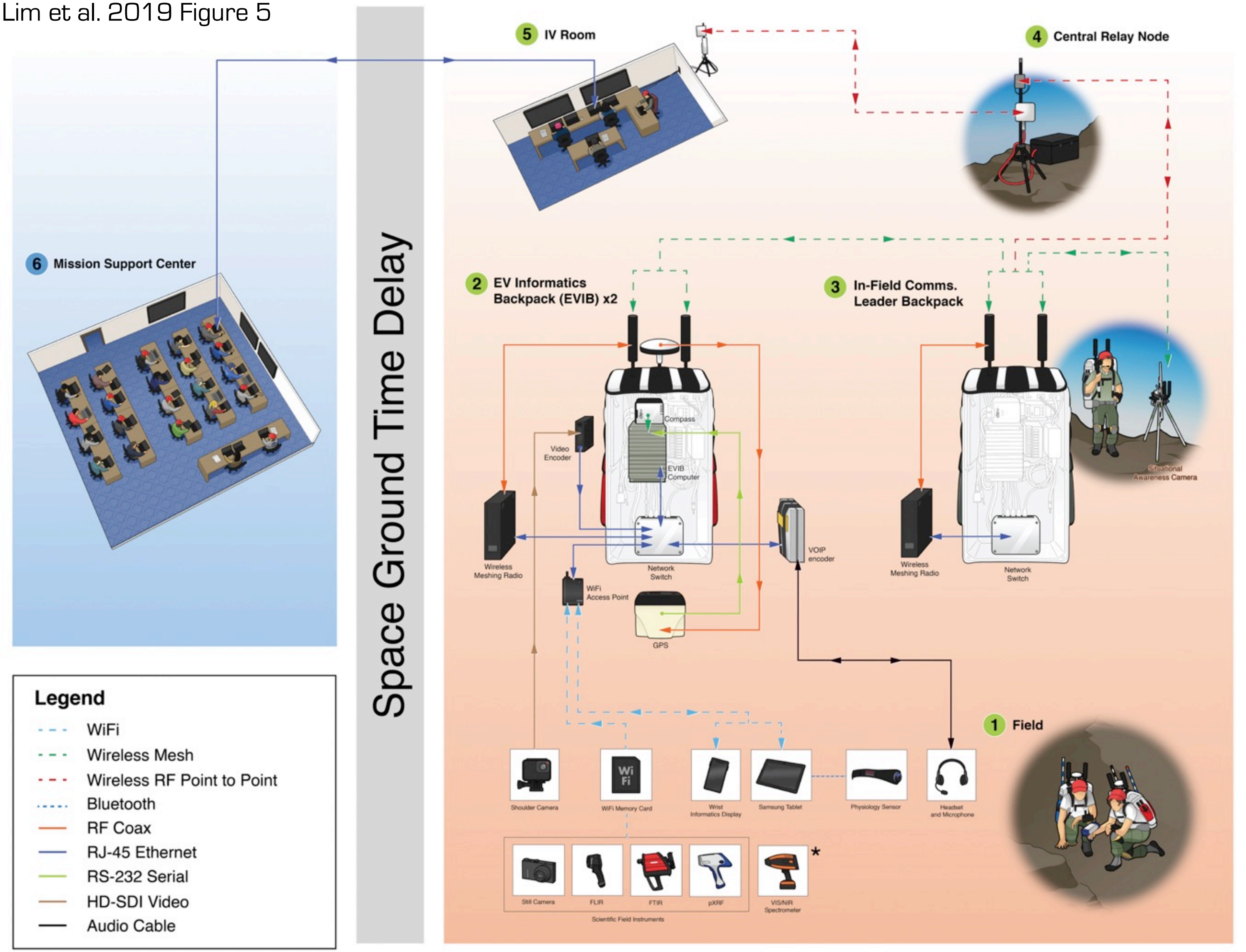
HoloSEXTANT: AR Traverse Optimization

HoloSkype: AR EV/IV Interactions

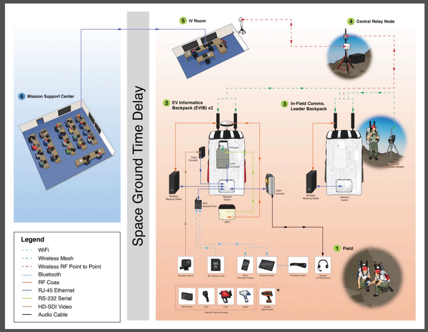


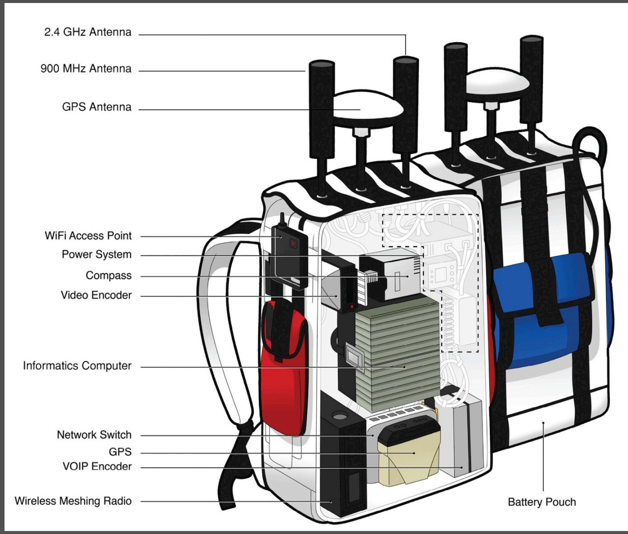
Identifying Capabilities Requirements: Communications & Network Systems

Lim et al. 2019 Figure 5

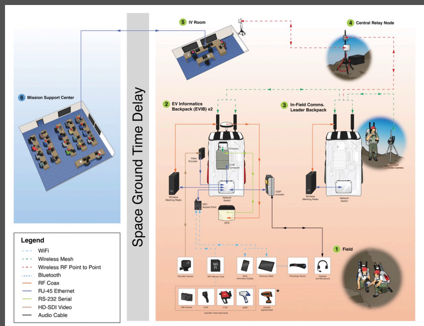


Identifying Capabilities Requirements: Communications & Network Systems – EVIB & Comms Lead

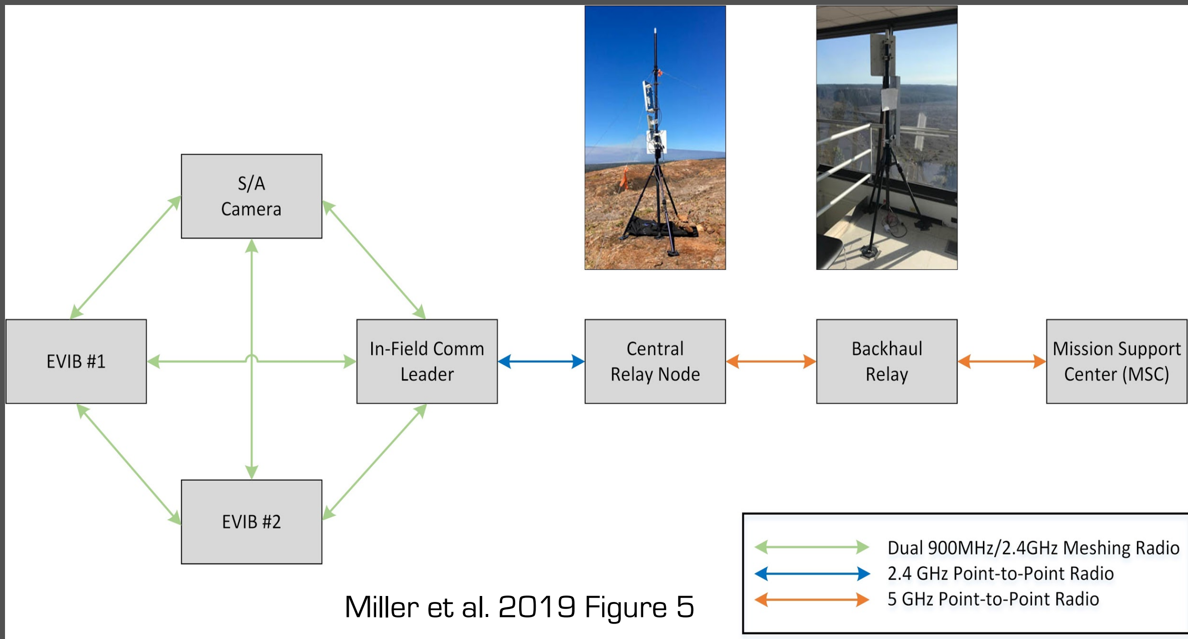




Identifying Capabilities Requirements: Communications & Network Systems – SA Camera & Wrist Displays



Identifying Communications Capabilities in support of future EVA ConOps



Miller et al. 2019 Figure 5

Simplified drawing of the field meshing RF communication nodes for the 2016 Hawaii field deployment. Miller et al Astrobiology special issue

A wireless mobile meshing communication system that provided dual-band redundant radios to optimize throughput and minimize loss of signal. When available, the 2.4 GHz radio provided higher throughput and was the prime radio used when there was line of site with the communications relay.

From prior experience designing communications systems for other NASA analogs, the communications team determined that a meshing radio system was the optimal method for the elements within the exploration zone of a planetary surface to communicate. These elements include EVA crew, robotic rovers, crewed rovers, and habitats. The meshing node on the habitat in future missions will also likely have a high-rate backhaul link either to an orbiting satellite or direct to Earth.

BASALT INSIGHTS

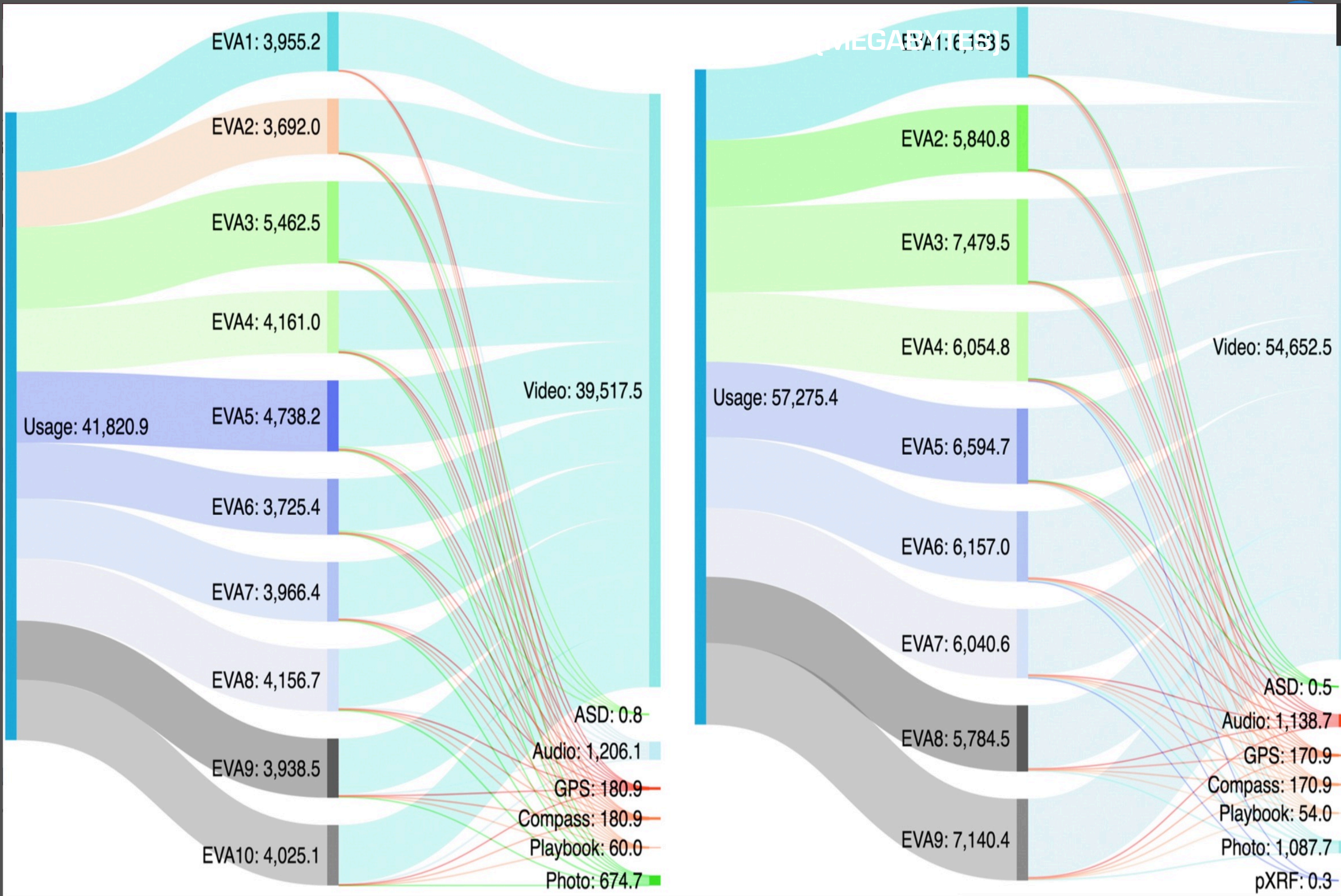


FIG. 14. (**Left**) Sankey Diagram showing total data transmitted per EVA day and data product type for BASALT-1 (Idaho 2016). (**Right**) Sankey Diagram showing total data transmitted per EVA day and data product type for BASALT-2 (Hawai'i 2016).

Miller, M.J., Miller, M.J., Santiago-Materese, D., Seibert, M.A., and Lim, D.S.S. (2019) A flexible telecommunication archi- tecture for human planetary exploration based on the BA- SALT science-driven Mars analog. Astrobiology 19:478–496. ONLINE: https://

Identifying Communications Capabilities in support of future EVA ConOps

HAWAII 2016

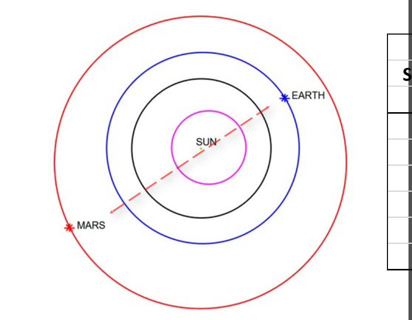
	Photos	Video	Audio	GPS	Compass	Playbook	pXRF	VNIR*	TOTAL
EVA1	76.4	5940.0	123.8	18.6	18.6	6.0		0.1	6183.4
EVA2	57.3	5625.0	117.2	17.6	17.6	6.0		0.1	5840.8
EVA3	101.4	7177.5	149.5	22.4	22.4	6.0		0.1	7479.5
EVA4	63.2	5827.5	121.4	18.2	18.2	6.0	0.1	0.1	6054.8
EVA5	141.1	6277.5	130.8	19.6	19.6	6.0		0.1	6594.7
EVA6	211.7	5782.5	120.5	18.1	18.1	6.0	0.1		6156.9
EVA7	164.6	5715.0	119.1	17.9	17.9	6.0	0.1		6040.6
EVA8	139.7	5490.0	114.4	17.2	17.2	6.0			5784.4
EVA9	132.3	6817.5	142.0	21.3	21.3	6.0			7140.4
Subtotal	1087.8	54,652.5	1138.6	170.8	170.8	54.0	0.4	0.5	57,275.4
% of total	1.90%	95.42%	1.99%	0.30%	0.30%	0.09%	0.00%	0.00%	100.00%
Avg.	92.8	4956.3	123.4	18.5	18.5	6.0	0.0	0.1	5215.6
Std. Dev.	54.8	1209.0	12.0	1.8	1.8	0.0	0.0	0.1	1245.3

Amount of data transmitted, by data type. All units are in megabytes (MB). Average values and standard deviation for all types of data for both deployments is shown at the bottom

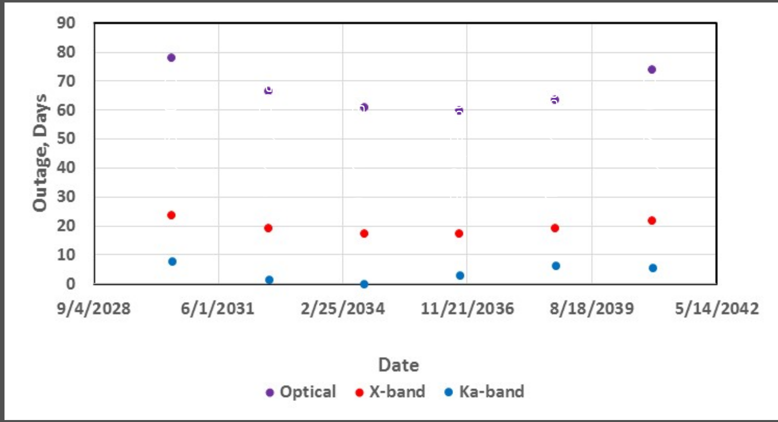
- The network performance data from BASALT, especially the observation that video consumed 95% of the data bandwidth, suggests that the current Deep Space Network (DSN) architecture for Mars must evolve to support the higher bandwidth requirements of human exploration missions, especially if live streaming video is a requirement.
- Further effort should also be devoted to investigating the optimal streaming video frame rate, resolution, and compression algorithms to maximize science return while making efficient use of network bandwidth. Studying the tradeoffs between various video options, including supplementing video with still images of varying sizes and compression rates will help determine the true bandwidth needed for imagery. For example, if lower resolution or frame-rate video were acceptable when augmented with a few higher resolution photographs, this could save substantial overall Intra-EVA bandwidth.
- As indicated in Beaton et al., video provided valuable situational awareness (SA) to the remote scientists in the MSC, so the BASALT team expect that efforts to improve its efficiency while still delivering the required SA will prove worthwhile.

Mars Telecommunication – E-S-M Conjunction Outages

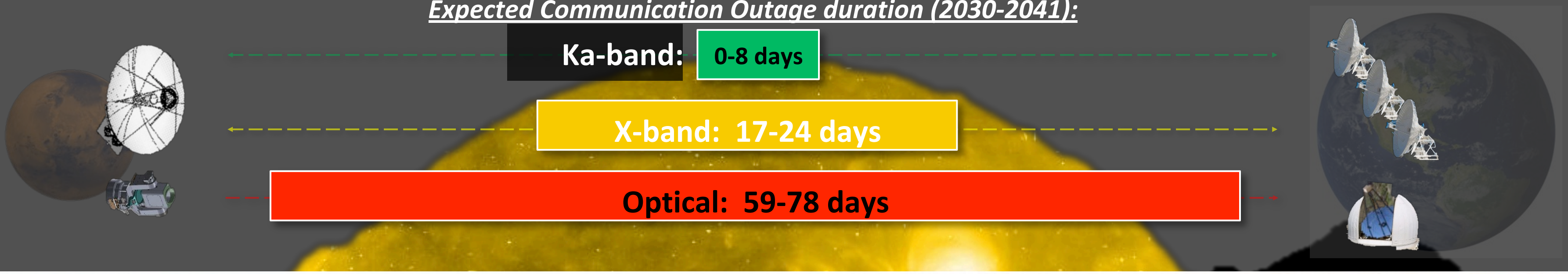
- Approximately every 26 months, the Sun moves in between the Earth and Mars, these are called "**solar superior conjunctions**" (SSC's)
- SSC's cause signal degradation and/or complete outages for days to weeks, **potentially impacting crew operations** (today: *some of our Mars ops team members take vacation during SSC's*)
- Outages expected in the 2030-2041 time frame are shown at right
- Two possible ways to mitigate these:
  - Relays around the sun (possible, may need mission pull, not in current SCaN architecture plan or budget)
  - Use of FSK/semaphore comms to enable **very low rate data messaging** (1 bit every 3-6 seconds, similar to submarine EHF comms). Used in recent Mars landings.
- We should consider **simulating the worst-case SSC outage scenarios, and testing crews & human operations during the crewed missions to Gateway**



Date of Solar Conjunction at Min. SEM	Min. SEM Angle (deg)	Optical Outage (Days)	X-band Outage (Days)	Ka-band Outage (Days)
5/25/2030	0.28	78.1	23.5	7.7
7/11/2032	0.98	66.4	19.0	1.5
8/19/2034	1.14	60.9	17.1	0.0
9/23/2036	0.86	59.8	17.3	3.1
11/1/2038	0.22	63.3	19.0	6.3
12/17/2040	0.66	74.0	21.7	5.7

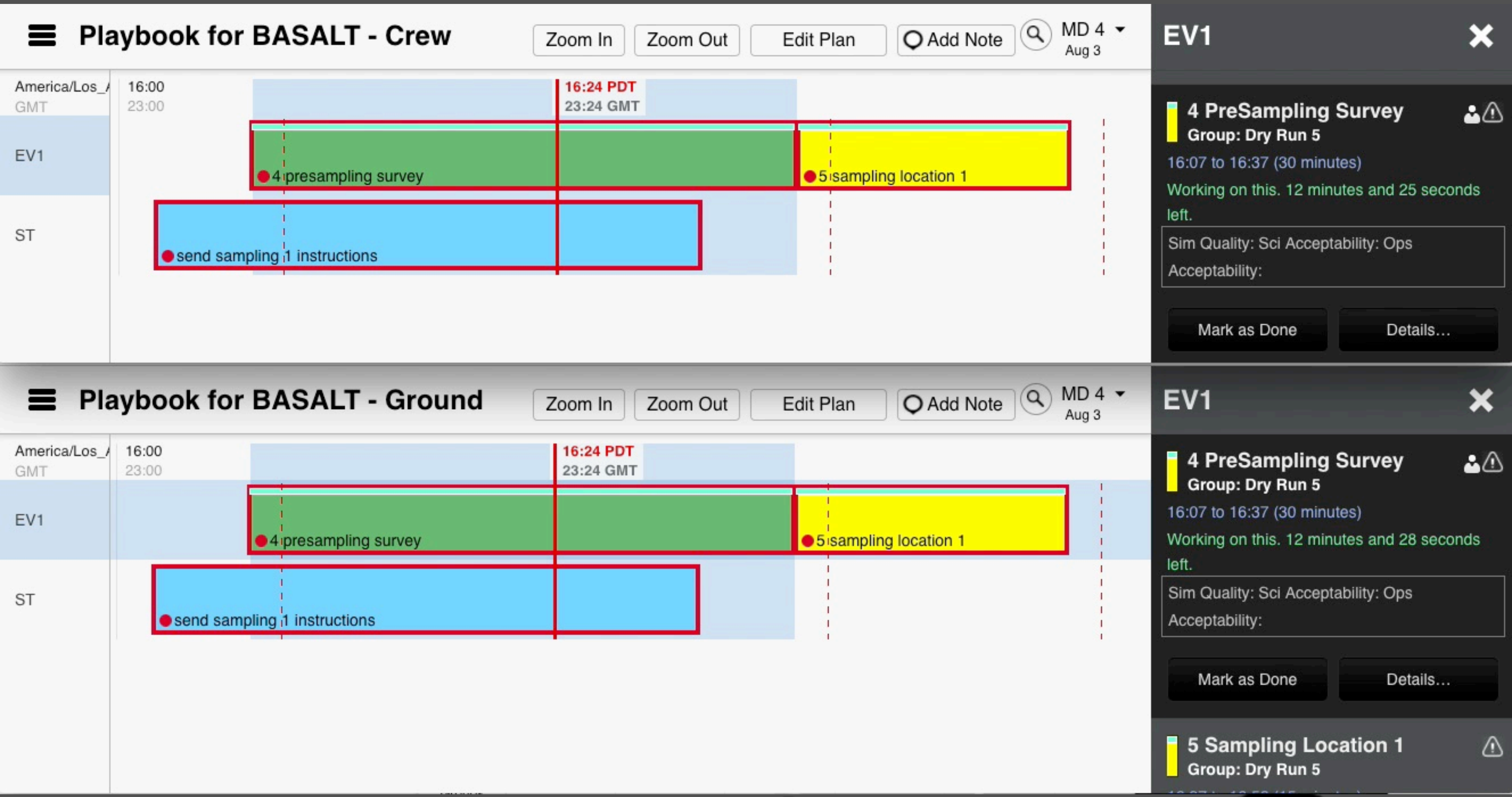


Expected Communication Outage duration (2030-2041):



Source: SCaN Team (M.Seibert, D.Morabito, J.Breidenthal, J.Schier)

Playbook Timeline Management Capability
The "Ah ya, what?" moments

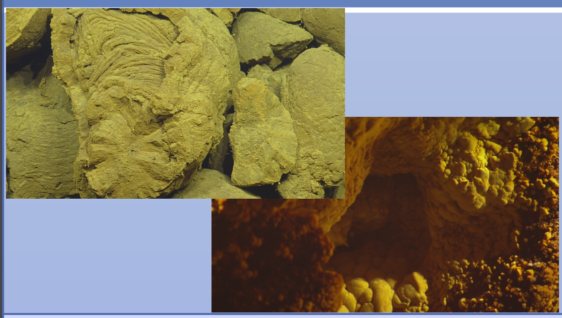
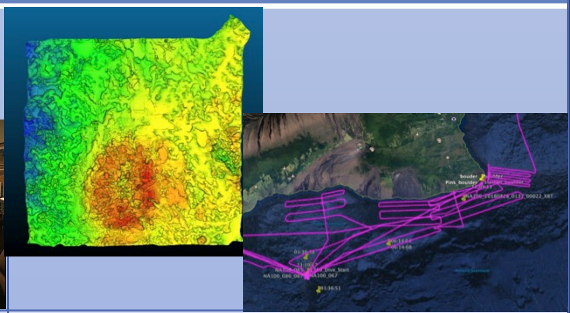


SUBSEA

- Funded July 2017 by NASA SMD ROSES-2016 Program Element C.14
- Planetary Science and Technology Through Analog Research (PSTAR)

Systematic Underwater Biogeochemical Science and Exploration Analog

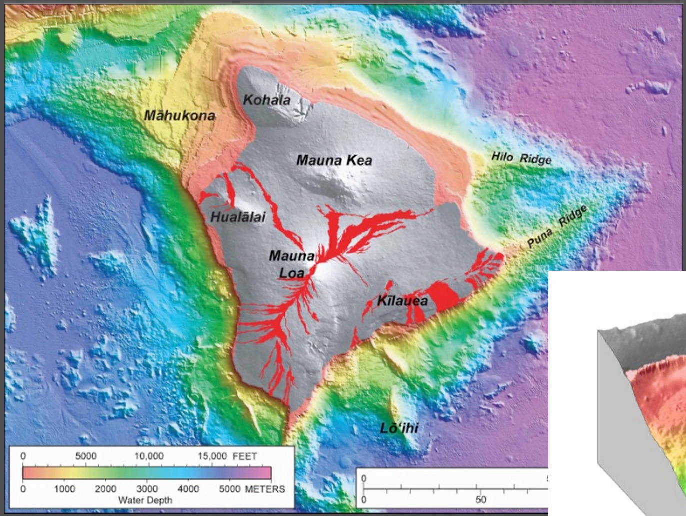
SUBSEA Research

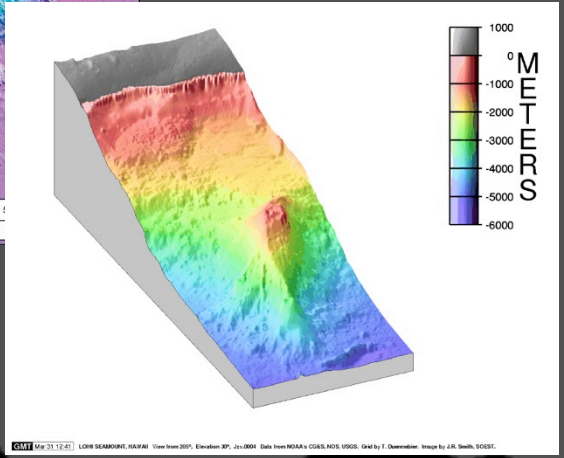
SCIENCE	OPERATIONS	TECHNOLOGY
		
Broaden our understanding of the potential habitability of other Ocean Worlds. Characterize novel deep sea environments on our own planet.	Study the telepresence architecture of the E/V *Nautilus* to evaluate and identify specific concepts of operations (ConOps) and capabilities that will have enabling and enhancing value for science-driven Low Latency Teleoperations exploration of deep space and Mars	Provide human/robotic software functionality to support integration and visualization of diverse data products relevant to future human exploration of deep space and current oceanographic exploration on Earth.

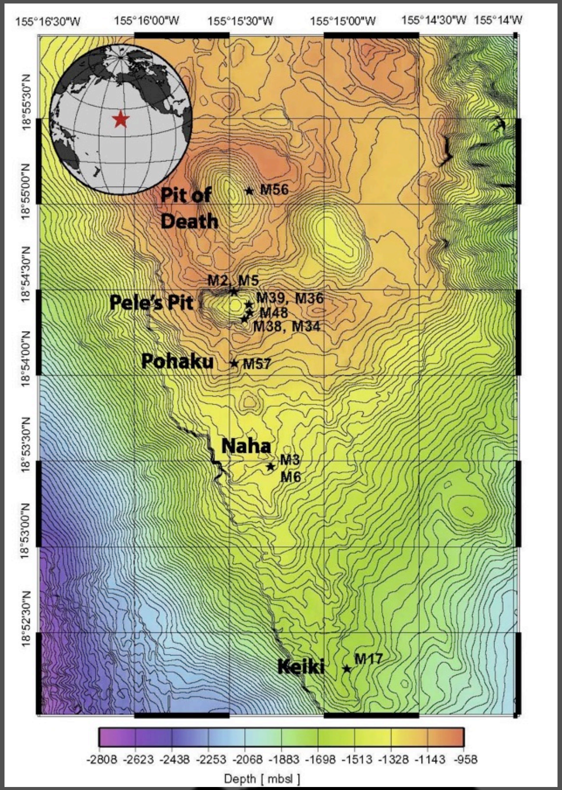
SUBSEA SCIENCE OPERATIONS

SUBSEA Cruise A Lo`ihi 2018

SUBSEA's first field campaign was focused on characterizing the geology, energetics, and microbial communities associated with the Lō`ihi seamount.





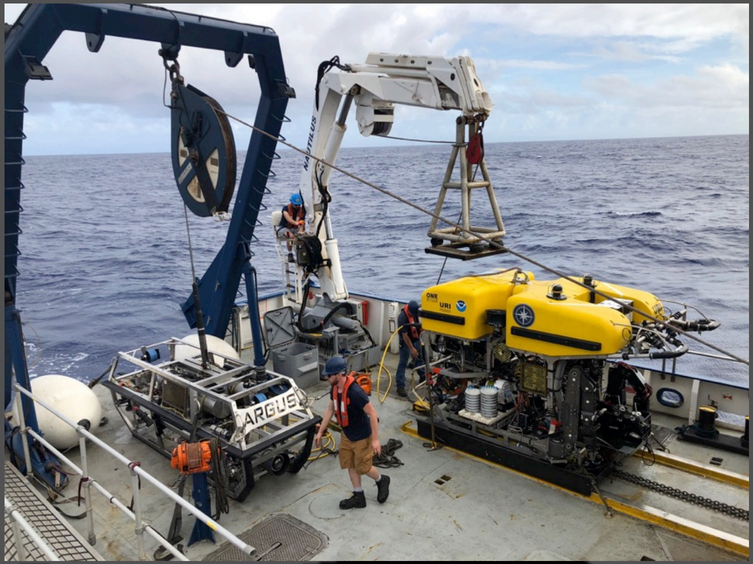


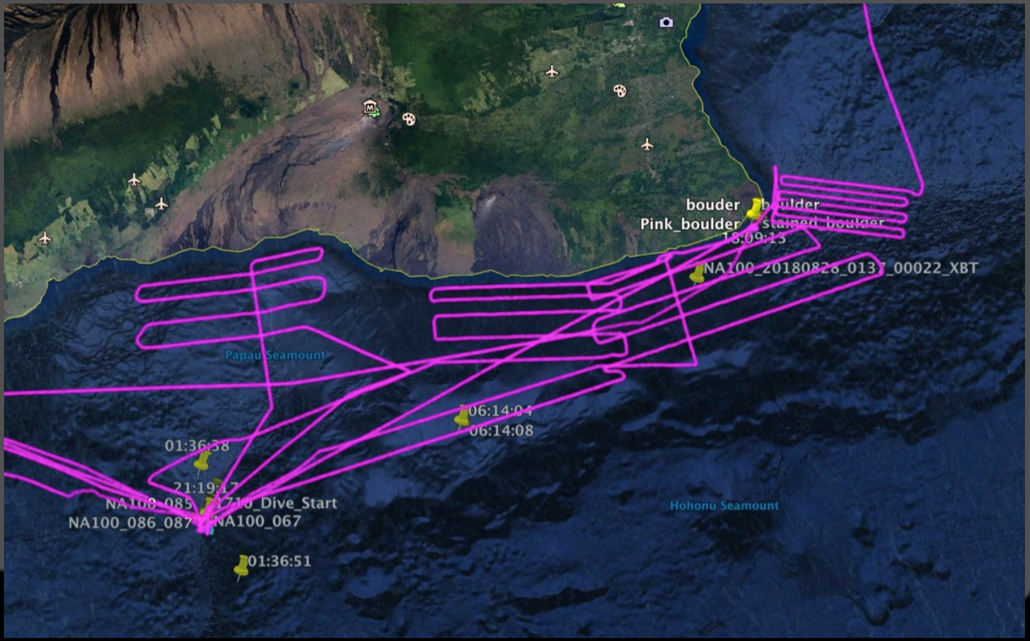
SUBSEA Team* on NA100

*Additional team members:
https://spacescience.arc.nasa.gov/subsea/people/

Output and Outcomes of Cruise A Deployment

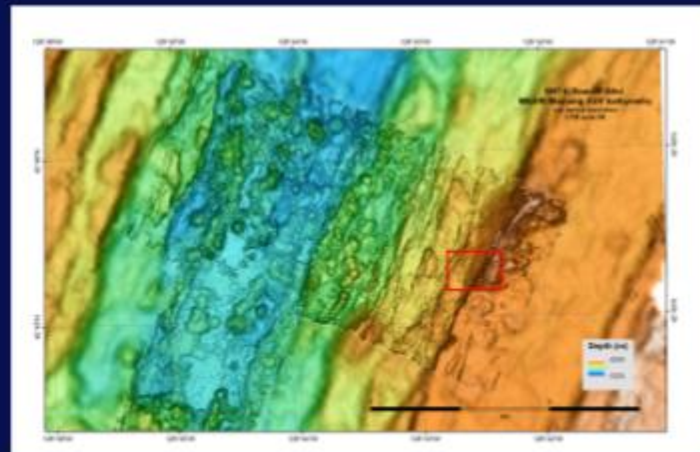
- 4 Hurricanes, 10 ROV dives; 110 hours of ROV bottom time
    - Loihi: 9 Dives, 5 GeoTransects, 5 known fluid flow sites sampled
    - Ocean EntrySite: 1 Dive, 1 GeoTransect, 1 fluid flow site sampled
    - Mapping Surveys: During down-time (10 Weather Days)
- 126 individual samples collected; 131 with subsamples
- All research (Science, Ops, Tech) objectives completed plus bonus dive on lava flow

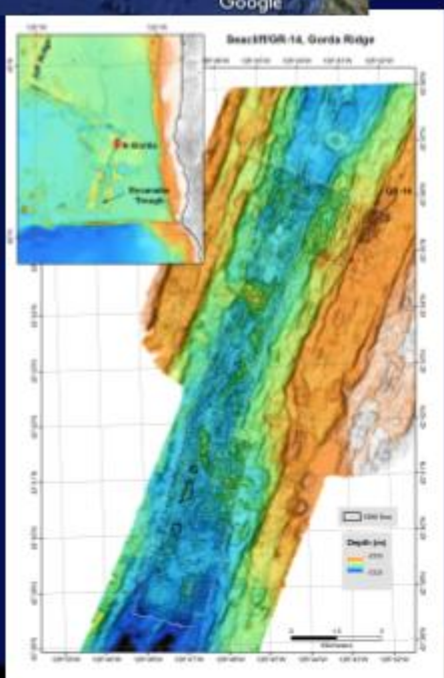




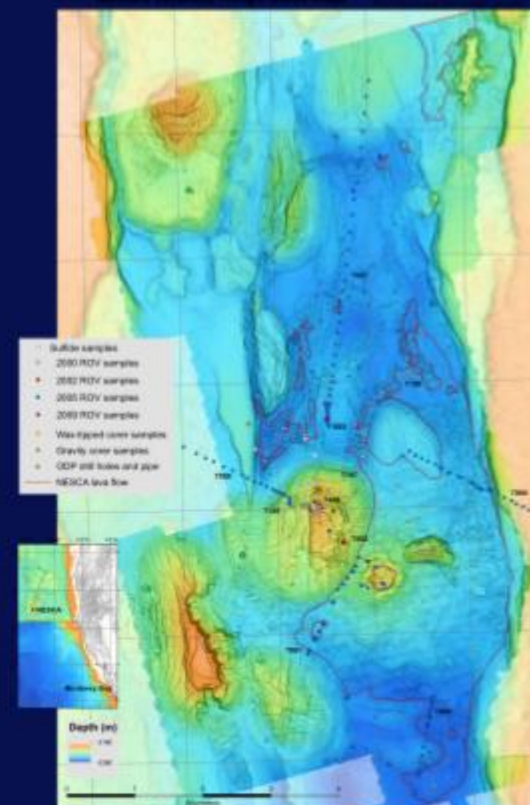
Cruise 2: NA108 Gorda Ridge, NE Pacific

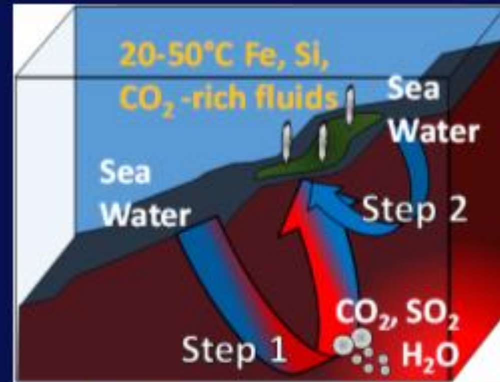
SUBSEA

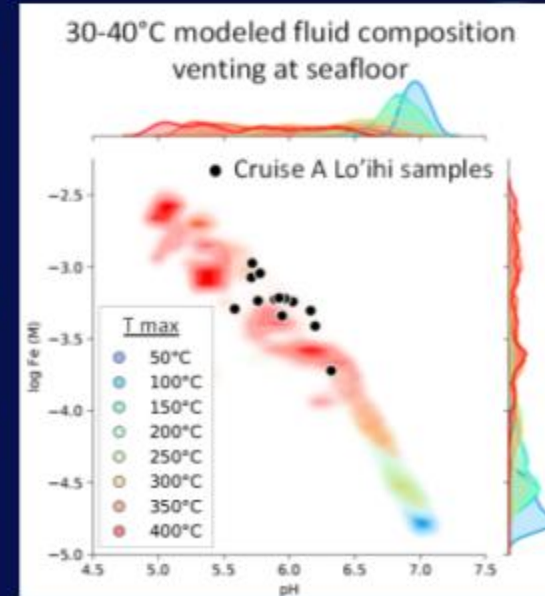




- SeaCliff vent field (above):
  - Clear vent-fluids hosted on bare rock at ~300°C
- North Gorda segment (left):
  - "Zero-age" lava flows &
  - Exploration for new vents
- Escanaba Trough (right):
  - Clear vent fluids hosted in sediments at ~200°C




20-50°C Fe, Si,
CO_2 -rich fluids
Sea
Water
Sea
Water
Step 2
Step 1
CO_2, SO_2
H_2O


30-40°C modeled fluid composition
venting at seafloor
Cruise A Lo'ihi samples
T max
50°C
100°C
150°C
200°C
250°C
300°C
350°C
400°C
log Fe (M)
−2.5
−3.0
−3.5
−4.0
−4.5
−5.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
pH

SUBSEA Operations
Research Priorities NA108

1. Provide NASA flight-like conditions for SUBSEA NA108 that produce communication latency on the order of approx. 10 to 24 hours between ship and shore

2. Collect data for comparative analysis with data collected during NA100

3. Collect data on communication content and information flow between ship and shore

SUBSEA NA108:
10 dives: 2 distinct work modes, Mode 1 and Mode 2

- Mode 1: scientists on shore will not have the ability to direct dive operations in real-time over audio channels (or written, via OET Science Chat). They will communicate by sending and receiving "SUBSEA Dive Plans" and "Dive Recovery and Data Report."
- Mode 2: scientists on shore will gain the ability to direct dive operations in real-time over audio and text channels in addition to the communication technologies described.
- 40% of the dives will be conducted using Mode 1; 60% of the dives will be conducted using Mode 2

Communication Flight-rules per Mode										
	Mode 1				Mode 2					
Dive	1	2	3	4	5	6	7	8	9	10
Dive type	map	vent	vent	vent	vent	map	vent	vent	vent	vent
Dive Plan Produced	before ROV in water	by ISC-located science team	by ISC-located science team	by ISC-located science team	by ISC-located science team	by ISC-located science team	by ISC-located science team	by ISC-located science team	by ISC-located science team	by ISC-located science team
Real-time communication between ship and shore										
People										
ISC scientists and control van crew using OET tools (audio/sci chat)	no	no	no	no	yes	yes	yes	yes	yes	yes
ISC scientists and control van crew using other communication modalities (e.g. mobile and computer text/email)	no	no	no	no	yes	yes	yes	yes	yes	yes
between Nav on ship and at Nav at the ISC	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Instrument team ship and shore (i.e. Eric and Chip)	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
NASA tech team at ISC with NASA team on ship	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Communication technology										
SUBSEA dive plan (authored on shore) emailed to ship*	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
SUBSEA dive recovery report (authored on ship) emailed to science team list	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
OET Science Chat	no	no	no	no	yes	yes	yes	yes	yes	yes
OET Audio Comms	no	no	no	no	yes	yes	yes	yes	yes	yes

Thank you!