OPINION

Telepresence is a potentially transformative tool for field science

Jeffrey Marlow[a,1], Chiara Borrelli[b], Sean P. Jungbluth[c,2], Colleen Hoffman[d], Jennifer Marlow[e], Peter R. Girguis[a], and the AT-36 Team[3]

Field expeditions have long played a critical role in advancing our understanding of the natural world. From the voyage of the *Beagle* to the HMS *Challenger* Expedition and the Apollo Moon landings, researchers have visited remote locations to collect samples and in situ data before returning to the laboratory for further analyses.

Although this approach has been a hallmark of science for centuries, field expeditions can be logistically, technically, and financially challenging. As a result, field science is inherently constrained, placing practical limits on the instrumentation and personnel involved, particularly in cases where site access requires specialized vehicles and equipment. Easing these constraints—while maintaining a human presence in the field to make real-time decisions and enact experimental procedures and repairs—would dramatically enhance the quantity and quality of data derived from field-based science. In recent years, telepresence technology has created such an opportunity to fundamentally change the way we study natural systems. Its broader adoption could have a dramatic effect on science research and data collection in multiple arenas.

A Promising Platform

Telepresence is the practice of using telecommunications technology to simulate physical presence at a site other than one's true location (1). It has seen a wide range of applications, including efforts to improve access to healthcare through telemedicine (2), equip remote field technicians (3), and enable incapacitated children to "attend" school (4). In the context of expeditionary science, virtual field laboratories have been proposed to streamline geological studies and field trips (5) and to allow deep-sea student research to be conducted from home institutions (6).

These compelling opportunities come with caveats and challenges, which we explore here through the lens of ocean-based research expeditions. Modern civilization is more dependent upon the oceans' ecosystem services than ever before (7, 8); given the rapid changes affecting marine systems—from constricted animal habitat ranges (9) to shifting currents and nutrient distributions (10)—enhancing the quality, scope, rate, and reach of ocean exploration and research is imperative.

Fig. 1. By allowing scientists in remote locations to engage with a network of experts in real time, telepresence could have a transformative effect on field science. Here, scientists at the University of Rhode Island's Inner Space Center use a telepresence link to discuss deep-sea sampling plans with scientists aboard the Research Vessel *Atlantis*. Image courtesy of Alex DeCiccio (Inner Space Center, University of Rhode Island, Kingston, RI).

Telepresence is uniquely suited to address several recent developments in sea-going science, including a diminishing fleet that accommodates fewer scientists (11), larger datasets that require substantial processing and analytical resources, and more exhaustive and affordable Internet bandwidth over even the most remote portions of our planet (12). For sea-going expeditions,

[a]Department of Organismic & Evolutionary Biology, Harvard University, Cambridge, MA 02138; [b]Department of Earth & Environmental Sciences, University of Rochester, Rochester, NY 14627; [c]Center for Dark Energy Biosphere Investigations, University of Southern California, Los Angeles, CA 90007; [d]Department of Earth Sciences, University of Minnesota, Twin Cities, Minneapolis, MN 55455; and [e]FX Palo Alto Laboratory, Inc., Palo Alto, CA 94304

The authors declare no conflict of interest.

Any opinions, findings, conclusions, or recommendations expressed in this work are those of the authors and have not been endorsed by the National Academy of Sciences.

[1]To whom correspondence should be addressed. Email: marlow@fas.harvard.edu.

[2]Present Address: Department of Energy, Joint Genome Institute, Walnut Creek, CA 94598.

[3]The Early Career Scientist & Telepresence Training Cruise AT-36 consisted of Chief Scientists Anne Dekas and Adam Skarke; Mentors Donna Blackman, Dan Fornari, Adam Soule, and Cindy Van Dover; and Scientists Laura Bagge, Roman Barco, Chiara Borrelli, Bridgit Boulahanais, Kaitlin Bowman, Mercer Brugler, Stephanie Bush, Anni Djurhuus, Julianne Fernandez, Robinson Fulweiler, Colleen Hoffman, Sean Jungbluth, Joanna Kinsey, Kevin Kocot, Jeffrey Marlow, Doreen McVeigh, Michael Navarro, Amanda Netburn, Alexis Pasulka, Katrina Twing, Amy Wagner, and Joe Zambon.

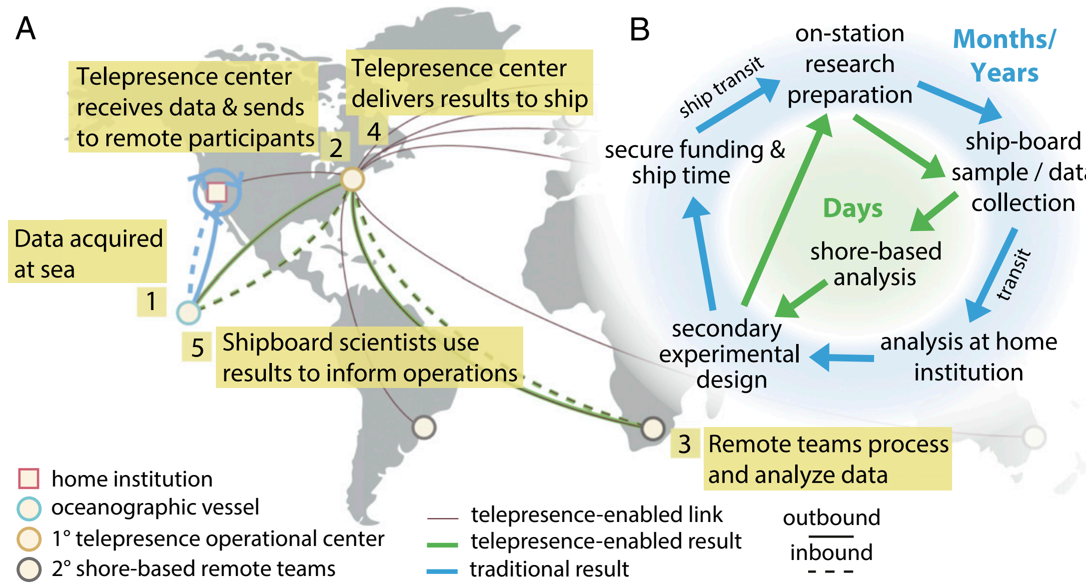

Fig. 2. In one example of a telepresence approach, high-bandwidth capabilities used at sea (*A*) enable communication with shore-based technical and scientific teams. Rapidly acquired and analyzed data allow oceanographic vessels to remain on-station and adapt operational plans. (*B*) The on-demand on-shoring of data processing and analysis allows the experimental cycle to accelerate from the scale of months-to-years (outer ring of arrows) to days-to-weeks (inner green arrows).

telepresence incorporates broadband data transmission—both shore-to-ship uplink and ship-to-shore downlink—to facilitate a range of virtual interactions, including video broadcasts, more rapid data transfers, and active engagement with students and the public.

Although telepresence has recently become a central feature of how exploration vessels, such as the National Oceanic and Atmospheric Administration's *Okeanos Explorer* and the Ocean Exploration Trust's *Nautilus* operate, more traditional research expeditions—the hypothesis-driven efforts that carry out the vast majority of sea-going work—represent a fundamentally distinct application of telepresence technology. To date, a handful of pilot projects aboard research vessels have exposed operational and cultural challenges, but have also hinted at the potential for telepresence to enable more efficient, fundamentally new, and more inclusive work.

Expanding Opportunities

Field expeditions are notoriously constrained operations, as logistical and financial pressures cap the number of participating scientists. The range of expertise encompassed by on-site participants is thus inherently limited, resulting in missed opportunities as erroneous observations may go uncorrected, deployment plans may be unoptimized, and serendipitous events can go unexplored.

At sea, many expeditions host several different research groups to maximize opportunities for scientists from different disciplines, a factor that further restricts the number of operationally active participants. These limitations can be eased through telepresence by involving shore-based experts, who provide experience and talent to complement shipboard operations. Shore-based scientists can contribute real-time input on sampling or observations, and can access additional resources (e.g., maps, publications, or reference samples) that may not be readily available at sea. Relevant participants could be notified in advance based on dive expectations, and "on call" lists could be curated to engage domain-specific experts when unanticipated features arise.

While conducting field work, scientists are time- and resource-limited, factors that could leave valuable samples uncollected or unattended and may impede adaptive, data-informed procedural changes that could benefit field operations.

On research vessels, these obstacles can be alleviated using shore-based servers and personnel, offering a particularly exciting opportunity to "on-shore" the processing and analysis of extensive or time-consuming datasets (Figs. 1 and 2*A*). Today's paradigm of sea-going science often involves a multiyear experimental cycle, a process that first arrives at a scientific finding through data collection and analysis and then designs and enacts secondary experimental efforts accordingly. The pace of this process is limited by the turnaround between research expeditions, which involves the time-consuming pursuit of funding and ship time. With efficient data processing accelerated by on-shore involvement, multiple experimental cycles could occur during a single expedition, cutting the time required for results-informed sampling from years to days (Fig. 2*B*). Particular use cases could include rendering of large sonar datasets to identify new midwater and seafloor features, high-throughput image analysis of pelagic and benthic organisms, and enhanced shipboard molecular biological analyses, such as genetic sequencing paired with shore-based genome reconstruction.

Telepresence also offers expanded opportunities for impactful education and public outreach. Field science frequently takes place in locations of aesthetic or cultural interest; such sites are often highly engaging and represent ideal opportunities for researchers to capitalize on public interest. However, the absence of infrastructure and competing priorities often curtail these activities or compromise scientific objectives.

Enabling students and the general public to participate in live oceanographic exploration is a current strength of telepresence efforts. At the broadest level, *Nautilus*' 2016 activities were featured in more than 6,500 news reports reaching a cumulative 400 million people, and public viewership of live feeds from the remotely operated vehicles surpassed 2.7 million (13). *Nautilus* operations include dedicated outreach personnel, who conduct several live broadcasts per day to school groups and museums.

At the most-targeted level, telepresence has been used as a collaborative tool for undergraduate students to conduct individual research projects (6). The most substantial educational gains occurred when students directed exploration and sample collection efforts from shore, and motivation decayed rapidly when data provisioning was delayed (14). These existing programs have been optimized for relatively flexible exploratory expeditions; managing the balance between outreach and science goals in the context of sea-going research expeditions will present new challenges. Given the range of potentially competing considerations, we recommend that shipboard personnel plan priorities and workloads well in advance, so that education, outreach, and research can productively coexist.

Such outreach efforts represent the leading edge of a larger impact from telepresence efforts: democratized science. Scientific access to remote environments is typically limited to a small group of researchers from a handful of developed countries. Access is further narrowed in extreme locations, such as space or the deep sea, as only a few nations have sufficient research funding and the technical expertise to operate the appropriate assets. Telepresence offers a compelling opportunity to increase the diversity of participating scientists by removing physical, cultural, or financial impediments; with more participants from distinct backgrounds involved, the quality of scientific research benefits (15).

Many developing nations with coastlines and marine "exclusive economic zones" do not have reliable scientific access to their territorial waters; this lack of agency in collecting primary data to drive management decisions effectively disenfranchises them from the process. Improved real-time access to the deep sea will allow developing countries to conduct experiments and make more informed decisions regarding resource exploitation (e.g., intensive fishing or seafloor mining) in their territorial waters. Enabling decision makers and other stakeholders to direct exploration and research activities from shore will likely bolster emotional and financial investment in research and preservation activities. We encourage funding agencies, commercial partners, and science parties to establish telepresence links and dedicate live participation time for under-resourced countries, prioritizing nations with cultural or economic interests in the study site.

The transformative benefits of live video, rapid data communication, and distributed manipulative control of deployed instrumentation have likely not yet been fully envisaged. As with any novel capability, empirical practices are underdeveloped, and telepresence will likely open doors to new types of research that are not possible even with time- and expertise-replete research expeditions. Scientists who may benefit from these tools should think creatively about what types of questions are newly addressable through multilocation, real-time manipulative control, and remote access to substantial computational power.

Challenges of a Changing Paradigm

Telepresence is poised to disrupt several aspects of current research culture across disciplinary boundaries. In the context of sea-going expeditions, shore- and ship-based participants, as well as vessel and vehicle operators, will need to reconsider important technical and social dimensions of remote collaborative work.

Optimizing telepresence will require flexible technological infrastructure, consensus building among the science party, and rational decisions about what requires live interaction or which transferrable products may be actionable during the field deployment. To manage these priorities and ensure smooth transitions between data streams, we encourage researchers to develop comprehensive data-transmission action plans to guide daily bandwidth use, and to retain telepresence-dedicated technical staff on both ends of a field expedition.

Given the varied capabilities of telepresence-enabled cruises—dataset transfer for onshore analysis, one-way video for public outreach, two-way video for scientific discussions, and so forth—data transmission between ship and shore will be in constant flux based on shifting priorities. Procedural lessons can be learned from operations such as NASA's Mars rover planning process, in which time and data constraints have been integrated into the design of customized software to streamline uplink and downlink priorities (16).

The challenges of remote participation for distributed teams are well characterized across a number of different work environments, including engineering, product design, and media production. When interpersonal interactions are distilled into visual or audio representations, "media richness" is lost; as a result, participation from remote individuals is reduced (17), trust and cooperation can be lower than in face-to-face situations (18), and riskier decisions may be made (19).

During fast-paced and high-stakes oceanographic research expeditions, additional challenges arise, as shore- and ship-based team members experience widely different levels of stress and physical comfort. Time-delayed or intermittent communications can quickly diminish rapport, as scientists ashore often feel they are being ignored, and scientists and crew members on site believe that incoming requests are not suited to real-time operational demands. Clarifying the factors that constitute collaboration or data ownership for shore-based team members will require preemptive discussion and involvement at the point of proposal writing and expedition scoping. To ensure the productive use of telepresence, users should appreciate the importance of team dynamics. Training, for example, on the procedures and etiquette of remote communication is an important component of predeployment activities.

Implicit Biases, Explored

Remote participation through telepresence represents a remarkable opportunity to expand the reach of field science, but it may alter its tenor in unanticipated ways. Studies of construal level theory (20) and "psychological distance" show that as one's distance from a study subject increases (as measured in time, space, egocentricity, or hypothetical situations), one's intellectual treatment of the subject becomes more abstract (21).

In the context of oceanographic science, for example, a scientist overseeing sampling efforts at deep hydrothermal vents from the comfort of her office may subconsciously prioritize "bigger-picture" contextual questions over detailed investigations of relationships occurring over short temporal or spatial scales. Understanding how these ingrained biases influence remote field research is an important priority that requires dedicated study and explicit attention during telepresence-enabled expeditions.

Telepresence technology can help realize a field expedition's full scientific potential through expanded involvement of scientific experts and the public alike. Rapid two-way data transfer is poised to dramatically change the quality, rate, and reach of field research; limitations of time, space, and data processing can be minimized, and a broader group of scientists, policymakers, educators, and the global public can be involved. Challenges associated with bandwidth priorities, cultural "rules of the road," and distance-based biases appear to be broadly manageable, but should be recognized and addressed as telepresence infrastructure is developed and research teams prepare for distributed operations.

Telepresence is a potentially transformative tool, and now is a critical time to think deeply about its relevance to field science. "Early adopters" of any new technology play a formative role in shaping broader community use, and it is important to initiate a discussion of best telepresence practices among a diverse community of scientists, technologists, psychologists, education experts, and policymakers. Doing so effectively will aid scientists in tackling the technical challenges, immense scope, and pressing urgency of field research, while accelerating the pace of discovery in the rapidly changing natural world.

Acknowledgments

We thank the captain and crew of the *R/V Atlantis*; Woods Hole Oceanographic Institution's Shipboard Scientific Services Group; Dwight Coleman and the technical staff at the University of Rhode Island's Inner Space Center; the *HOV Alvin* and *AUV Sentry* Teams; Robert Ballard and Ken Feldman for helping to facilitate cruise AT-36; Allison Fundis and Michelle Jungbluth for thoughtful discussions on earlier versions of the manuscript; and National Science Foundation program officers Rose DuFour, Brian Midson, Jim Holik, and the University National Oceanographic Laboratory System Deep Submergence Science Committee for their help in the planning, implementation, and funding of the early-career training cruise from which this manuscript resulted. Funding was provided by National Science Foundation Grant OCE-1641453 (to C.V.D.).

1. Minsky M (1980) Telepresence. *Omni* 45–51.
2. Berman M, Fenaughty A (2005) Technology and managed care: Patient benefits of telemedicine in a rural health care network. *Health Econ* 14(6):559–573.
3. Paul SA, Bolinger JW (2015) Ask an expert: Mobile workspaces for collaborative troubleshooting. *Proceedings of the 48th Hawaii International Conference on System Sciences* (IEEE, New York), pp 442–451.
4. Newhart VA, Warschauer M, Sender LS (2016) Virtual inclusion via telepresence robots in the classroom: An exploratory case study. *International Journal of Technology in Learning* 23(4):9–25.
5. Ramasundaram V, Grunwald S, Mangeot A, Comerford NB, Bliss CM (2005) Development of an environmental virtual field laboratory. *Comput Educ* 45(1):21–34.
6. Van Dover CL, German CR, Yoerger DR, Kaiser CL, Brothers L (2012) Telepresence field research experience for undergraduate and graduate students: An *R/V Okeanos Explorer/AUV Sentry* success story. *American Geophysical Union Fall Meeting Abstracts* 1:1909.
7. Cardinale BJ, et al. (2012) Biodiversity loss and its impact on humanity. *Nature* 486(7401):59–67.
8. Worm B, et al. (2006) Impacts of biodiversity loss on ocean ecosystem services. *Science* 314(5800):787–790.
9. Poloczanska ES, et al. (2013) Global imprint of climate change on marine life. *Nat Clim Chang* 3(10):919–925.
10. Doney SC, et al. (2012) Climate change impacts on marine ecosystems. *Marine Sci* 4:11–37.
11. Kintisch E (2013) A sea change for U.S. oceanography. *Science* 339(6124):1138–1143.
12. Foley S, Meyer J, Orcutt J, Berger J (2014) Upgrading the HiSeasNet ship-to-shore satellite network. *American Geophysical Union Fall Meeting Abstracts* 1:3714.
13. Fundis A, et al. (2017) Nautilus education and outreach programs. *Oceanography* 30(1):18–23.
14. Stephens AL, Pallant A, McIntyre C (2016) Telepresence-enabled remote fieldwork: Undergraduate research in the deep sea. *International Journal of Science Education* 38(13):2096–2113.
15. Hong L, Page SE (2004) Groups of diverse problem solvers can outperform groups of high-ability problem solvers. *Proc Natl Acad Sci USA* 101(46):16385–16389.
16. Norris JS, Powell MW, Vona MA, Backes PG, Wick JV (2005) Mars exploration rover operations with the science activity planner. *Proceedings of the 2005 IEEE International Conference on Robotics and Automation* (IEEE, New York), pp 4618–4623.
17. Biehl JT, Avrahami D, Dunnigan A (2015) Not really there: Understanding embodied communication affordances in team perception and participation. *Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work and Social Computing* (ACM, New York), pp 1567–1575.
18. Rockmann KW, Northcraft GB (2008) To be or not to be trusted: The influence of media richness on defection and deception. *Organ Behav Hum Decis Process* 107(2):106–122.
19. Lee MK, Fruchter N, Dabbish L (2015) Making decisions from a distance: The impact of technological mediation on riskiness and dehumanization. *Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work and Social Computing* (ACM, New York), pp 1576–1589.
20. Liberman N, Trope Y (1998) The role of feasibility and desirability considerations in near and distant future decisions: A test of temporal construal theory. *J Pers Soc Psychol* 75(1):5–18.
21. Trope Y, Liberman N (2010) Construal-level theory of psychological distance. *Psychol Rev* 117(2):440–463.