Antarctic Undersea Exploration Using a Robotic Submarine with a Telepresence User Interface

Carol R. Stoker, Donald R. Barch, and Butler P. Hine III, NASA Ames Research Center
James Barry, Monterey Bay Aquarium Research Institute

THIS FIELD EXPERIMENT USED A TELEPRESENCE-CONTROLLED, REMOTELY OPERATED UNDERWATER VEHICLE TO STUDY SEA FLOOR ECOLOGY IN ANTARCTICA. IN USING ENVIRONMENTAL DATA TO CREATE THE VIRTUAL REALITY MODEL IN NEAR REAL TIME, THIS EXPERIMENT REPRESENTS THE FIRST COMBINED USE OF TELEPRESENCE AND VIRTUAL REALITY FOR SCIENTIFIC PURPOSES.

THE OPERATION OF REMOTE SCIentific exploration vehicles benefits greatly from the application of advanced telepresence and virtual reality operator interfaces. *Telepresence* and *virtual reality* provide a very high-fidelity control interface and an enhanced understanding of the remote environment being explored, as well as a heightened sense of presence in the remote environment.[1–3]

Telepresence projects human senses into a remote location. In remote vision, for example, a human operator uses a head-mounted display to view images from a remote vehicle's cameras. This gives the operator a strong sense of presence in the remote environment. To further enhance this sensation, the operator's head motions can control the position of the remote cameras so that vision corresponds spatially with head position. For scientific applications, telepresence provides scientists with a much greater intuitive understanding of the environment under study than do simple camera display systems.

Virtual reality uses highly interactive three-dimensional computer graphics to give a user a sense of presence in a model environment. For scientific applications, the virtual reality model is based on imaging data or other information from the remote environment. In operating a remote robotic vehicle, virtual reality models both enhance an operator's situational awareness of an environment and compensate (to some degree) for low bandwidth or long time delays in the communications channel between the operator and the vehicle.[1,4] These advanced operator interfaces are important for science and exploration applications, and are critical for exploring hostile and extreme environments involving very dangerous or very difficult access. Examples of such environments important for scientific study abound on Earth, particularly in undersea research. The exploration of other planetary surfaces probably will hinge on the applications of such technologies (see the box).[5–7]

Immersion in the study environment

Our project's key objective is to provide field scientists with powerful tools for observation and, later, for data analysis, so that restrictive equipment interfaces will not inhibit the observational abilities of a trained field scientist. Ultimately, our goal is to allow scientists to feel as if they are immersed in the study environment. The use of high-resolution color stereo cameras, mounted on a pan-and-tilt platform controlled by the operator's head motions via a head tracker, provides this feeling.

Telepresent operation of a remote vehicle

0885-9000/95/$4.00 © 1995 IEEE

requires real-time control accompanied by live video. However, for some applications, particularly the exploration of planets other than Earth, real-time control is not possible. In this case, virtual reality can provide a high-fidelity interface and an enhanced sense of presence in the remote environment. A user will simply interact with a model environment generated from the data, and the model will be upgraded continuously as better information is received.[6,7] Thus, telepresence and virtual reality provide synergistic capabilities for collecting and analyzing data.

Using telepresence and virtual reality to control remote vehicles for exploration also allows for ready distribution and sharing of the exploration experience. Telepresence allows real-time sharing of the immediate experience, but synthesis of virtual environmental models using real data allows other scientists, educators, students, and the interested public to access the recorded experience. Again, the strong sense of presence and intuitive understanding of such environments afforded by using virtual reality strongly enhance this recorded experience.[1]

Given the extreme cost and limited access afforded by more conventional means, exploration of underwater environments is a very useful application of telepresence and virtual reality as exploration and data-analysis technologies. Scientific exploration of marine environments has traditionally involved scuba diving and submarines. However, depth and time limitations imposed by human physiological constraints limit scuba diving. Submarines are capable of deeper water exploration, but are very expensive to operate and often have relatively limited mobility for either close-up observations or sample collection.

More recently, remotely operated vehicles have come into play, offering many advantages over both submarine and diver operations. An ROV can be quite small and can operate with great dexterity for close-up inspection and sample collection. It can deploy to great depths, remaining underwater indefinitely. Despite the many advantages ROVs offer for exploration, however, the scientific community has been relatively slow to embrace their use: many researchers feel that they are cumbersome to operate and that the techniques for data visualization and analysis impede the observational powers of the field scientist. One difficulty is in maintaining spatial orientation underwater where turbidity and the poor penetration of light limit visibility. The field of view for underwater cameras typically spans no more than a few meters and often less. Telepresence and virtual reality offer a quantum-level improvement in the ease of operation of ROVs and the ability to understand environments studied using them.

Fly me to the moon

Exploration of other planetary surfaces by surface rovers is another application of telepresence technology. This technology will provide much greater ease of operation and data interpretation from planetary surface rovers. Telepresent operation has the potential for expanding the range of surface rovers, and vastly decreasing the cost of mission operations for planetary surface missions. This may well prove enabling for future planetary surface exploration as well as having an application for operating in dangerous or hostile environments on Earth.

Recently, NASA Ames has used the remote control system developed for the Antarctic TROV mission to control planetary surface rovers in experiments that simulated missions to other planetary surfaces. The latest in a series of experiments with surface rovers featured the Russian Marsokhod rover. In February 1995, NASA Ames deployed the Marsokhod on Hawaii's Kilauea volcano to simulate missions to Mars and to the Moon. The Marsokhod rover chassis was equipped with stereo cameras on a pan-and-tilt platform, a digital high-resolution body-mounted camera, and a manipulator arm on which was mounted a camera with a close-up lens. The six-wheeled Marsokhod rover is 2 meters long and has a mass of 120 kg. Two modes of mission operations were simulated for three days each:

1. long time delay, low data bandwidth (simulating a Mars rover mission), and
2. live video and wide-bandwidth data (simulating a Lunar rover mission).

The rover was operated from NASA Ames by a team of planetary geologists and exobiologists who analyzed the data returned to deduce a detailed geologic description of the field site. During the six-day mission simulation, the rover was operated remotely for over 30 hours and traversed over 2 km of rugged terrain ranging from lava flows to sand and loose gravel.

After the science mission simulation, remote operation of the Marsokhod by school children was featured in televised broadcasts as part of the Jason project.

The NASA Ames project team is continuing to work with realistic planetary rovers to develop flight-qualified control systems for planetary surface exploration.

An end-to-end approach

Our approach to solving the problem of remotely operating a complex robotic vehicle designed for science exploration involves designing an end-to-end system that includes the human operator as a critical component. The human does what humans do best: defining strategic goals, planning high-level task sequences to accomplish those goals, and fusing and interpreting multiple sensor data streams. The onboard control system for the exploration vehicle should handle all of the closed control loops, such as navigating to a specific location, station keeping, moving articulated instruments, and keeping itself safe.

This approach differs from that of full machine autonomy as exemplified by the Ambler rover.[8] In Ambler, all of the sensing, planning, and execution occurs aboard the rover, with little or no guidance from an operator. While this is a worthwhile goal, missions to extreme environments on Earth, or even missions to other planets, will not likely operate without human supervision and control for longer than the operator-to-vehicle communications time delay. If humans are inevitably part of the system, they should be used to maximum advantage, especially in areas in which machines are not yet competent.

Exploration of the marine environment in Antarctica is particularly challenging. Antarctica has the most hostile environment on Earth. Researchers face a number of environmental challenges there, including extreme cold and nearly constant winds. These conditions dramatically reduce the functional efficiency of both people and equipment. Equipment, particularly mechanical and electrical devices, fails more frequently and requires more maintenance. Engines often fail to start and motors fail to run; blowing snow penetrates electrical components and shorts them out; and the extreme cold makes operating anything difficult.

In contrast to the largely barren terrestrial environments of Antarctica, marine habitats

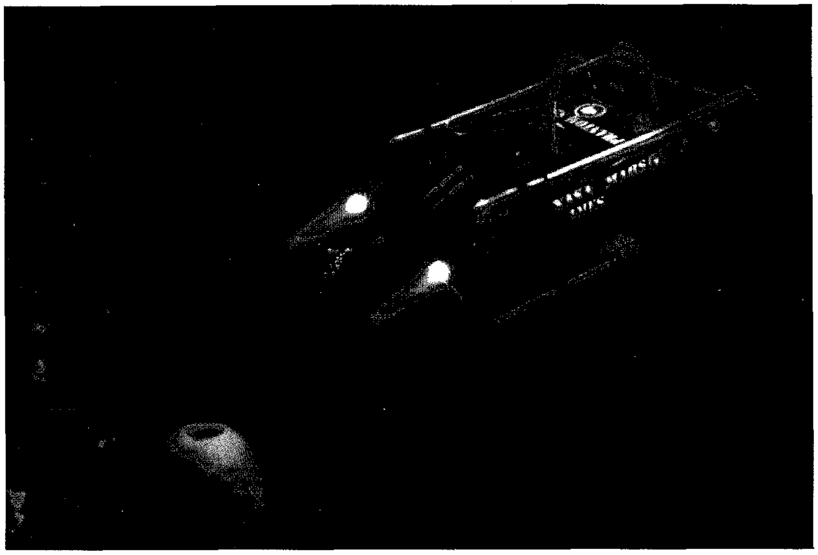

Figure 1. Photograph of the TROV taken 30 meters beneath the sea ice in McMurdo Sound, Antarctica. The stereo camera platform, zoom camera, and manipulator arm are visible in the front of the vehicle. The large white object at the lower left center is a Volcano sponge.

support very rich biological communities, with dramatic seasonal cycles tied to light and ice cover. Dense phytoplankton blooms in spring and summer fuel pelagic food webs dominated by euphausids (krill), fishes, squids, penguins and other sea birds, seals, and whales.

Benthic ecology is the study of the diversity of organisms growing on the *benthos*, or sea floor. Rapid sinking of organic material and growth of benthic algal populations support very diverse benthic faunal communities on Antarctic continental shelves, where diverse communities of sponges and other filter-feeding biota abound. Ecological studies of Antarctic benthic communities have focused on the diversity and persistence of benthic faunal communities under seemingly harsh conditions. At the most southern areas, such as McMurdo Sound, Antarctica, ice cover and winter darkness result in the near exclusion of the luxuriant macroalgal communities typical in shallow-water habitats somewhat further north.

In the experiment described here, we used a TROV to study the sea-floor ecology of McMurdo Sound ranging to 330 meters deep, and to collect samples for chemical analysis from several of these sites.

Antarctica: Earth's harshest habitat

The 1993 austral spring TROV Antarctica experiment was sponsored jointly by the National Aeronautics and Space Administration and the National Science Foundation Division of Polar Programs as part of the Antarctic Space Analog Program, which was created to demonstrate technologies relevant for use in future space exploration in Antarctica. The field experiment had two mutually supportive goals:

- *Technology demonstration*—to demonstrate the use of telepresence and virtual reality technology by performing field science in a challenging environment.
- *Scientific exploration*—to survey the distribution of benthic marine organisms in the Antarctic coastal region and characterize the diversity along the depth gradient from 10 to 300 meters. A secondary objective was to collect and chemically analyze selected organisms from a variety of depths.

The field experiment took place in McMurdo Sound, a coastal inlet immediately adjacent to the McMurdo Research Station on Ross Island, off the coast of Antarctica. We performed benthic surveys in six study sites, each approximately 100 meters square and with bottom depths varying from 10 to 300 meters. McMurdo Sound, near 78° south latitude, is one of the Earth's harshest habitats. Sea ice near McMurdo Station persists nearly year-round, with short seasonal reductions in cover. Sea-surface temperatures are near −1.6°C, and light levels are low, even during summer, because of thick sea ice cover.

Oceanographic features near McMurdo Sound largely regulate biological productivity by controlling rates of primary productivity and the importation of organic carbon. Near McMurdo Station, flow from the north carries phytoplankton-rich waters to benthic habitats, where it settles to the bottom and feeds local benthic communities. In contrast, western Sound habitats only 30 km distant are bathed by waters from under the Ross Ice shelf, with extremely low levels of organic material, insufficient to support high secondary benthic productivity.

This juxtaposition of dramatically different oceanographic conditions over such short spatial scales provides a nearly unique setting in an extreme polar environment to study benthic faunal communities with apparently vastly differing energy limitations. Although some studies have compared the abundance and distribution of benthic fauna in shallow-water communities (less than 45 meters) in McMurdo Sound, very little is known from deeper on the continental shelf.

TROV local equipment. Figure 1 shows a picture of the TROV operating in Antarctica. The TROV is a modified Phantom S2 vehicle, built by Deep Ocean Engineering. Surrounding aluminum pressure chambers containing the electronics payload is a hull made of molded rigid syntactic foam, which yields a neutrally buoyant vehicle. Four electrically powered thrusters control vehicle motion: two mounted longitudinally, so the vehicle turns by driving them differentially, and two mounted at 45° to vertical, so the vehicle is driven vertically when they are driven together, or crabs sideways when they are driven differentially. A pair of high-resolution stereo video cameras mounted at human interocular distance sit on a rapid pan-and-tilt platform that can slew ±90° at rates approaching that of the human head.

The vehicle also carries a *spyglass camera* with a power zoom lens pointing forward, and a downward-pointing camera mounted under the vehicle's midsection. A manipulator arm mounts to the crash frame that surrounds the TROV hull. The arm is about the size of a human arm from the elbow down, and has three degrees of freedom: swing (like an elbow joint with 120° range), wrist twist (180°), and open and close of the gripper claw. Wires in a 340-meter umbilical tether from the surface console supply power for thrusters, lights, and electronics. A fiber-optic cable attached to the umbilical carries all four video signals and control signals such as focus, zoom, and arm commands.

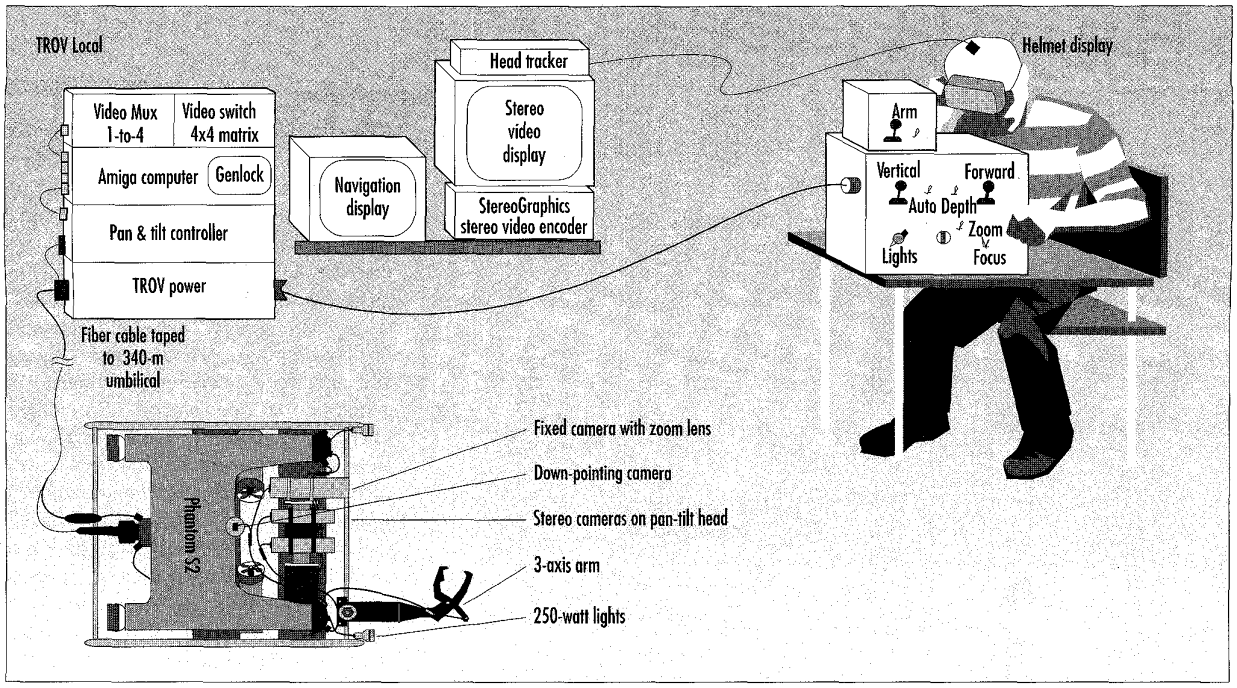

Figure 2. TROV systems include stereo cameras on a pan-and-tilt platform, a body-mounted camera with zoom lens, a downward-pointing camera mounted in the center of the TROV body, and a three-axis manipulator arm. The local operational configuration includes a joystick box (upper right) to control local functions; an Amiga computer provides menu functions on a video overlay. Stereo images are viewed on a StereoGraphics video system.

Figure 2 shows the equipment configuration for local control of the TROV. The local operator controls the vehicle's thrusters with joysticks while viewing stereo video camera images on a StereoGraphics video monitor. The StereoGraphics system uses a 120-Hz scan rate to alternately display the left and right camera of the stereo pair at 60 Hz each. Operators wear Crystal Eyes shuttered liquid-crystal glasses that are synchronized with the images on the monitor so that they alternately see the scene from one camera in each eye. Another monitor displays the monoscopic image from either the forward- or downward-pointing camera when selected by the operator.

An Amiga 2000 computer controls the position of the pan-and-tilt camera platform in one of two modes: by tracking the operator's head motion, or by using the mouse to position a graphic icon. The Amiga also provides a graphics overlay on the video display that includes heading, depth, time, and camera position. Finally, the Amiga provides local data logging of position information, a time stamp, and data from scientific sensors.

The position of the TROV under water was determined using a Sharps Navigation System (Marquest Group), which uses acoustic transponders to transmit and receive ranging signals. Two transponders were mounted on the TROV (front and rear) and three more hung in the water column on cables to form the apexes of an equilateral triangle with 100-meter legs. The Sharps system works well only when the vehicle is within 100 meters of all three transponders for triangulation. A control program on an IBM PC clone provided a graphical and numerical display of the TROV position, heading, and depth. The graphical display showed the history of TROV's positions (a track), which helped the operator to understand the current position and direction of travel. This information was also transmitted as telemetry to the remote controller.

Remote control of TROV. All vehicle functions could be controlled remotely via satellite through an Internet link to a VME-based 68030 single-board computer running the VxWorks embedded real-time operating system. As Figure 3 (next page) shows, the local computer interfaced to the TROV control console so that it emulated the joystick box for providing relay closures and control voltages. The local operator could select local or remote operations at any time. Live stereo video was transmitted from the operations hut on the sea ice via an infrared laser to a receiver in McMurdo Station. There, it was compressed to 768 Kbps, with the rest of the 1.2-Mbps channel bandwidth designated to provide a bidirectional Internet link and telephone service. From there, the signal went via microwave to a satellite station on nearby Black Island, where it was retransmitted to NASA Ames over a T1 satellite channel.

The system architecture is an example of the Ames Robotic Computational Architecture, a highly portable computational architecture designed at NASA Ames to provide a unified framework for integrating diverse subsystems and components for telerobotic applications. ARCA provides a system for interprocess communications and synchronization across a heterogeneous and distributed processing system. In presenting a common programming interface, standardized communications facilitates teamwork by enabling modular development and reducing systems integration difficulties.

At the time of this experiment, we achieved standardized communications via the base layer of Carnegie Mellon University's Task Control Architecture, a distributed, layered architecture with centralized control.[9] Communications occurred via coarse-grained message passing between modules. TCA's base layer implements a simple remote procedure call, in which the central control determines which module handles a particular message and in what order. This RPC interface operates via Ethernet network transmission devices and transmission control protocol/Internet protocols (TCP/IP).

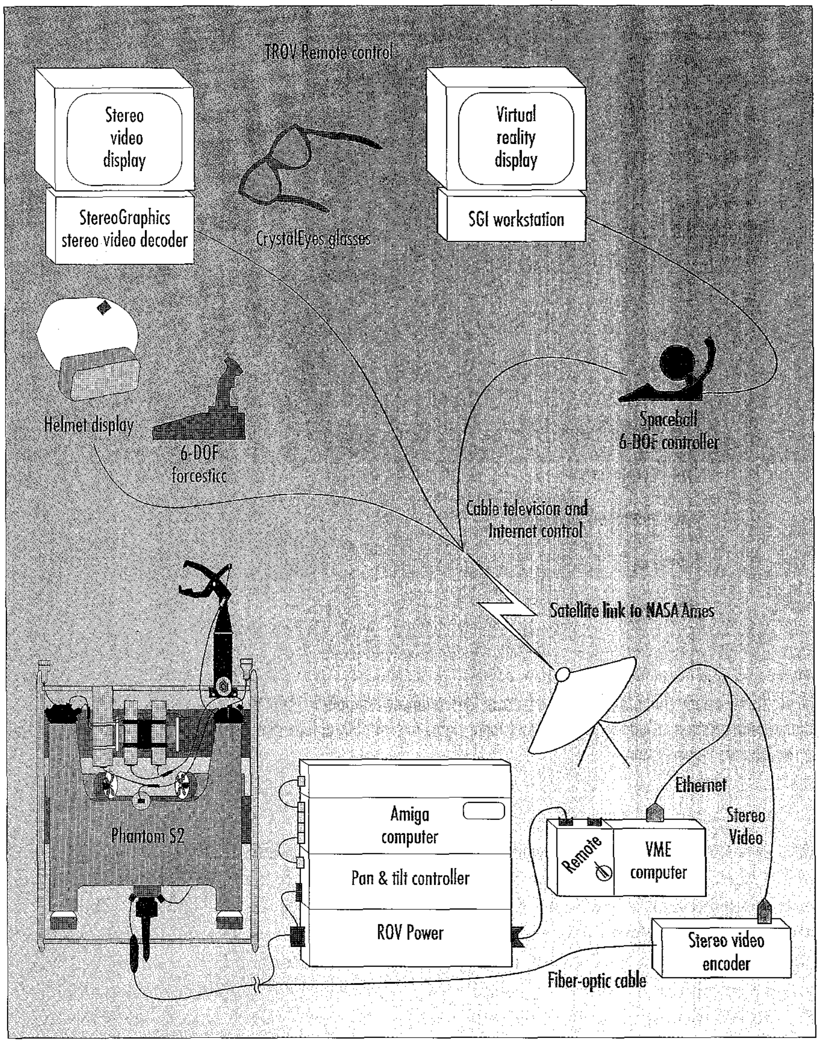

Figure 3. TROV remote control configuration.

To remotely control the vehicle over the satellite link, we used the Virtual Environment Vehicle Interface (VEVI) control software developed at NASA Ames.[10] Figure 4 shows a photograph of the remote control station. The remote operator interface included either a stereo display monitor similar to that used by the local operator, or a stereo head-mounted, head-tracked display. In addition to live stereo video, the remote operator could view a computer-generated representation of the underwater terrain, modeled from stereo images combined with navigational information and generated offline using a Silicon Graphics workstation.

This virtual environment contained an animated graphic model that reflected the vehicle's state, along with ancillary information such as the vehicle navigation track, virtual navigation markers, and locations of video snapshots. Figure 5 shows an example of the terrain model. Operators could drive the vehicle either from within the virtual environment or through a live telepresence interface. They controlled the vehicle from within the virtual environment by moving a graphic model of the TROV around the graphic terrain model using a 3D trackball. The TROV in Antarctica executed the corresponding commands. Operators controlled the TROV by live telepresence with the same trackball, but using the live stereo video to provide feedback on position. In practice, the remote operators preferred to drive the TROV by watching both the virtual environment graphical model and the live video displayed on two different screens.

In generating the terrain models used in the virtual environment interface from the onboard sensors, we used two independent techniques. The first technique recorded the Sharps position information over the telemetry link while an operator (either local or remote) drove the vehicle over the terrain at a nearly constant altitude. This ground-hugging technique provided streams of spatial coordinate values along the vehicle track that were interpolated onto a uniform terrain elevation map, provided the area coverage was sufficient. The second technique involved digitizing stereo camera frames and using them to create range maps. We generated the range maps by running a Laplacian-of-Gaussian filter over the images, and then using a windowed cross-correlation technique to produce disparity values everywhere in the image that had sufficient contrast. These range maps, when combined with the navigation information and the pan-tilt camera angles, produced local terrain elevation values in a wedge from the vehicle position.

To produce large-area uniform-grid elevation maps of the terrain, we used a simple weighted-average interpolation technique to combine multiple terrain elevation wedges generated from stereo frames taken while the vehicle moved. Once the vehicle had covered an area of interest, typically 100 meters square, the algorithms required approximately 10 minutes to produce the elevation map of the area. The terrain elevation maps created with either of these techniques went directly into the VEVI software to visualize the vehicle in the terrain. Once the terrain was input to the VEVI software, remote operators could drive the vehicle purely from within the virtual environment. The registration between the virtual terrain and the actual terrain, as determined by comparing the live video signal with the correspondent virtual terrain, was quite good.

On the ground

We set up field operations for local control of the TROV in a heated portable habitat, called a *hypertat*, stationed on the sea ice in McMurdo Sound. Mounted on skis, the hypertat could move from one location to another across the sea ice. Two 5-kW diesel generators powered the hypertat. Because all the electronic systems resided inside the hypertat, we could conduct most of the field operations in a shirt-sleeve environment. A hatch in the hypertat's floor allowed us to deploy and retrieve the TROV without going outside. Operations out in the Antarctic cold were required for brief periods to set up and service the power generators, navigation, and video transmitter systems, and to handle the TROV umbilical cable.

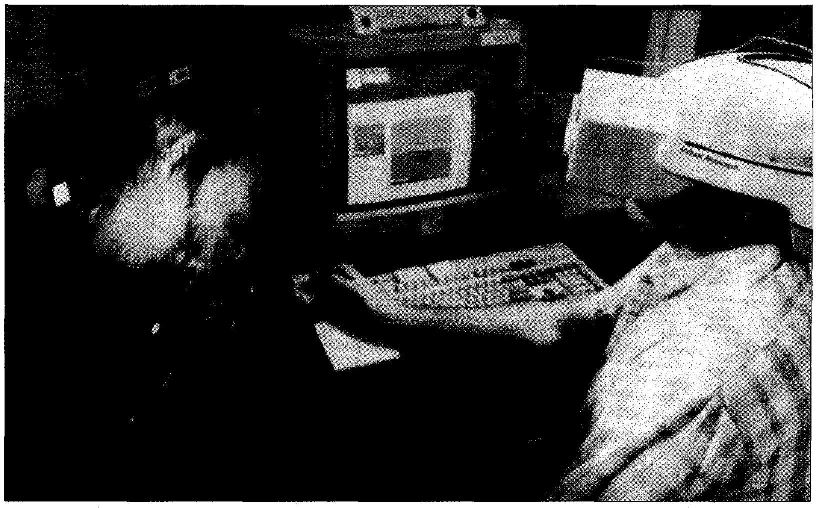

Figure 4. Photograph of the TROV remote control station showing an operator in a helmet-mounted display, a screen showing the stereo video display, and a monitor displaying the computer-generated representation of the underwater terrain.

Benthic ecology survey. Our experiment involved conducting two types of benthic ecology surveys using the TROV stereo cameras, close-up camera, and position information obtained from the navigational system. First, we surveyed an area that had been set up for survey by divers in 1969 and monitored periodically over the years. This way, we could compare our results with those from a diver survey. The divers had laid out 20- to 30-meter rope lines and staked them into position. The depth in the survey area ranged from 12 to 40 meters.

To perform the survey, we first had to find each rope line—they were very well camouflaged with growth—and then drive the TROV along it at a constant height (0.5 meter) above the bottom. We recorded stereo video of the sea bottom on Hi-8 videotape. The rate of transit was slow enough to maintain a constant height and to resolve all organisms within the approximately 1-meter diameter field of view. After reaching the end of the transect line, the TROV drove over it again, this time looking at the scene with the zoom camera zoomed to maximum magnification. This served as a close-up lens for detailed imaging of organisms; it had a field of view of approximately 15 to 30 cm in diameter.

Performing transects with the Sharps system was basically similar, except that we used the graphic display for the navigation system to provide a spatial reference, rather than a rope line. The TROV flew approximately 30 such transects in each survey area, surveying a total of six areas, with depths ranging from 20 to 340 meters. (The "Hole in the ice" box, next page, describes the oceanographic research conducted in McMurdo Sound.)

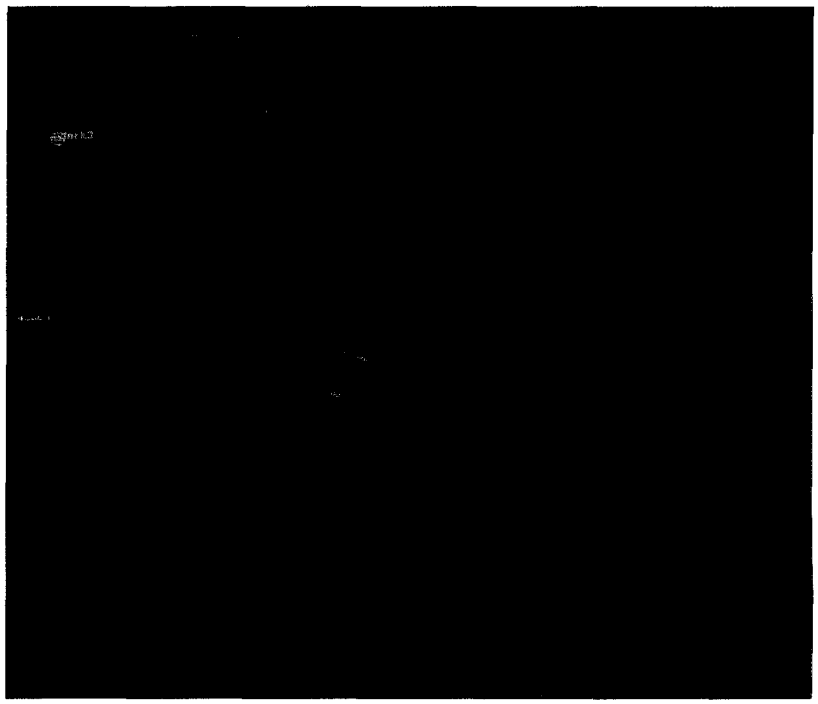

Figure 5. Close-up view of the virtual environment model graphical display showing the vehicle position and state and the vehicle position track (bright line at top) within the terrain.

Sample collection. The three-function manipulator arm picked up sample organisms and put them into a collection basket that resembled a picnic basket frame covered with fishnet. The basket rode in the gripper and, because the TROV had only one arm, the operator had to set the basket down to use the gripper to gather a sample. By noting the navigation coordinates of the basket, the operator could leave it behind on the bottom, drive around to find a sample of interest, and grasp that with the gripper claw before returning to the basket and pushing the sample through the hinged door. We repeated this procedure until the basket was full, whereupon the TROV carried it in its gripper to the surface ice hole. Sample collection required two operators: one to control the TROV thruster motors (two joysticks were used to drive the TROV), and another to control the arm functions.

How well does TROV work?

Telepresence and virtual reality technologies provide significant advantages for underwater exploratory research, particularly for habitats where little or no preliminary information exists. Simple ROV video observations are most effective when the spatial

A hole in the ice

Polar marine biologists have long been puzzled by the very different communities of animals populating the two sides of Antarctica's McMurdo Sound. On the western side is a veritable ocean desert—little plant life, very few animals, a barren sea floor—like something from the sea's deepest reaches. A scant 50 kilometers away, however, the eastern slope presents a very different picture. Starting at about 80 feet, a thriving community of sponges and similar animals carpets the bottom far into the depths.

Same frigid waters on both sides of the sound, same ice cover nearly year around, same lack of native plant life to support the animal communities—so what explains the difference?

Figure A. The accommodations at McMurdo Station.

Charting the currents

To Jim Barry, a biological oceanographer from the Monterey Bay Aquarium Research Institute (MBARI) who hooked up with the NASA scientists on the TROV (pronounced *tee-rove*) project, this is just the kind of question any ecologist worth his or her salt would want to know: What processes regulate the living communities in a particular ecosystem? "In a forest, ecologists want to know why this is a pine forest, not an oak forest. Or why is it a forest at all, and not a grassland. What are the interactions between the major players? Are the biological interactions more important than the physical factors?"

In recent years, biological oceanographers have been paying more attention to the links between the atmosphere and upper ocean, mid-ocean, and benthic, or deep-sea, communities. Polar systems are fairly well defined and not quite as complex as those in more temperate waters, so despite the harsh working conditions, they provide a good environment for studying the interplay between plants and animals and their surroundings.

Starting in the mid 1960s, Paul Dayton of San Diego's Scripps Institute of Oceanography began taking teams to McMurdo Sound, Antarctica's most southerly point accessible to a ship and one of the harshest environment on earth.[1-3] Joining those expeditions in the 70s and 80s before moving to MBARI in 1991, Barry has spent eight field seasons in Antarctica studying the dynamics of polar ecosystems. Figure A shows a typical camp.

Dayton's scuba divers dove to depths of 50 to 60 meters in the freezing waters at McMurdo Station to stake out transects, or grids, on the bottom. By checking back in subsequent years, they could track the demographics of the animal populations. They also set out current meters and temperature gauges to get a handle on the factors influencing life in the undersea polar environment.

In the 1960s, diving technology was more primitive and Dayton and his comrades used wet suits. Although a new, well-fitting wet suit could keep divers relatively warm, their hands usually became very cold very quickly in the –1.8°C (28°F) water. They now use insulated dry suits, with interlocking dry (and warmer) gloves, so the dives are much more comfortable.

"Diving in the early spring is best, when visibility in the plankton-poor waters can reach 1,000 feet or more," says Barry. "As the summer progresses, the phytoplanton bloom develops, and by late December or early January visibility drops to 10 to 20 feet at times."

During these low-visibility periods the divers must take greater caution in maintaining contact with the access holes through the 6 to 8 feet of sea ice. They either abandon diving or use tethers. "The major factor is that you are required to enter and exit through holes in the ice, and cannot simply surface anywhere at any time," says Barry. "Cold is quite important, but we've pretty much overcome that with technology."

Anchor ice

Of particular interest to marine biologists is the zonation of the communities—what animals live at what depths and why. In McMurdo

dimensions and landscape characteristics are known, allowing the observer to place the ROV in a spatial perspective. For unknown or poorly known environments, telepresence provides a feeling of immersion in the habitat, while virtual reality provides a spatial perspective beyond the immediate ROV camera view. Thus, the observer can get spatial orientation in three dimensions by using the video imagery to create mental maps of the terrain, as well as by referring to the larger spatial scale represented in the virtual reality terrain model. Moreover, plots of the TROV track in the virtual terrain provide a spatial history on the landscape. This is a distinct advantage over more conventional ROV video, in which the myopia associated with a narrow field of view and lack of knowledge of the recent history of observations makes it difficult or impossible to generate an integrated perspective that these new technologies provide.

Biologists using the TROV system were very impressed by several features, includ-

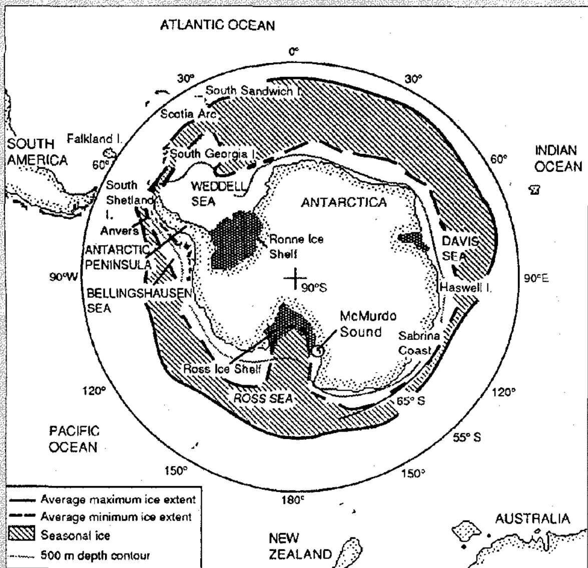

Figure B. Antarctica's Ross Sea and McMurdo Sound.[4]

Sound, a phenomenon called *anchor ice* prevents many animals from living in the shallower waters. Near McMurdo Station, currents commonly come in contact with the undersurface of the Ross Ice Shelf (see Figure B). When currents carry this extremely cold water to diving depths near the station, it freezes, often attaching to rocks, animals, or whatever is on the sea floor. Because the temperature of freezing is lower under high pressure, ice doesn't form in water deeper than about 80 feet near McMurdo Station, and the thickest ice (up to about 1.5 feet thick) is found in water less than 50 feet.

Ice crystals will grow on objects to that depth. The crystals will be lighter than the surrounding water, so if they grow large enough, they can actually rip the sponge or rock or whatever they're growing on and float it to the surface. Things just float away, often attaching themselves to the undersurface of the sea ice, where they remain until the ice floats away, or melts and drops them to sink to the sea floor.

"You'll find there's really not a lot on the bottom until around 30 to 40 feet," says Barry. "There are also some animals such as anemones that are not affected by the anchor ice because they can shed the ice crystals. Also, there are episodes of high recruitment by some animals like certain sponges, which populate extensive regions of the shallows during one or two years, then slowly but surely are reduced by anchor ice or eaten by sea stars."

Sponges predominate from the depths that anchor ice can affect them, down to about 130 feet, when *bryozoans*, another group of animals, begin taking over (see Figure C). Many are hexactinlid sponges, or glass-spicule sponges typically found in very deep ocean environments. Using MBARI's remote operating vehicle, Barry finds similar sponges—not the same species, but the same major groups—off the coast of Monterey at depths of 500 to 1,000 meters. Handily for marine biologists, the deep-water environments of temperate climates resemble the shallow waters of polar regions because the water is very cold, the temperature remains stable year around, and there is little light, unlike most shallow-water environments that are subject to seasonal fluctuations in light, plankton growth, and temperature.

The deeper the divers would go in Antarctica, the more abundant the bryozoans seemed to become, down to the limits of their dives. With the TROV, Barry was able to extend his observations down to about 900 feet, and he is currently analyzing the videos taken from those dives.

Besides allowing him to study the bottom to much greater depths from the toasty confines of a heated hut on the ice's surface, the TROV gave Barry excellent control for fine work. "For manipulating objects on the bottom, for trying to grab something, the stereo vision NASA has developed is just marvelous." A similar system has already been installed on the ROV he uses at MBARI, the nonprofit oceanographic center founded in 1987 by David Packard of Hewlett-Packard fame.

For finding and setting out transects and certain other visual tasks, though, a normal, high-resolution camera works better. Also, Barry found the TROV difficult to control at great depths because it didn't have the

Figure C. Bryozoans living in McMurdo Sound.

ing the telepresence effects of stereo imagery, operational ease, and potential for quantitative measures from video imagery. The key science objective of this experiment was to obtain estimates of the densities of the dominant benthic fauna along video transects in McMurdo Sound. For meeting this objective, the TROV was a considerable advance over conventional ROVs. Stereo imaging clearly enhanced biologists' perceptual abilities from video imagery. In that organisms were "viewed" in 3D space, the biologist could much more easily identify the shapes, sizes, and spatial relationships of species than when using 2D camera systems. Stereo vision had enormous advantages over 2D systems in terms of TROV operation and positioning. Data analysis incorporating stereo vision and Sharps navigation accuracy enabled direct calculation of spatial dimensions from stereo imagery: such quantitative estimates of spatial features are very difficult or impossible using currently available nonstereo systems. Coupling of TROV operational features with power to pull against the currents. "There's a lot of windage against the long tether column. The currents would come up during a certain part of the day and literally pull the thing off the bottom, sweeping it back and forth like an upside down kite."

Plankton blooms

Because McMurdo Sound is covered by ice and dark skies most of the year, there's not much primary productivity (plant growth) in the area. There is a little algal growth on the bottom and very little in the water column, except during the summer season.

"If you look at the energetics of the whole system, you realize that something's got to be supplying food to all these animals," says Barry. "It doesn't take more than a couple of dives to realize that this is a very rich community. There's a lot of productivity, at least in the animal communities, which must be sustained by plant communities."

Studies of the currents in the sound over the years have shown that the western, barren shore is bathed by waters that come from the south, from under the permanent Ross Ice Shelf itself. On the eastern side, the currents come from the north, from the Ross Sea, which is covered seasonally with ice, but has intense plankton blooms during spring and summer months.

Each summer, somewhere between December 15th and Christmas Day, a plankton bloom miraculously descends upon the eastern shore of McMurdo Sound. The change is dramatic. "The water will be clear—we've measured visibilities of up to 1,000 feet—then it will start to get cloudy. We'll hear that the bloom has arrived 10 to 20 miles north, and then a few days later, boom!—it's at McMurdo." Visibilities fall to 10 feet or less in a matter of days. Barry estimates that this bloom means that as much as 10 times as much carbon filters to the bottom on the eastern side compared to western McMurdo Sound, hence the thriving communities of animals.

Open water off Ross Island

The oceanographers theorize that the plankton bloom comes from a *polynya*, or area of open water that develops northeast of Ross Island, at the edge of the Ross Ice Shelf, during the winter. Satellite imagery has shown that the size of this polynya can vary from roughly 20,000 to 30,000 square kilometers some years, down to virtually nothing other years. The size of the opening largely determines the intensity of the phytoplankton that ultimately visits McMurdo Sound.

Katabatic surges, or the intense winds that blow off the Antarctica ice cap, create the polynya. "Those winds just roar toward the north," says Barry. "They run up off the Ross Ice Shelf and literally blow the sea ice to the north to create this area of open water." Barry and his fellow researchers think that higher light levels early in the season allow the phytoplankton to grow, especially during relaxation periods between surges. In addition, strong winds cause an *Ekman transport* of the surface waters: the winds blowing north cause the water to shift to the left, or west. The waters then swing around the north end of Ross Island and into McMurdo Sound, conveying their load of life-giving phytoplankton.

At MBARI, Barry plans to start a project next year that will study these interactions that influence communities in McMurdo Sound on a much broader scale. Looking not just at McMurdo Station, but throughout the Ross Sea, he and his co-investigators will look at airflow off the Antarctic continent, the ice cover, the structure of the upper water column—temperature, density, and phytoplankton dynamics and productivity—water currents, sedimentation, and the kind of benthic communities living there and their rates of growth. That will paint a clearer picture of the linkages between atmospheric processes, upper ocean response, and consequences for sedimentation and food input to deep-water communities. In other words, how much food is produced in the whole Ross Sea ecosystem, where it is carried by currents, how much lands on the bottom in various areas, and what type of benthic animals it supports.

Temperate climate analogs

The results from the shallow-water benthic community in Antarctica are directly analogous to the deep-water community off Monterey, where Barry conducts the bulk of his research. Both communities are removed from the area where food is produced. Off Monterey, the food production takes place in the upper ocean, and the carbon then filters down to feed the animals below the *euphotic zone*, or region where plants live. In the Antarctic, the food shift is both vertical and lateral.

"This project gives us a chance to dissect the system to see how the relationships between the physical and biological processes and systems work." It also gives them an opportunity to look at environmental and climatic variability and how that variability might affect the production of food and its distribution through the upper ocean and the bottom, with implications for ocean foodstocks throughout the world.

—Dick Price, Managing Editor

References

1. P.K. Dayton and J.S. Oliver, "Antarctic Soft-Bottom Benthos in Oligotrophic and Eutrophic Environments," *Science*, Vol. 197, July 1, 1977, pp. 55–58.
2. J.P. Barry and P.K. Dayton, "Current Patterns in McMurdo Sound, Antarctica, and Their Relationship to Local Biotic Communities," *Polar Biology*, Vol. 8, 1988, pp. 367–376.
3. J.P. Barry, "Hydrographic Patterns in McMurdo Sound, Antarctica, and Their Relationship to Local Benthic Communities," *Polar Biology*, Vol. 8, 1988, pp. 377–391.
4. J.M. Grebmeier and J.P. Barry, "The Influence of Oceanographic Processes on Pelagic-Benthic Coupling in Polar Regions: A Benthic Perspective," *J. Marine Systems*, Vol. 2, 1991, pp. 485–518.

virtual reality modeling of local study areas will undoubtedly enhance the quality and effectiveness of remote surveys.

Our experience from this experiment indicated that several features needed improvement. As mentioned, performing sample collection required two operators. A single operator with three hands could have controlled the TROV and its arm, but since these are not readily available, we plan to develop a control interface that uses a single 3D control stick to drive the TROV and a data glove to operate the arm. Because the collecting procedure is repeated several times each run, it offers a good opportunity for semiautomatic programming. When the behavior of the arm and gripper are adequately modeled, inserting the collected sample into the basket could be an automatic procedure. Without force feedback on the gripper claw itself, it is difficult to grasp and uproot a soft organism without damaging it excessively. The collection task therefore depends heavily on live visual feedback.

A computed path planner could aid the process by remembering the location of the basket and any major obstacles, and driving directly to it. This is easy in the underwater environment, where most obstacles can be simply avoided by flying over them. Thus, a virtual reality interface will greatly simplify the workload by allowing the human operator to quickly scan through a prerecorded video environment, placing virtual markers on objects of interest. Then, at the press of a button, the operator could invoke an automatic procedure to return to the sample basket, insert the sample, and continue until the basket is full and sent to the surface.

To our knowledge, this experiment represents the first use of telepresence and virtual reality in exploring a previously unknown scientific environment, using rendered terrain models. The combined use of telepresence and virtual reality for scientific exploration could well revolutionize the study of hostile and extreme environments. Keeping human controllers actively involved, but giving them better interfaces to the machines and better data visualization, lets us do better science. The fidelity of the data record allowed by this technology and the ease with which it can be recreated for study offer a quantum leap in the capabilities for data analysis. Finally, telepresence and virtual reality, both as control systems and as data visualization methods, afford the potential for distribution to a wider scientific community than would be possible with more conventional methods.

Acknowledgments

We performed this project under the auspices of the Antarctic Space Analog Program. We thank program directors Carl Pilcher and Carol Roberts for their sponsorship and support. Scientific collaborators were sponsored by the National Science Foundation Division of Polar Programs under Polly Penhale. TROV program funding came from NASA Solar System Exploration Advanced Technology Development and Exobiology Program offices. We thank the NSF and Antarctic Support Associates for outstanding logistical support in Antarctica.

References

1. S.R. Ellis, "Nature and Origins of Virtual Environments: A Bibliographical Essay," *Computing Systems in Engineering*, Vol. 2, No. 4, 1991, pp. 321–347.
2. O. Gwynne and C. Stoker, "Telepresence for the Exploration of Hostile and Remote Environments, from Sea to Space," *Proc. IDEAA 1, Int'l Conf. Design for Extreme Environments*, 1991.
3. B. Hine et al., "The Application of Telepresence and Virtual Reality to Subsea Exploration," *Proc. ROV '94, The Second Workshop Mobile Robots for Subsea Environments*, Int'l Advanced Robotics Program, Monterrey, Calif., 1994, pp. 117–126.
4. T.B. Sheridan, *Telerobotics and Human Supervisory Control*, MIT Press, Cambridge, Mass., 1991.
5. C.R. Stoker et al., "Science Strategy for Human Exploration of Mars," *Advances in Space Research*, Vol. 12, 1989, pp. 479–490.
6. M.W. McGreevy and C.R. Stoker, "Telepresence for Planetary Exploration," *Proc. Soc. Photo-Optical Engineering Conf. Space in the 21st Century*, Soc. Photo-Optical Engineering, Bellingham, Wash, 1990, pp. 110–123.
7. C.R. Stoker, "Telepresence in Human Exploration of Mars: Field Studies in Analog Environments," *Proc. Vision 21: Interdisciplinary Science and Engineering in the Era of Cyberspace*, NASA Conf. Publication, 1993, pp. 23–34.
8. J. Bares et al., "Ambler: An Autonomous Rover for Planetary Exploration," *Computer*, Vol. 22, No. 6, June 1989, pp. 18–26.
9. L. Lin, R. Simmons, and C. Fedor, "Experience with a Task Control Architecture for Mobile Robots," Tech. Report CMU-RI-TR 89–29, Robotics Inst., Carnegie Mellon Univ., Pittsburgh, 1989.
10. T.W. Fong, "A Computational Architecture for Semi-Autonomous Robotic Vehicles," *AIAA Computing in Aerospace 9 Conf.*, AIAA 93-4508, 1993.

Carol R. Stoker is a planetary scientist in the Space Sciences Division at NASA Ames Research Center, Moffett Field, California. Carol leads the "Telepresence for Planetary Exploration" project to develop telepresence technology for operating robotic vehicles on the surfaces of other planets. Currently, she is focused on using telepresence-controlled scientific exploration vehicles to perform field studies of space-analog environments on the Earth. Carol has previously worked with the Voyager imaging team for the 12-year mission of exploration of the outer solar system where she studied the atmospheres of the outer planets. In addition, she has done theoretical and experimental research on a variety of problems related to the origin and evolution of life in the solar system. She is also a key figure in the Mars Underground, a group which develops concepts for and advocates human exploration of Mars. Carol received her PhD in astrogeophysics from the University of Colorado in 1983. She can be reached at MS 245-3 NASA ARC, Moffett Field, CA 94035; Carol_Stoker@qmgate.arc.nasa.gov.

Donald R. Barch can be reached at the NASA Ames Research Center, Moffett Field, CA 94035; Barch@artemis.arc.nasa.gov.

Butler P. Hine III is currently the group leader for the Intelligent Mechanisms Group at the NASA Ames Research Center. His research interests include instrumentation for space astronomy, image processing, machine vision, and time-delayed teleoperations of rovers. He received his BS in physics and mathematics from the University of Alabama in 1981, and MS and PhD in astronomy from the University of Texas in Austin in 1985 and 1988. He is a member of the American Astronomical Society, the Astronomical Society of the Pacific, the Association for Computing Machinery, the IEEE, the Optical Society of America, and the International Society for Optical Engineering. Readers can contact him at the NASA Ames Research Center, Moffett Field, CA 94035; hine@artemis.arc.nasa.gov.

James P. Barry is a scientist at Monterey Bay Aquarium Research Institute (MBARI). His research interests concern the biology and ecology of benthic organisms, including intertidal, shallow subtidal, and deep-sea communities in polar and temperate environments. Much of the polar research focuses on the role of oceanographic processes in regulating the distribution and abundance of benthic organisms. He has investigated the potential effects of climate change on invertebrate communities in rocky intertidal habitats of Monterey Bay, and is currently investigating the biology of deep-sea chemosynthetic communities in Monterey Bay using MBARI's ROV. Jim's training include a BS and MS from San Jose State University, and a PhD from Scripps Institution of Oceanography. He can be reached at the Monterey Bay Aquarium Research Inst., 160 Central Ave., Pacific Grove, CA 93940; barry@mbari.org.

For more information on the TROV project, access http://maas-neotek.arc.nasa.gov/TROV/trov.html.