Full Report

Space Exploration Via Telepresence: The Case for Synergy Between Science and Human Exploration

Findings and Observations from:

"Exploration Telerobotics Symposium"

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NASA Goddard Space Flight Center

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http://telerobotics.gsfc.nasa.gov/

Topic Areas

The Symposium Framework

Achieve exploration and science goals via “*proximity*” robotic operations to reduce risk and cost, as well as explore inaccessible and hazardous locations.

- Humans remain in locations where they have **near real-time** control of robots at the Exploration sites
- Extend human cognition to the surface of Moon, Mars, and other bodies **without the challenges, expense and risk** of putting humans on hazardous surfaces or within gravity wells
- Achieve **synergy** between human and scientific exploration of other planetary bodies by surface **telepresence** of “astronaut” scientists
- **Assemble, repair, and upgrade** complex space facilities not otherwise accessible due to contamination, their fragility, extreme low temperature, etc.

The GSFC Exploration Telerobotics Symposium

- Goal: Assessment of **opportunities** & **challenges** of **telepresence for space exploration**
  - Science, Human Space Flight, Technology

- Attendence: Approximately 100 professionals, including folks at this LEAG meeting
  - "**NASA not just talking to NASA"** - NASA discussing with the community – science & technology experts ; small/large industry, academia, international space agencies

- Output: Report to NASA and outreach to greater community
  - Findings and observations delivered to HQ program managers
    - *Science, human space flight, technology*
  - Additional presentations at professional conferences, engagement with NASA HQ

Photo: Dr. Ruthan Lewis

Symposium in the Media

What is Telepresence?

- Telepresence is about projecting human cognition (i.e., intelligence, relevant human senses, responsiveness, dexterity) to a remote operations site without physical human presence

- To achieve a satisfactory level of **low-latency** telepresence (LLT) requires three independently desirable technological capabilities:
  - *Low communication latency, comparable to human response time*
  - *High bandwidth, comparable to current video rates*
  - *High-capability telerobotic action surrogates, mobility, and sensors*

- Remote operation of space robots capable of competing with humans *on site* requires an effective combination of all three.

Why Explore via Telepresence?

- Entry, Descent, and Landing (EDL) and ascent are **risky and expensive**.
- Low latency, advanced robotics, and high bandwidth are **independently enabling**. Applied together, a powerful new capability for human exploration.
- Humans may be **severely constrained** in current EVA suits.
- Key technologies are **at hand or in the near future**.
- Human surface exploration requires **special ECLSS systems**.
- Surfaces of other worlds - **contamination issues** complicate human operations.
- A human can be only in **one place at a time** at an exploration site.
- **Planetary protection issues** make humans potentially harmful or harmed.
- Opens up destinations humans **may never directly visit** (e.g. Venus, Titan)
- **Build upon terrestrial experience**, make field science "as if we were there".

Exploration telepresence can lower cost and risk to humans,
increase capabilities, amplify science return and even create new science.

If latency is the fundamental limit to high-performance telepresence, where to put humans, if not on the surface?

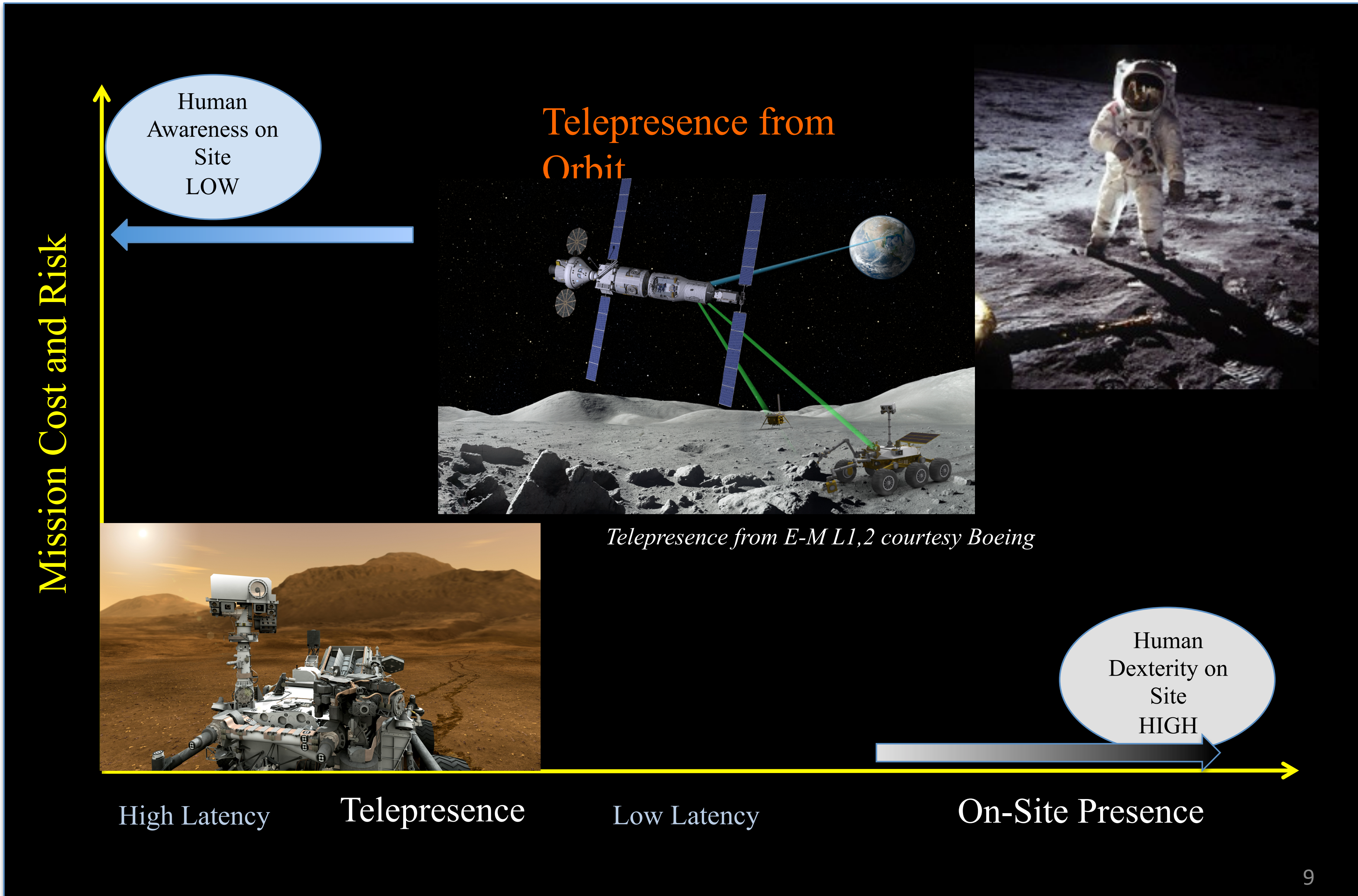
To ensure a high-level cognitive connection between telerobots and humans, human explorers must be within a "cognitive horizon" defined as the distance over which the communication latency is of order than, or smaller than, the human reaction time. This is a maximum of ~ 100 - 200 ms (i.e., one-way distance of ~15 - 30,000 km at the speed of light).

Orbital sites provide operational simplicity for humans in many respects. On-orbit human habitation (technology and operations protocols) is well-developed by ISS.

For the Moon, low lunar orbit allows very low latency (10 – 20 ms), but is limited by orbital instability, frequent shadowing, and rapid rising and setting of surface targets. Earth-Moon L1 and L2 have a latency of ~400 ms (round trip) from the lunar surface. These locations offer 24/7 access to multiple sites on one hemisphere and nearly continual sunlight, although they are slightly beyond the "cognitive horizon".

For Mars, aerostationary orbits offer advantages for long-duration operation at multiple sites. Molnya-type orbits offer extended-duration connections. Operations from Phobos and Deimos orbits have been proposed as sites that offer extra radiation shielding, although suffer from very limited surface contact times and can be in difficult-to-reach orbits.

Human Exploration Spectrum: *Presence* to *Telepresence*



Three Essential Capabilities Enable Effective Telepresence

– *Low communication latency,*

comparable to human response time

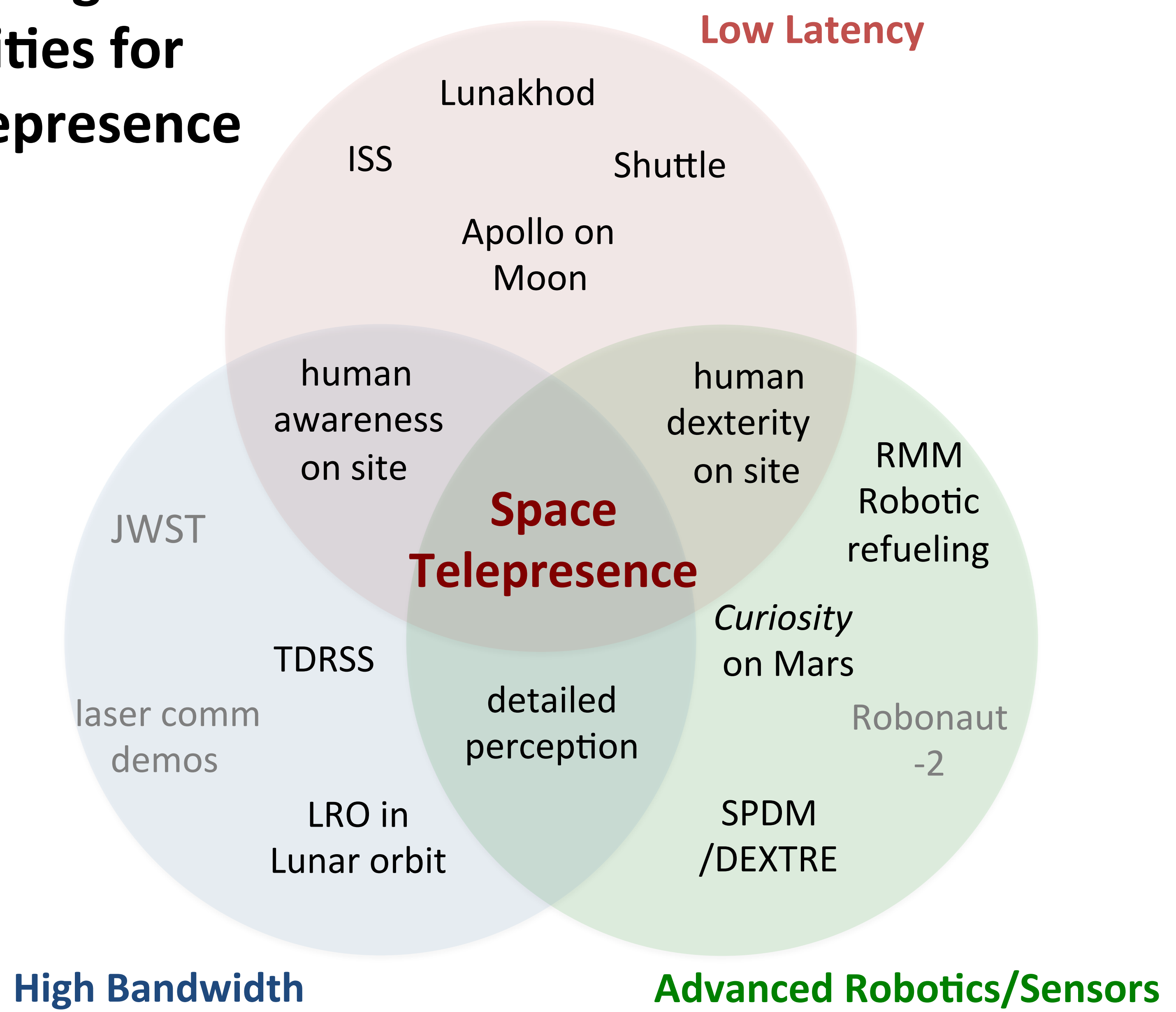
– *High bandwidth*

comparable to human eye-brain *(~10 Mb/s)*

– *High capability action surrogates (advanced robotics)*

mobility and sensing comparable to human

Enabling Capabilities for Space Telepresence



Status of Three Essential Capabilities for Low-Latency Telerobotics

- High-bandwidth communication and high-performance telerobotic surrogates are current or near-future capabilities. Latency is ultimately limited by the speed of light.

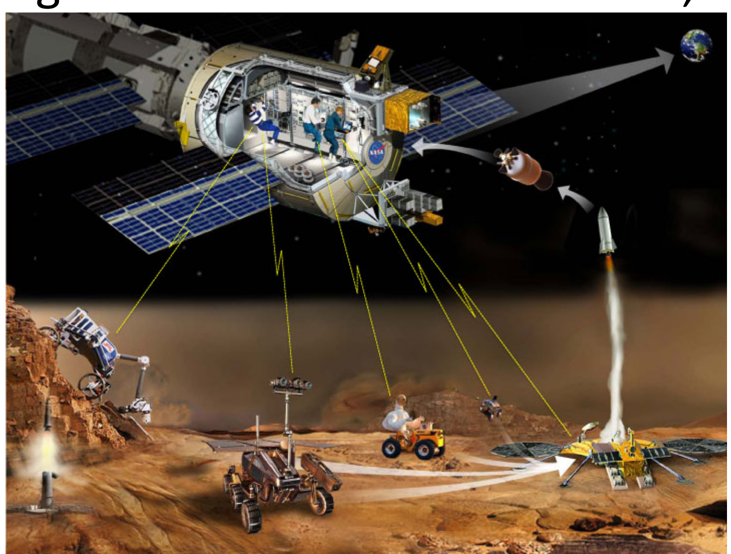
- The human eye-brain system has an equivalent bandwidth of ~10 Mb/s. Mobility and manual dexterity, even with force feedback/haptics, can be much less demanding, which is usable with current space telecommunication technologies.

- High-capability telerobotic surrogates can be more challenging. Although robotic sensor systems are vastly more capable than corresponding human senses and do not limit our cognition, mobility and dexterity are more difficult. However, terrestrial telerobotics (surgery, undersea oil & gas, mining) have a high degree of mobility and dexterity. Technology investment will surely increase capability.

- Communication latency is a fundamental constraint, limited ultimately by the speed of light. For the Moon, the two-way light time latency is 2.6 seconds. For NEOs, it can be many minutes, and for Mars it is 8 - 40 minutes. These latencies impose a range of penalties on task completion times. *Putting humans in proximity to an operations site is the only way to improve latency.*

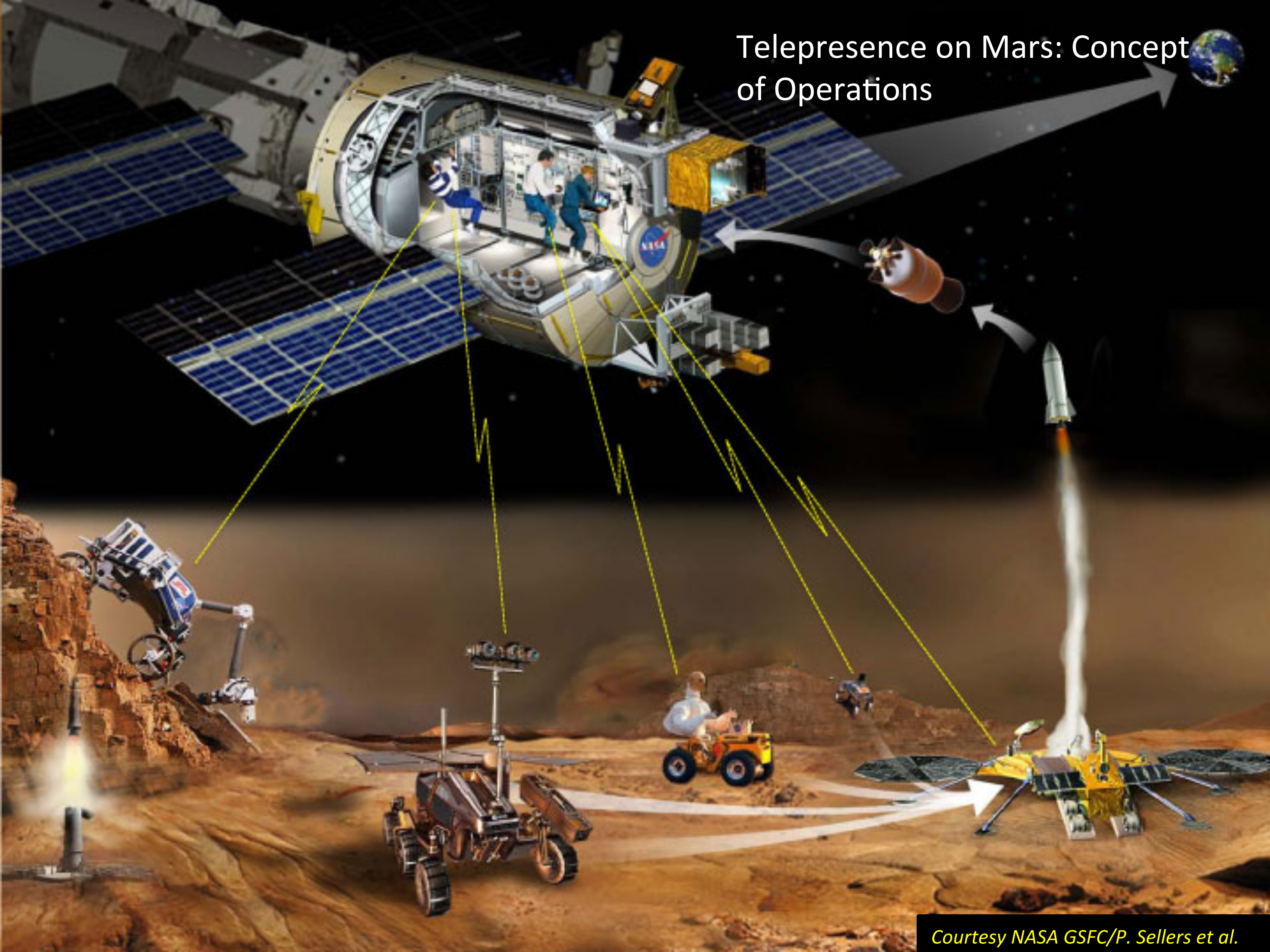
Themes in Low-Latency Space Telepresence

- Humans remain in locations where they have **near real-time control** of robot surrogates at the required destinations or operations venues: e.g., planetary surfaces, NEAs, in-space assembly or servicing sites.
- Extend human cognition to the surfaces of the Moon, Mars, and other planetary bodies **without the additional risk and expense** of putting humans on hazardous surfaces or within deep gravity wells, thereby enabling **new science capabilities**
- Apply human dexterity and flexibility to **assembly of complex and delicate structures** in free-space, such as for satellite upgrades and servicing, and on planetary surfaces
- Required technology capabilities are **available now** – or will be soon – and are advancing rapidly: high-bandwith communications, advanced robotic systems



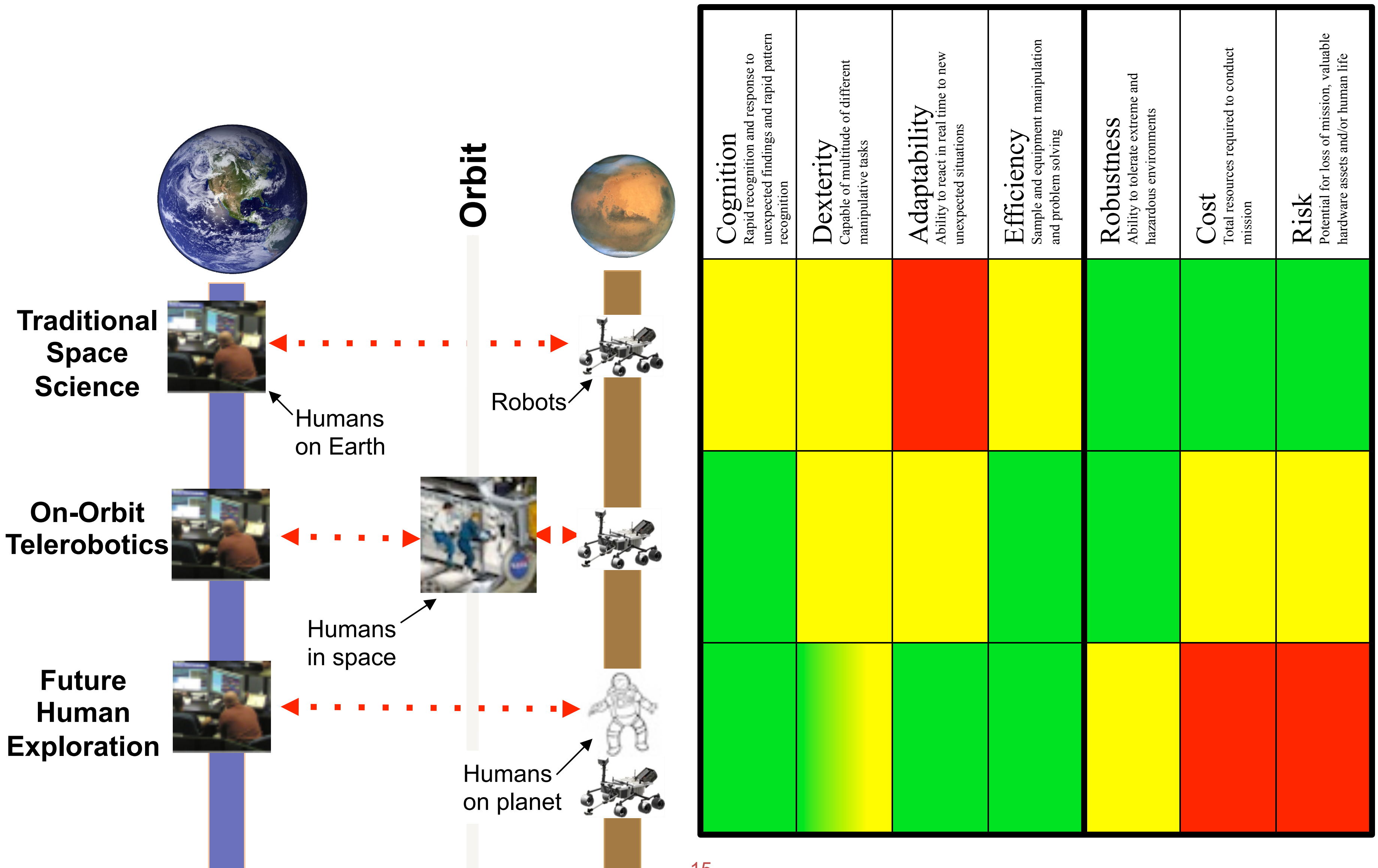
Notional concept of operations for telepresence field science and sample return for Mars (Sellers et al., 2012)

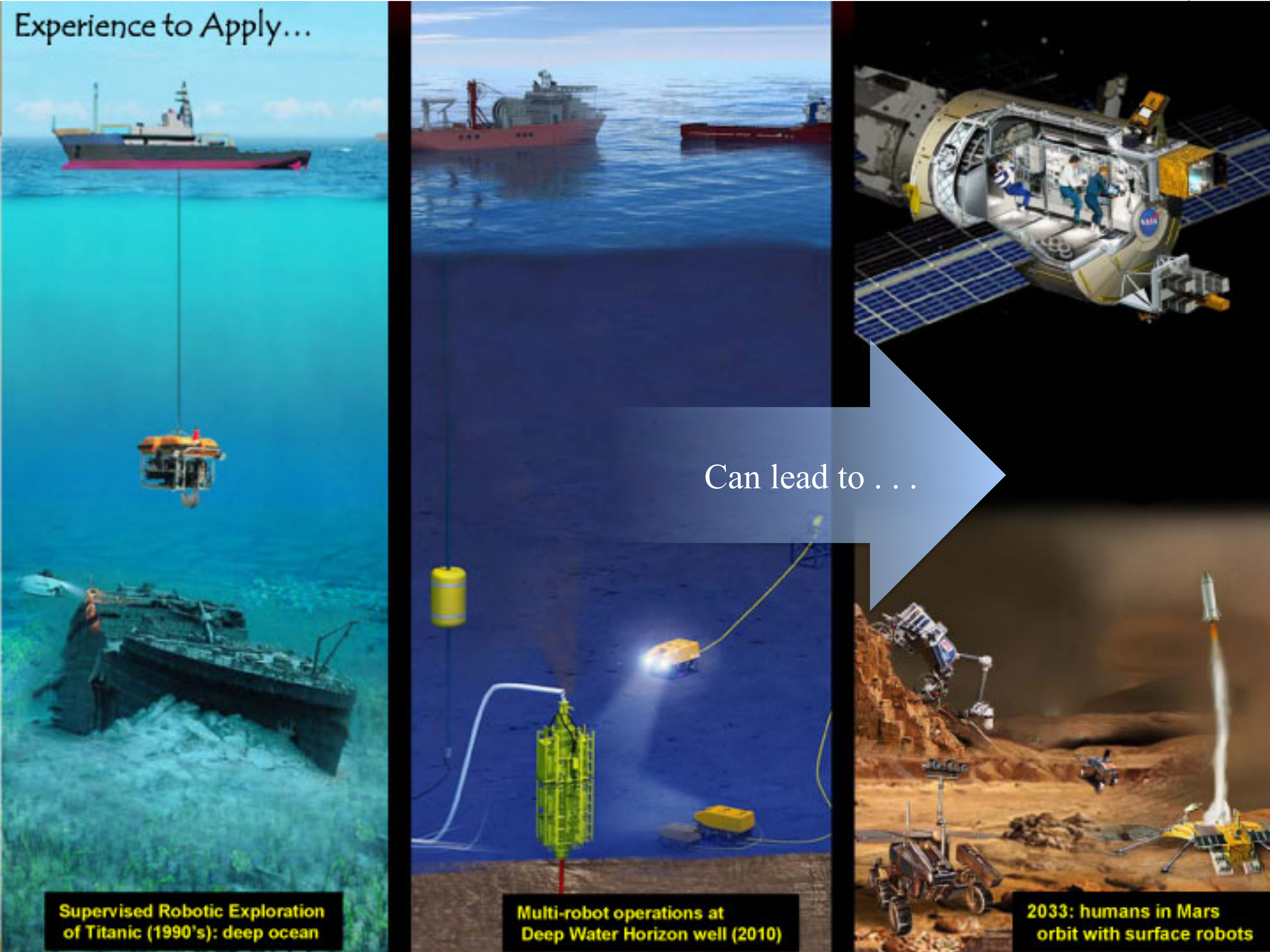
Telepresence on Mars: Concept of Operations



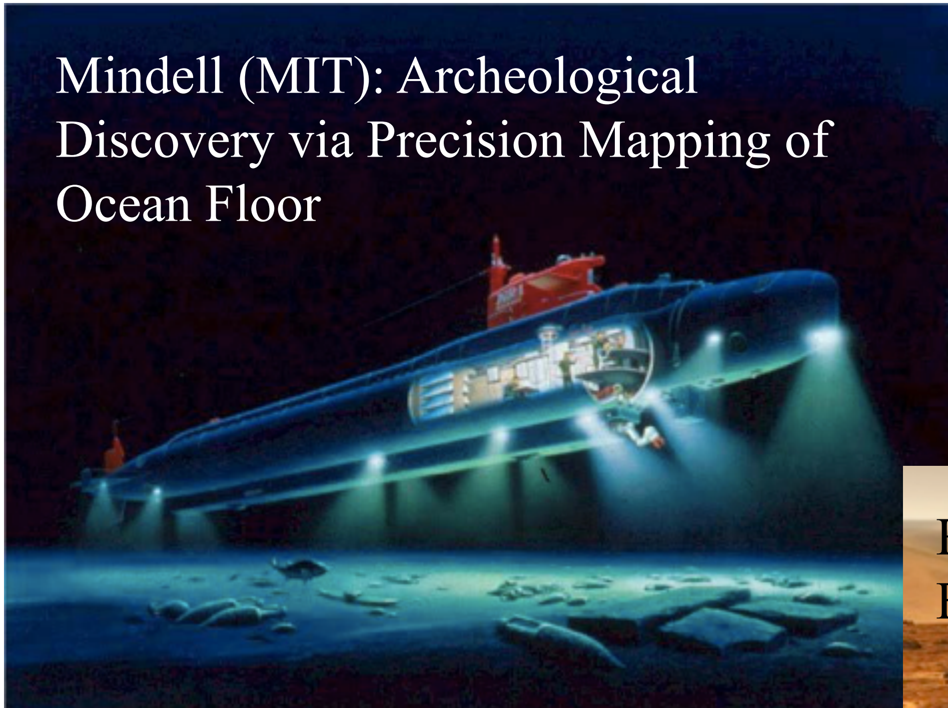
Courtesy NASA GSFC/P. Sellers et al.

Multiple Capabilities for Space Exploration




Experience to Apply…
Can lead to . . .
Supervised Robotic Exploration of Titanic (1990's): deep ocean
Multi-robot operations at Deep Water Horizon well (2010)
2033: humans in Mars orbit with surface robots

Experience that May be Applied: Highlights of Symposium Day 1



Mindell (MIT): Archeological Discovery via Precision Mapping of Ocean Floor

Whitcomb (JHU): 50 years of Deep Ocean Telerobotics Exploration

Hodges (ASU): Collaborative Field Geology

Vertesi (Princeton): Telerobotics Sociology

Experience that May be Applied: Highlights of Symposium Day 1

Ambrose (NASA/JSC): State-of-the-Art Space Telerobotics

Kazanzides (JHU): Telerobtics in Medicine

Whittaker (CMU): Terrestrial Robotics

Schiele (ESA): METERON

Suggested Path Forward

Establish a working group chartered by SMD & HEOMD and representing community scientists, engineers, and technologists that will:

- Identify analogs for telepresence exploration on Earth as suggested by NASA HQ and consistent with community priorities,
  - *Determine value and decision matrix of cost/benefit for science, exploration*
- Organize workshops and other similar organized interactions with the community
  - *Topic- and scenario-specific*
  - *Continue assessment of telepresence: low/high-latency, low/high-bandwidth*
- Organize field-based multi-scale human-robotic interactions with multiple latencies at analog sites and small mission test-beds, including ISS
  - *Includes evaluations of operations, control systems, displays, etc*
  - *Leverage ongoing field studies liking to existing SMD-HEOMD joint efforts*
- Identify and advocate investments in key robotics technologies
  - *sensing, mobility, manipulation, human systems integration, autonomy*
- Enable discussion on international collaboration and public/private partnerships

Highlights:
Science Breakout Sessions

Highlights of Symposium: Day 2

Science Observations

- Discussions on science scenarios for Moon, Mars, Small Bodies, and Venus and relevance to the priorities of the Decadal Survey
- Low-latency human-robot collaborative work in surface geological exploration of Mars (vs point of departure from MER, MSL)
- On-orbit telerobotic sample recovery and return to the crewed orbiting facility for immediate analysis by resident astronauts (e.g. may enable rapid analysis of volatile bearing samples without requiring long-term cryogenic storage)
- Areas that precludes human access can particularly be explored via telepresence
- Keeping humans away from sites where extant life may exist could be a compelling rationale given Planetary Protection

Science Group Discussions - 1

- **Field science is immersive and is well-established here on Earth:**
  - *Limited practice of robotic telepresence in Earth context (at least in field geosciences) represents a lack of practical experience*

- **Examples of problems where low-latency telepresence *may* be enabling can be described further and assessed:**
  - *Volatiles on the Moon (and their access, encapsulation)*
  - *Lunar farside astrophysical observatory (microwave?), and surface geophysical/interior network*
  - *Mars surface biogeochemical sampling (and related issues)*

- **New science can be enabled via telepresence at places that are:**
  - *Distant (e.g., Mars)*
  - *Hostile to human presence (25 K lunar polar regions, surface of Venus, surface of Titan, surface of Mercury, etc.)*

Science Group Discussions – 2

- **Need to consider *Science Readiness Level* (SRL) together with TRL in telepresence discussions [*Define SRL: low SRL vs high SRL?*]**
  - *To what degree scientists can fully exploit a capability to achieve science goals*
  - *e.g., MER rovers: would have been more efficient to do the science if higher SRL in addition to other capabilities (e.g., power), although SRL improved over time*
- Huge scientific benefit for rapid *in situ* sample analysis and reduced environmental exposure: reduce time lag between analysis and encapsulation (and Earth return)
- If motivated to send humans to surfaces then large number of collateral benefits to science via telepresence in advance of astronauts
- **Where does telepresence make a difference?**
  - *When humans are there, augmented reality on surface before the people are on the surface (i.e., humans explore virtually before literally)*

Science Group Discussions – 3

- **Telepresence involves at least two factors**:
  - *Latency (distance of robot to nearest controlling human)*
  - *Bandwidth (for enhanced sensory information)*
    - *A critical enabling factor (function of distance and assets for communications)*
  - *Nature and quality of the sensors involved*
- **Not clear that low latency telepresence is <u>always</u> optimal in science problems:**
  - *But it can be enabling far beyond current robotic capabilities*
- **Scientists must be engaged in technology development of capabilities** (*i.e., science pull*) –
  - *The more science is involved early the better the tools for science*
  - *Related to field science as immersive process here on Earth (where there is a large experience base)*

Science Group Discussions – 4

- It is important to learn from non-NASA *state of the art* what technologies and capabilities are useful (UAV's and telemedicine, deep sea exploration):
  - *How did they get to high SRL? How does this apply to NASA and space exploration for science?*
  - *What is their equivalent to SRL?*
  - *Not just about technologies… operations management and protocols…*
  - *Implementation scenarios*
- Learn from MER and MSL experience what increased telepresence is germane or useful (or how so) to in planetary field science
  - *Take advantage of lessons learned from high-latency telerobotics (MER, MSL)*
- Hindsight learning from past (*Lunakhod*) is worthwhile, as well as from Earth (oceans, airborne sensing)
- As latency is reduced is there a natural breakpoint where increase complexity of tasks gives increase in potential of science value?
  - *For Moon: if it is seconds, do from Earth; if fractional seconds, do from orbit or EM L1,2*

Science Group Discussions – 5

- **The tasks and goals are poorly known, but likely to be important :**
  - *No traceability yet to NRC Decadal Surveys (e.g., 2011* Visions and Voyages*)*
  - *Need programs of activities of milestones for technology and science*
  - *Understand near term questions*
  - *Need investment strategy*
- **Important trade study**: geologists (two) in field *vs* role of robust "back room"
  - *Communications (large cadre) rely on capabilities of limited numbers*
  - *Understand the social networking issues and advantages*
  - *Robotic assistant with you brings "back room," although not social aspects*
- **Technologies that are needed to enable the science via low-latency telerobotics must be captured in near term**
  - *If people go to planetary surface and without this, then lower science return and greater risk*
  - *Adds value for future human surface exploration: get ready and do better science when people get there…*

Science Group Discussions – 6

- **Participatory Exploration assumes low latency (deeper topic)**
  - *Public engagement and education, citizen scientist program beginning with the Moon*
  - *Commercial activities may grow if public thought they themselves could explore (even if vicariously)*
  - *Protein-folding MPG game as example: gamer figured it out*
  - *Create way for public participate to do own via virtual entity via telepresence*

Notional Examples of Low-Latency Telepresence From Science Breakout Sessions

Small Bodies (SB), Moon, Mars,
Venus, Mercury, Outer Planet Moons

Small Bodies

- **NEO telescopic survey with intervention on the basis of discoveries, although no requirement for low-latency telepresence**
  - *Robotic survey with event detection*
  - *Earth intervention to interrupt/intercept*
  - *Options for deployable "search craft"*
  - *Human on Earth (i.e., high-latency telepresence)*
  - *Humans required to break modes to decide on adaptive redeployment*
- **E-M L1,2 station**
  - *Deploy to discovered NEOs for sampling and return*
  - *Integrates human proximal operations at E-M L1,2 with the robots at nearby NEOs*
  - *Reusable deployable NEO explorer to visit subsequent targets*
  - *Samples cached and analyzed at E-M L1,2*
  - *E-M L1,2 laboratory*

Small Bodies (Continued)

- **NEO collision mitigation test**
  - *Practice diverting a small NEO*
- **Proximal human mission to NEO for low latency operations (safety and science)**
  - *Complexity of operations for knowing we have a sample (and related issues)*
  - *Using on-site human triage to optimize sample mass to Earth (Planetary Protection factors and science optimization)*

Moon

- **Polar sample return (PSR) of ices using low-latency sampling decision making**
  - *Could be part of E-M L2 architecture with crew remaining in space*
  - *Could be human on surface controlling sampling in PSR over the horizon*
  - *Rationale is safety of assets (people or robots)*
  - *Humans could be on Earth if robot is visible in sampling location*
  - *Real-time observation of cryo samples as they react and are contained*
- **Operation of robotic telepresence in areas hazardous to humans**
  - *Mare pits, escarpments, fresh rugged impact craters…*
  - *Critical issue for South Pole Aitken (SPA) Basin – rugged terrain to maintain robotic (rover) as resource and to sample most interesting materials*
- **Low-latency telerobotics will open up all SPA Basin for better sampling**
  - *Improved access to better samples in rugged exposures*
  - ***Question**: reducing latency to tolerate a less-capable or expendable robot? Multiple robots?*

Moon (Continued)

- **Low-latency telepresence for real-time entry, descent, & landing (EDL)**
  - *In-the-loop control to guide EDL for ultra-precision landing to minimize surface mobility requirements*
- **Robotic assistants with Earth control working with crew on lunar surface**
  - *Robotic scout concept*
  - *Crew could also be controlling at E-M L2*
  - *Parallels between Moon and Mars operations, depending on operator position (greater value of low latency)*
- **Farside (RF ultra-quiet) observatories including robotic construction**
  - *Value of E-M L2 over Earth for farside implementation: latency and bandwidth*
  - *E-M L2 may be data richer*
  - *Opportunities for piggyback experiments (e.g., GRB detection)*
- **Lunar Geophysical Network (LGN)**
  - *10 km arrays laid out to study the interior (i.e., seismic studies)*
  - *Issue: orbiting autonomous relay or human telepresence from E-M L2*

Mars: Notional Surface Mission

- **<u>Notional Mission</u>: One or two rovers on surface with visual tools to allow low-latency comm and operation from on-orbit crew, and also**
  - *limited set of instruments on rovers for in situ reconnaissance*
  - *Capabilities to send selected samples to on-orbit human habitat for analysis: recon for sample context and selection:* ***SOE***
  - *Two rovers are "productivity amplifier:" repair each other*
  - *If perchlorates are abundant could be resource for human crew in orbit via surface-based ISRU*
  - *Probably work in tandem on project (cooperative)*
  - *Two entities working on science with low-latency control*
  - *On-orbit habitat laboratory: engineers and scientists critical*
  - *Possible value of extracting constituent for resources (storage and experimentation)*

Mars: Candidate Venues

- **Special (surface) region exploration requires higher-fidelity science activities, but precludes human access (at least now)**:
  - *Require low-latency robotics to address*
  - *Need Category V Planetary Protection isolation facility spacecraft?*
  - *Disposable robots (sterilized)?*

- ***Phobos and Deimos:*** **Human on-orbit lab could benefit analysis of Phobos and Deimos samples, if they are a science requirement**
  - *Is this different from humans nearby at any NEO? Probably not!*

- ***Sun-Mars L_n orbits*****: teleoperate robots on Mars from 1.5 x 10^6 km for low-latency telepresence**:
  - *Needs capability assessment*
  - *Mars Example: Polar regions (SRs) for low-latency telerobotics with crew on orbit or in libration points (Mars-Sun L_n)*

Moon & Mars: Common Issues

- ***Cliffbots*** on rugged, inclined surfaces for Moon and Mars… and other bodies requiring local telepresence for access: up and down in gravity wells and in hard-to-get-to places
- Public impatience and appetite in latency: participatory exploration (commercial?)
- Extensibility: do on the Moon to learn for Mars
  - *Learn lessons for what is enabling for the Moon and then apply to Mars as appropriate*

Other Targets: Venus and Outer Solar System

- Short surface lifetime required for Venus due to environmental constraints: 450 C at 95 atm and a CO_2 atmosphere
- Local decision making must be rapid and responsive to discoveries
- Network of multiple telerobotics with local communication among them and with crew on orbit (aka, a "swarm"):
  - *Large robot can communicate with small ones*
  - *Low latency between robotics, but not have to be between them and crew???*
  - *Expendable robots to do recon and then deploy larger systems down to get most science return in shortest possible time*

- There are other targets where low-latency robotic exploration for science makes sense, including Mercury and Titan (Enceladus?)
  - *More work needed to flesh out the specific benefits*

Highlights:
Technology Breakout Sessions

Highlights of Symposium: Day 2

TECHNOLOGY Observations

- A few areas that need development and testing with proximity in mind (*cf,* NASA OCT Robotics, Telerobotics & Autonomy Roadmap (TA04)):
  - **Sensing and Perception**
  - **Mobility**
  - **Manipulation**
  - **Human-System Integration**
  - **Autonomy**

- Sample return technologies: e.g. canister rendezvous, acquisition and return to the orbiting station needs to be demonstrated.

- High-fidelity analog missions with **authentic science** to test a range of **operational concepts** and **telerobot control modes**

Technology Group Discussions

- **Proximity Telerobotics**
  - If you put humans and robots in "proximity", what does that enable (in terms of supporting surface science)?
- **Sample Return**
  - Sample return to orbiting human station for analysis or preparation to send back to Earth

Proximity enables …

- **Lower-comm latency**
  - *Bilateral force-reflection (due to low latency)*
  - *Force/haptic user interfaces*
- **High-comm bandwidth**
  - *Collect more data (more Gb logged)*
  - *More sensor data (downlink **all** of the data we want to get from MER)*
  - *Use new sensors (that have very high data volumes: MSL MastCAM)*
- **Better-comm quality of service**
  - *Less jitter, more link availability, less loss of signal*
  - *Can operate continuously (commanding and/or monitoring) unlike Earth-based ops*
- **Collect more (and better?) samples**
  - *Bring more/better kgs of samples to humans (on-orbit triage)*
  - *Transfer more/better electronic data (due to higher bandwidth)*
  - *Q: how much of this will you be able to bring back to Earth?*

Proximity enables . . .(continued)

- **“Flexicution”**
  - *Enabled by lower-latency, high-bandwidth telecomm.*
  - *Real-time "data collection" decision making*
    - *Retargeting/fine-tuning of passive sensors data (imagers, etc.)*
    - *Down-selection of samples to collect*
  - *Continuous & flexible operations*
    - *Instead of (or supplement to) planned command sequence cycle*
  - *Address serendipitious discoveries*
    - *Re-task to target dynamic phenomena (Mars dust devils)*
    - *Interrupt plan to focus on something unexpected (Apollo 17 Shorty Crater)*
- **Additional options for failure recovery**
  - *Human-in-the-loop for contingency handling (getting unstuck)*
  - *Diagnosing what went wrong*

On the other hand…

- **Small science team in proximity**
  - *Oceanography research cruise can have large science team on-board & off-board, but in space may only have **1-2 scientist astronauts***
- **Does not increase speed of overall science**
  - *Speeding up data collection likely will not speed up the rest of the scientific process*
  - *Still need to do (re)planning, analysis, interpretation*
  - *A two-week research cruise will often collect data that takes more than a year to process and analyze (to first order)*
- **Cannot operate indefinitely**
  - *Cannot ask astronauts to "just stay in orbit for another year…" (nominal Mars mission may only last 30-60 days)*
  - *Finite consumables, fixed return windows*
  - *Will not be able to run an extended, multi-year mission (e.g., MER) with humans in orbit that is able to take advantage of long-duration interpretation for (re)planning*

Technology Gaps

- A few areas that need development and testing…
  with proximity in mind
- NASA Robotics, Telerobotics & Autonomy Roadmap (TA04)
  - 4.1 Sensing and Perception
  - 4.2 Mobility
  - 4.3 Manipulation
  - 4.4 Human-Systems Integration
  - 4.5 Autonomy

Discussed in following sections . . .

Technology Observations - 1

- **Sensing and Perception**
  - *High-data volume sensors might provide nearby operators with better situation awareness (SA) and better information for real-time decision making (for robot operations or science observations)*
  - *Tactile sensing (and display) does not require low-latency or high bandwidth*
- **Mobility**
  - *Human-equivalent mobility (speed, agility, etc.) would help robots to be moved around in real-time "like a field scientist"*
  - *Super-human mobility (e.g., flying) would allow robots to be used to provide real-time access to different perspectives, scales, etc.*
- **Manipulation**
  - *Bilateral force-reflection would enable humans to feel (force, torque, tactile) objects in the remote environment (this requires very low latency, if not high-bandwidth)*
  - *Grasp planning in unstructured environments highly benefits from direct teleoperation (in terms of execution time)*

Technology Observations - 2

- **Human-Systems Integration**
  - *A system that supports multiple modes of control could be operated by humans in proximity (when they are in orbit) and by human teams on Earth (like MER)... after humans leave orbit*
    - *Proximity: direct rate control*
    - *Proximity: safeguarded teleop (shared autonomy)*
    - *Both: command sequencing*
  - *Real-time situation awareness would help improve robot safety*
- **Autonomy**
  - *Higher performance computing would enable better robot performance at all levels*
  - *Low-level safeguarding is autonomy too!*
  - *Vision processing for collision avoidance at "high-speeds" requires a good CPU*

Technology Observations - 3

- **What can you put in proximity (e.g., a human orbital habitat) so that you do not have to put it on the robot?**
  - *"SneakerNet in the sky" (data cache to return to Earth)*
  - *On-orbit power (beamed to robot)*
  - *Non rad-hard supercomputer in orbit (simple robot CPU)*
- **Terrestrial telerobotic science operations can provide best practices for operations (organizational structure, flow of control, decision making processs) that might be relevant**
  - *The field science must be real (not simulated)*
  - *ROV used for science on an oceanographic research cruise*
- **High-fidelity analog missions with authetic science that test a range of operational concepts and telerobot control modes would provide insight into the efficacy of these concepts and modes**
  - *Test different robot sensors and communication parameters*
  - *Test different human-robot team configurations*
  - *Test different operational tempo*

Sample Return to Orbiting Human Lab

- Assume mission is humans in cis-Mars space.
- It may be that making faster strategic decisions is "worth it“.
- Short-stay human missions (30-60 days at Mars) may be “worth it”.
- Force-multiplier of many robots taking samples all the time, with decision-making up on orbit. Local humans take over when something interesting or bad happens.
- Flying (e.g. through Vallis Marinaris, or looking for local methane sources) may require real-time control.
- Fast generation and validation of command sequences would be required – military does this routinely.
- Keeping humans away from sites where extant life (modern habitats) may exist could be a compelling rationale.
- Sample canister rendezvous, acquisition and return to the orbiting station needs to be demonstrated.

Observations for a Mars sample return to a crewed orbiting laboratory -1

- If a human mission to Mars orbit were decided for national reasons, it would be an unfortunate mistake not to include low-latency control of robots on the surface.
- Most of the telerobotic technology exists for this mission, although its TRL needs to be advanced and validated for flight.
- Technology needed will be highly dependent on the nature of the mission and its timeline.
- On-orbit laboratory facilities, in terms of sample preparation and instruments, will be drivers.
- The ability for the on-orbit crew to control multiple robotic assets on the surface is imperative, or to take over control of one of them from Earth operators when interesting or time-critical situations arise.
- Power and communications bandwidth are major drivers. Public outreach is a major driver for even-larger bandwidth.
- Taking a sample of biological significance may require very rapid encapsulation of the sample which benefits from low-latency teleoperation.

Observations for a Mars sample return to a crewed orbiting laboratory - 2

- It would be an unfortunate mistake not to perform a cis-lunar demonstration of this technology as a pre-requisite to a similar Mars mission. This may also return samples of South Pole Aitken Basin and permanently shadowed regions that may not be otherwise acquired.
- A terrestrial demonstration of this technology would be an essential pre-requisite to any similar cis-lunar mission. These analog missions would drive-out the value and need for immersive displays, real-time re-projection from arbitrary vantage-points, and help define telepresence requirements, and to drive-out the operational protocols required.
- Fast generation and validation of command sequences would be a change to existing NASA process flow.
- Geospatial posititioning infrastructure is highly enhancing.

Closing General Observations

- We do not understand some of these missions well enough to know that low-latency teleoperation is required: biology missions, permanently-shadowed regions on Moon, etc.

- Crew time is a scarce resource and telerobotics can be used to perform habitat maintenance; a method must be found to free-up enough crew-time to do the primary mission. Robonaut-2 can help prove this technology at ISS.

- Many aspects of these alternative missions seem unbounded. Many parameters are poorly constrained by our uncertain state of knowledge.

Highlights:
Human Space Flight Breakout Sessions

Telepresence and Human Exploration Findings

Synergistic science and human exploration activities via low-latency telerobotics:

- **Science operations on Mars** controlled from orbit or Lagrange point, or on the surface
- **Assembly operations of large structures** from orbit or Lagrange point

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Specific Findings

Extending human capabilities and insight through telepresence will be a significant capability of future human activity in space.

In particular, the mission scenarios that will be enhanced include:

- Science operations on the Moon or Mars controlled from orbit, Lagrange points, or on the surface
- Robots controlled from Earth (e.g., satellite servicing in GEO from Earth's surface)
- Assembly operations of large structures from Lagrange point (e.g., large telescopes of the 2020s and beyond)
- NEO/Mars orbit proximity operations
- Service operations on board ISS or other spacecraft controlled by crew

Next Steps

- What are the key questions about low-latency telepresence that must be answered? [Consistent with NRC Decadal Surveys]
  - *Prepare consensus set of top-level findings and observations*
  - *Iterate initial ideas to secure best results*
- Identify science examples requiring further study from scientific expertise present (and then reach out to special communities: "AG"s)
  - *To determine value, use a decision matrix with cost/benefit for the science in addition to that identified in this symposium*
- Periodic face-to-face workshops, conferences
  - *Occasional virtual workshops, using NLSI approach*
  - *Topic- and destination-specific*
  - *Engage full group in continuing discussions of science enabled by different types of telepresence (LLT, SLT, HLT)*
  - *Room for inputs from attendees to impact development of white paper (and beyond)*
- Field human-robotic interactions for science with multiple latencies (multi-scale observations) at analogue sites and small mission test-beds, including ISS
  - *Includes evaluations of operations, control systems, displays, etc.*

Next Steps (continued)

- Virtual environment simulators for telepresence training in space and assessment of priority capabilities
- Trade studies with the simulations to assess the value of telepresence
  - all scale sizes of investigation and operation: very small (micro-operations) to very large (assembly of large, complex optical systems; flying in Mars canyons).
- Investments in key robotics technologies
  - *sensing, perception, mobility, manipulation, human systems integration, autonomy*
- Foster international collaboration and public/private partnership.
  - *interoperability standards need to be defined and agreed upon*