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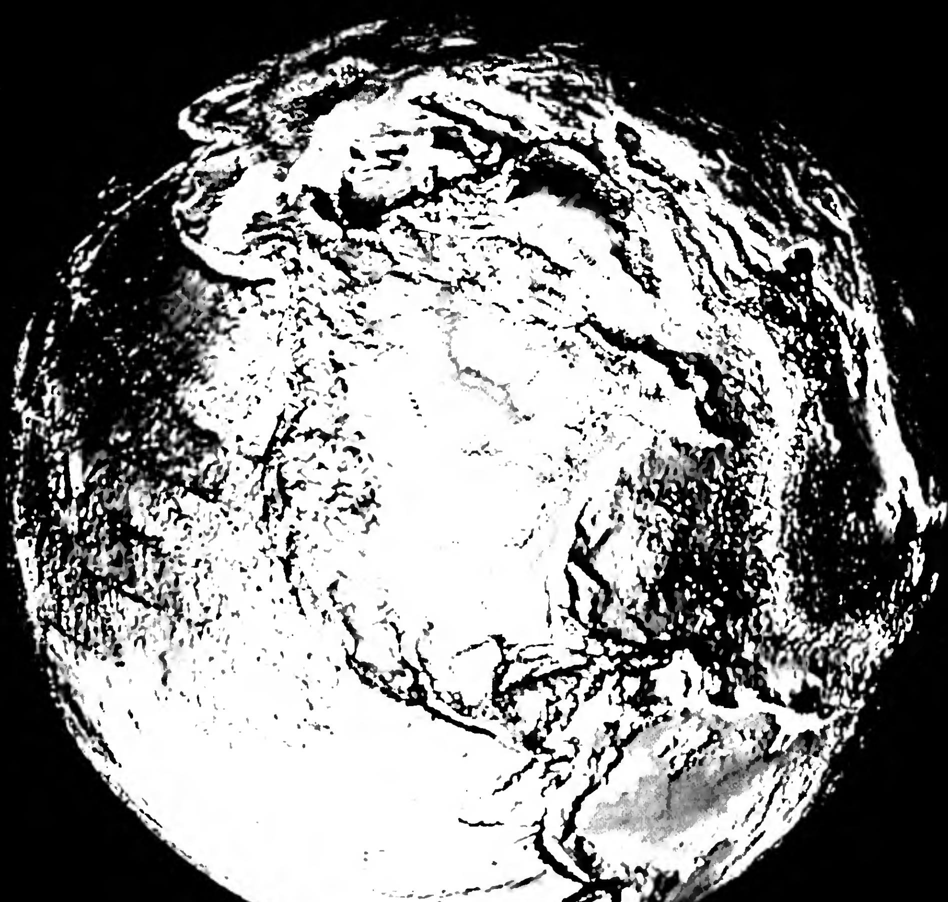

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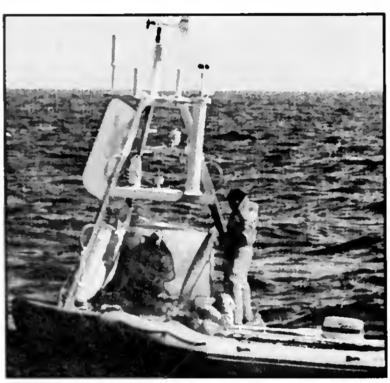

THE COVER: Computer-generated image courtesy of Peter W. Sloss, NOAA National Geophysical Data Center, Boulder, CO. For more information see page 45.

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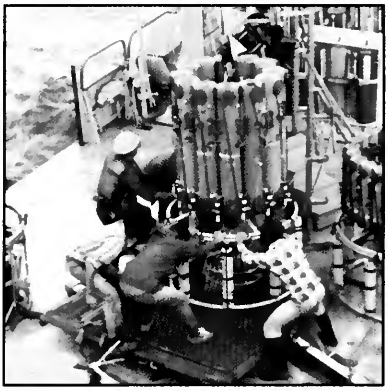
Headings and Readings



Ocean Engineering

Albert J. Williams 3rd

Only in the last 25 years have undergraduate degrees been granted in ocean engineering.

Ocean engineering is too new a field for us to generally agree on its contents. Derived from mechanical, electrical, and civil engineering, and the ocean sciences, ocean engineering addresses applications requiring combinations of these disciplines that are peculiar to it. The collection of these applications and the special approaches taken to study them help legitimize ocean engineering as a new discipline. Practitioners are typically trained in the physical sciences or one of the engineering disciplines, then serve an "apprenticeship" applying engineering techniques to ocean problems. Only in the last 25 years have undergraduate degrees been granted in ocean engineering, and the Massachusetts Institute of Technology/Woods Hole Oceanographic Institution joint graduate program is only 22 years old.

The special engineering-related activities in the ocean that most clearly define this new discipline are those in the instrumentation area, or what some of us call oceanographic engineering (to remind us that they are related to the study of the ocean!). These include underwater vehicles, float systems, moorings, and many sensor and telemetry systems. These instruments share the task of extracting information from the ocean. Structures support sensors to acquire data that is then processed and communicated or stored. Underwater acoustics has a special place in this scheme due to the sea's transparency to sound. Fluid considerations also rank highly in our priorities, both through our concern about the interaction of flow with structures and the importance of flow as a sensed quantity. The informational sciences play an ever-increasing part in ocean engineering as computational power continually increases and size and electrical power demands decrease.

Manned and unmanned vehicles provide precisely controlled presence on the seafloor for observations, collection, and manipulation of objects from the bottom. Control systems, cables, navigation systems, and, for autonomous underwater vehicles, telemetry systems, are vital ocean engineering specialties. Clearly the vehicles and systems are not limited to information extraction; recovering valuables or emplacing work systems are major tasks of submersibles, but the informational aspects remain a high priority. While fluid displacement modifies the manipulator response for submersibles, flow considerations dominate the design of moorings and tow cables. Designing moored arrays, such as DUMAND or acoustic beam forming arrays, requires engineering research in cable dynamics that is peculiar to ocean applications. Adding telemetry along cables creates an ocean engineering system of great complexity, pushing materials, dynamic modeling, mechanisms, and even logistics of marine operations to their limits.

In an effort to recover data from an expanding geographic range at increasing bit rates and decreasing cost, expendable instrumentation is being developed. Freely drifting platforms sacrifice precise positioning for long deployments, and actively controlled free platforms might even recover the station-keeping capability of moorings at reduced cost.

However, ships are still our most important platforms for observation. The design of appropriate research ships is at the edge of ocean engineering, and is primarily the domain of naval architecture, but is also influenced by factors other than transportational ones. Ships will be used at least as much in the next two decades as in the past, but with a different mission profile: They will deploy autonomous instrumentation and provide seagoing development labs instead of serving largely as observational platforms. A similar transition can be expected in manned submersibles. Air-deployable instrumentation will further open our geographical range and reduce deployment costs over those of ship-deployed instruments, but its development requires still more ocean engineering research to become practical.

Control systems, cables, navigation systems, and, for autonomous underwater vehicles, telemetry systems, are vital ocean engineering specialties.

One traditional ocean-related civil engineering task is not principally informational: harbors and breakwaters. This aspect of ocean engineering uses ocean knowledge to provide solutions to societal problems. In a similar vein, oil spill movement, recovery, and prevention are practical ocean engineering tasks. Waste disposal at sea is another practical solution to a societal problem that requires ocean engineering as well as other scientific study. The emplacement of seafloor structures, their design, and even their purpose become ocean engineering concerns. Artificial reefs, dredge-spoil emplacement, channel-scour enhancement, and wave-diverting structures are proper targets. Power generation from waves, tides, ocean thermal differences, and wind have in the past been major ocean engineering projects and will continue to draw on the special combination of engineering and ocean knowledge that constitutes our discipline. In the end, engineering is a practical and applied pursuit to solutions for problems of social importance with constraints. Ocean engineering is ultimately the solution to these problems in the sea.

Albert J. (Sandy) Williams 3rd is a Senior Scientist and Chairman of the Applied Ocean Physics & Engineering Department at the Woods Hole Oceanographic Institution.

The Heard Island Experiment

In late January this year, an international team of scientists conducted a pioneering experiment to test the possibility of measuring world ocean warming by means of long-range acoustic transmissions. The speed of sound in the ocean is determined primarily by temperature; therefore, the time it takes for an acoustic signal to travel from one point to another can be translated into a temperature gauge. The idea is to use such an underwater acoustic thermometer to measure the magnitude of warming due to the greenhouse effect, which is caused by the atmospheric build-up of carbon dioxide and other gases. The concept, an outgrowth of suggestions made a decade ago by Walter Munk (Scripps Institution of Oceanography) and Carl Wunsch (Massachusetts Institute of Technology) in connection with ocean acoustic tomography studies, was formulated by Munk and Andrew Forbes (Commonwealth Scientific and Industrial Research Organization, Australia).

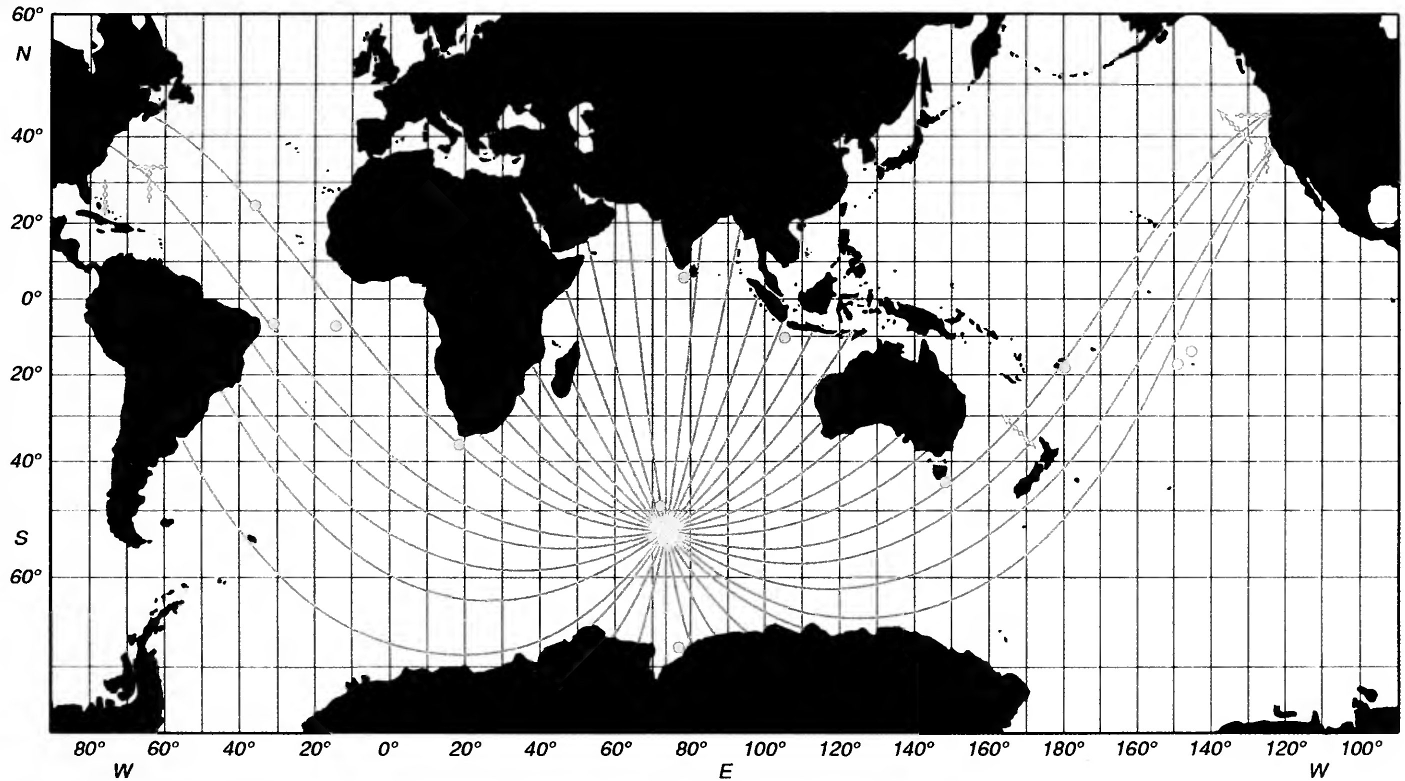
The oceans cannot be ignored in any meaningful study of climatic variation resulting from greenhouse gases. Their role is twofold: storage of heat and storage of carbon. In response to greenhouse gases, an Earth without oceans would warm two or three times faster than an Earth with oceans. Yet while there has been ample theory and speculation as well as a handful of computer models dealing with the combined ocean-atmosphere system, none have been validated or denied by appropriate observations. Thus, predictions of global temperature and sea level changes arising from projected increases in greenhouse gases are uncertain because the numerical models they are based on lack consistent and reliable input data. The need for warming-rate data is of particular concern.

The Heard Island Experiment was a first step in the development of a method to obtain warming data. Direct atmospheric measurement of surface warming, estimated to be about 0.02°C per year, is difficult due to contamination (from urban "heat islands," for example) and wide fluctuations in the ambient background that can be as much as 60°C per year. By contrast, the expected mid-latitude signal in the upper ocean, while about five times less at 0.005°C per year, may be easier to measure.

Why not simply suspend a thermometer from a deep-sea mooring and record for a period of time? Because even in the ocean, the background temperature variation, or "noise," would mask the small underlying trend due to greenhouse warming. We would have to measure for several centuries to be sure the trend was detected. Fortunately, instead of taking one measurement over a long period of time, it is possible to take many measurements at separate points to help average out the noise, thus reducing the required time. A thousand independent measurements would reduce the time from several centuries to a decade.

By its very nature, an acoustic transmission accomplishes this because it averages out the noise. The travel time from one point to another is the average travel time along the path or, in other words, a measure of the average temperature along the path. Long ranges provide the equivalent of many separate thermometers. Long ranges also yield large, easily measurable travel-time changes. Global ocean warming of 0.005°C per year will produce an increase of 0.02 meters per second over the 1,500 meters per second nominal speed of sound in seawater. Over global paths (18 megameters, or 18 million meters), this results in a travel-time reduction of a few tenths of a second per year—an easily measured change. Ten or so paths, monitored over a decade, meet the criteria for a significant probability of revealing a trend in ocean warming.

(continued on page 8)



The curved lines represent acoustic paths (or axially refracted geodesics) and are drawn every 10°. Heard Island, the site of the sound source, is located where these acoustic paths converge. Horizontal lines represent horizontal arrays off the American west coast and off Bermuda; vertical lines designate vertical arrays off Monterey and Bermuda; and lines with arrows indicate towed arrays. The 18 receiver sites are noted by circles.

These large ranges exceed, by an order of magnitude, those for which there is any experimental experience. The only previous comparable transmission was in 1960 from an explosive source near Perth to some receivers at Bermuda; but explosive sources are not suitable means for a decade of reproducible precision travel-time measurements. Hence, the Heard Island Experiment. The site was chosen because it appeared possible to send acoustic signals from there through the Atlantic, Pacific, and Indian Oceans to nearly all continents. It was an ideal location from which to test the practicality of global acoustic transmissions.

On January 26 of this year, 19 receiving stations manned by scientists from 9 nations—the USA, Australia, Canada, New Zealand, South Africa, India, Japan, France, and the USSR—were poised to listen to a series of hour-long transmissions sent at three-hour intervals. Scattered around the globe, some were land based, some were on mid-ocean islands, and 11 were on ships at sea.

In what was truly a shot heard around the world, the signals emitted from a projector suspended beneath a ship near Heard Island were received worldwide. For six days signals in the South and North Atlantic were recorded with remarkably high intensities. Eastward transmissions through the New Zealand-Antarctic window were detected in the North Pacific. Signals were received in the Tasman Sea region between Australia and New Zealand, and possibly further north into the Pacific. Northward transmissions into the Indian Ocean were good, as were southward transmissions to Antarctica.

The January test was exploratory, and was the forerunner of a possible decade-long experiment. It was conducted simply to see if acoustic transmissions over global paths were possible and, if so, to determine the characteristics of the signal needed to measure oceanic warming. Further, we need to know if the required signal characteristics are compatible with marine mammals and other sea life.

At this early time we do not have all the answers. We know that the signals were heard worldwide, at some locations with surprisingly high volume. Based on comprehensive acoustic measurements and an extensive marine mammal observational program conducted during the six-day test, we believe that acoustic signal compatibility with marine life is possible. We do not yet know if we can measure travel time to the required precision to actually measure ocean warming; that will require detailed analysis of the data. If all the answers are positive, the next step is to choose source sites for long-term monitoring.

—The Heard Island Principals
Walter Munk, Scripps Institution of Oceanography; Andrew Forbes, Commonwealth Scientific and Industrial Research Organization, Australia; Robert Spindel, Applied Physics Laboratory, University of Washington; Theodore Birdsall and Kurt Metzger, University of Michigan; Arthur Baggeroer, Massachusetts Institute of Technology; and Melbourne Briscoe, US Office of Naval Research.

High-Resolution Optical and Acoustic Remote Sensing for Underwater Exploration

W. Kenneth Stewart

It has become a truism within the marine science community that the surfaces of the moon and other celestial bodies have been better explored than the ocean floor of our own planet. Perhaps less than a tenth of one percent of this vast undersea domain has ever been seen by human eyes. In contrast with remote sensing through the atmosphere, the relatively opaque and inhospitable ocean presents formidable challenges to those who would probe its depths. Impenetrable to most forms of electromagnetic radiation, the ocean yields a picture of the seafloor mainly through acoustic and optical means.

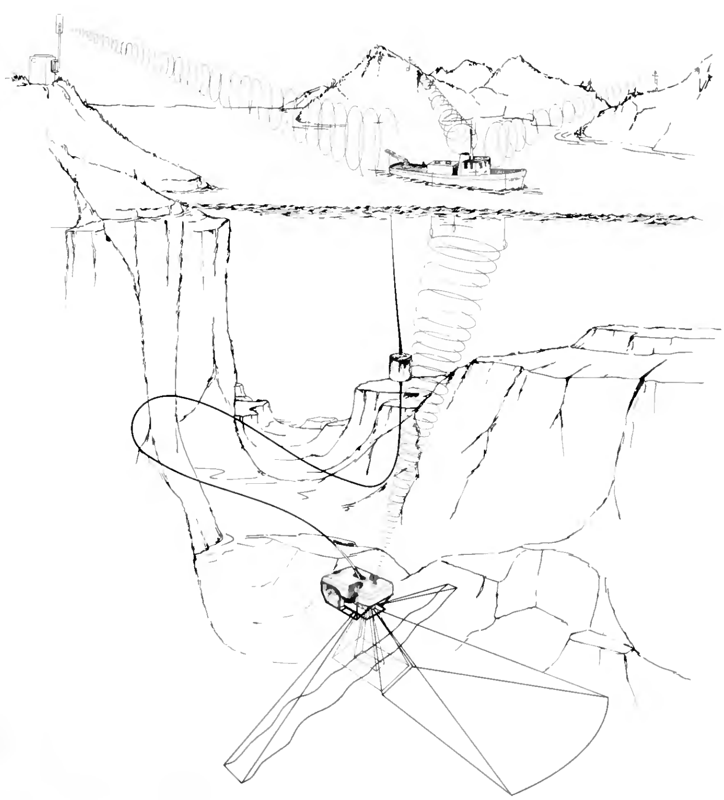
Whether using sound or light, the fundamental trade-off is range for resolution. Low-frequency acoustic systems survey a swath tens of kilometers wide, but they can only resolve features larger than several tens of meters. Higher frequency sonars have better resolution, but coverage is limited. Cameras and other optical systems see greater detail, but image even smaller areas. Special problems with both methods include attenuation, scattering, noise, and distortion; these are compounded by the difficulty of measuring position underwater and deployment costs that rise sharply with depth.

Remote-sensing platforms are under continuous development, promising cheaper, more flexible sensor deployment. The sensors themselves are increasing in range, resolution, and bandwidth, pushing physical limits in many cases. However, the ability of these combined systems to conduct successful and efficient operations demands an acute capability not only to sense and model the undersea environment, but to do so in real time. Further, as our understanding of subsea processes is refined and our questions grow more subtle, the limitations of individual sensors are more apparent.

Considering the full scope of a detailed site survey, for example, a suite of sensors encompassing a hierarchy of range, resolution, and measurement types must be accommodated. Such a mission is shown below: An underwater vehicle can carry different sonars (obstacle avoidance, downlook, sidelook), cameras (video, film, and digital still), a scanning laser, and other sensors (gravity, magnetic field, temperature, salinity, etc.). Though a tethered, remotely operated vehicle (ROV) is represented, this scenario also applies to free-swimming, autonomous underwater vehicles (AUVs) or towed instrument sleds. In all cases, this remote-sensing probe is capable of collecting an enormous amount of multisensor data as it moves through the undersea terrain.

The issues associated with the many different sensing modalities are complex and varied, and cannot be fully addressed here. Instead, I focus on optical and acoustic sensing, two of the more important tools for remote subsea exploration, and illustrate present capabilities with examples from real systems familiar to us at the Deep Submergence Laboratory (DSL) of the Woods Hole Oceanographic Institution (WHOI). If we are to more fully understand our ocean planet, to better protect our common heritage, and to avail ourselves of resources now hidden by an aqueous shroud, then remote-sensing systems offer a practical means of projecting our human senses and capabilities into this mysterious and important realm.

Remote-sensing platforms are under continuous development, promising cheaper, more flexible sensor deployment.



Illustrated by E. Paul Oberlander

A remotely operated vehicle illustrates the exploration process that is also followed by free-swimming, autonomous underwater vehicles or towed instrument sleds. A wealth of information may be obtained as these instrument systems move through the sea, from mounted sonars, cameras and/or various sensors. Data may then be transmitted to land stations or satellite links for timely use.

Remote Sensors Provide Information

Scientists require information, whether represented as a map, an image, or a digital model in a computer, about the physical characteristics of the subsea environment—the shape and composition of the seafloor, for example, to help geologists and geophysicists understand the origin and evolution of our Earth's dynamic (on geological time scales) crust. Biologists want to know the content and distribution of seafloor ecosystems, often over time, to understand their roles within a global ecology and the influence that mankind now exerts on fragile marine environments. Archaeologists, marine policy experts, and other scientists all need facts about our past and present to help shape a propitious future.

Acoustic sensors are often used to sweep a large area and locate possible targets before zeroing in with cameras and video.

Commercial and defense needs also drive the evolution of remote-sensing technology. During search and survey, whether for natural or man-made objects, acoustic sensors are often used to sweep a large area and locate possible targets before zeroing in with cameras and video. Offshore resource exploration—including oil, minerals, and sand or gravel for the construction industry—involves using acoustic and optical sensors of various types and capabilities. Preinstallation surveys and in-place inspection of transoceanic cables, oil and gas pipelines, and offshore production platforms all depend on remote underwater sensors.

Of value, also, is the role of remote sensors in promoting public awareness of the richness and diversity of our subsea domain. Whether vicariously swimming through a coral reef, watching the camera view as an ROV pilot navigates among "smoking" hydrothermal vents, or observing a sonar display as it recreates the three-dimensional shape of a sunken warship, the remote viewer shares an experience with lasting impressions. This kind of experience can foster an ambition in young people to prepare for a career in science or engineering to participate in the exploration, exploitation, and preservation of our ocean resources.

To help satisfy all these needs, visual images derived from remote sensing allow us to take best advantage of our highest-bandwidth sense—about half our brains are devoted to visual processing. Visual images permit a more natural interpretation of remotely sensed data and offer the only realistic means of digesting the massive information flow now available from today's high-resolution devices. Still, an image, like a map, is really a model of what our sensors perceive about the subsea environment. It is a representation, poor in some cases, of physical characteristics being observed, for example, shape (bathymetry), or optical and acoustic reflectivity.

Looking Through the Ocean Medium

Though the underlying physics of optical and acoustic sensing are quite different, the difficulties inherent in applying the two approaches underwater are similar in fundamental ways. Light is a form of electromagnetic energy, as are radio waves and X-rays. Sound, though, is more a mechanical phenomenon, dependent on the alternate compression and expansion of its medium (air or water) as it propagates. Light is sensed at our retinas by electrochemical means; sound produces vibrations at our eardrums. In most modern systems, remote-sensing transducers convert the two forms of energy to electrical signals.

In both cases, we rely on an ability to detect energy arriving along a known path. By detect we mean that our receiving device has enough sensitivity to measure the signal (the arriving energy we want to observe) and that the signal is not overwhelmed by noise (any other form of energy the receiver is sensitive to, but in which we are uninterested). If the signal-to-noise ratio is high enough, or if the signal is repeated in some way to help distinguish it from the noise, then we can derive information from the detected signal. Trying to carry on a conversation at a crowded restaurant is a very direct analogy.

Dynamic range is related to the sensitivity of optical and acoustic devices. If the signal level is too high, the receiver can become saturated and additional increases are "wasted." Ruptured eardrums are an extreme indication that the highest sound level the human ear can use has been exceeded. Similarly, highly sensitive cameras developed for low-light-level, underwater use can be ruined by exposure to direct sunlight. What we are really interested in is the number of different signal levels, between the lowest measurable and highest useful, that can be distinguished: This defines a sensor's dynamic range. A device combining high sensitivity and wide dynamic range usually provides more information than a receiver boasting just one of these qualities, as more subtle features of the environment can be detected.

The term "bandwidth" is sometimes used imprecisely, but often connotes a rate of information availability. High-bandwidth television channels convey more information than lower bandwidth telephone lines (a picture is worth a thousand words). Higher bandwidth sensors convey more information by combining wider dynamic range, greater resolution, and faster areal coverage than their lower bandwidth cousins. A precise definition of resolution is the ability to distinguish between two closely situated features; what is usually meant, though, is the ability to sense finer detail.

As an optical or acoustic signal travels through the water it is attenuated, or weakened, because of spreading loss, absorption, and scattering. Spreading loss is as simple as it sounds: Optical and acoustic energy spread out like a flashlight beam, becoming weaker with distance. Absorption also applies to optical and acoustic signals alike, but is more complex. Basically, a frequency (wavelength or, in the case of light, color) dependence governs how much sound or light energy is lost. The lowest levels of light absorption occur for wavelengths (of about 520 nanometers) that correspond to a blue-green color. This is why the ocean appears to have its characteristic hue: Red wavelengths are attenuated rapidly, while more energy from the deeper-penetrating blues is scattered back to our eyes. Similarly, absorption explains why optical images taken underwater usually have a bluish tint, and why the spectacularly colorful images from coral reefs are always close-up views. There are further, significant implications in the design of underwater lighting sources and in the choice of blue-green lasers as optimum for greatest underwater range.

For acoustic systems, absorption losses rise steadily with acoustic frequency. Because of other factors, we cannot simply increase the transmitted energy of higher frequency sonars to achieve greater range, but

As an optical or acoustic signal travels through the water it is attenuated, or weakened, because of spreading loss, absorption, and scattering.

instead must use lower frequency systems to survey larger areas at a reasonable level of effort. The trade-off is that lower frequency acoustic systems also have lower resolutions. To conduct the highest resolution acoustic surveys, a high-frequency sonar must be positioned near the bottom. Such a system covers a narrower swath than a lower frequency sonar and, because the rate of advance is limited by the speed of sound in water (a constant), higher resolution survey time and costs are greater than for lower resolution coverage of an area the same size.

As they propagate through water, light and sound are further weakened by scattering from bubbles or suspended particles. In other words, the energy is reflected away from the receiver, lowering the signal-to-noise ratio: This is called forward scattering. For sonars, forward scattering is usually a problem only at the highest frequencies. For optical sensing, though, it is a significant determinant of underwater range. Forward scattering also decreases overall resolution. Our terrestrial analogy is trying to see clearly in fog or thick smoke: Not only is visual range reduced, but edges appear fuzzy and fine details cannot be resolved.

Fortunately for our work, the deep ocean is often nearly crystal clear.

Scattering is also a source of noise. Back-scattered energy, that unwanted portion scattered directly back toward the sensor before illuminating a target, can mask useful information received at the same time. Signal-to-noise ratio again suffers, not because the signal has weakened, but because the noise level is stronger. The fog-and-smoke analogy also illustrates this problem. Most motorists know that using high-beam headlights in fog actually reduces visibility. This is because light is being back-scattered more directly into the eyes, masking the "signal" of, for example, an oncoming truck, which the driver would like to detect. In a back-scatter-limited underwater environment, increasing the lighting power serves no purpose, since scattering increases proportionally with illumination energy. The solution in underwater optics, similar to that of switching to an automobile's more downward-pointing low beams, is to separate camera from lights, thereby increasing the proportion of forward- to back-scattered energy and enhancing the signal-to-noise ratio.

Fortunately for our work, because of the distance from major inland and coastal sediment-transport mechanisms, the deep ocean is often nearly crystal clear. Exceptions occur in regions of heavy marine "snow" or around sites of thermal-vent activity. (As an aside, the color of inland and coastal waters as seen from the surface often contains more components of brown, yellow, and red because the high incidence of back-scattering particulates do not allow for much light penetration and the concomitant predominance by the blues.)

Back-scattering can also be a problem in acoustic sensing. In this domain, however, it is usually referred to as "reverberation" and can be caused by volumetric or sea-surface effects. A somewhat similar source of acoustic noise is "multipath," where a signal echoes from multiple seafloor features before arriving back at the receiver. These effects can either mask the desired signal, or result in the "detection" of targets at a false range. A familiar analogy is the degraded sound quality in a poorly designed concert hall, where echoes from hard surfaces muffle the more subtle undertones of fine instruments and musicians. Television "ghosts" in urban or mountainous locations are caused by electromagnetic multipath, as attenuated replicas of the signal arrive with successive delays.

Particularly in acoustic remote sensing, environmental noise can have significant effects and may be the primary determinant of maximum range. In both optical and acoustic domains, maximum range is a function of decreasing signal-to-noise ratio as the signal attenuates (or noise increases), until the lowest threshold of detection is crossed. At the lowest frequencies, earthquakes and man-made explosives predominate and can carry for great distances. At increasing frequencies, shipping sounds begin to govern the equation until such effects as ocean waves, even heavy rains and surface spray, become the main sources of noise.

The ultimate limit in acoustic sensing is set by thermal noise, which causes a random molecular agitation against sensitive, very-high-frequency transducers. Also limited by thermal noise, sensitive optical devices are designed to overcome the same obstacle to increased performance. These electronic still cameras (ESCs) were developed for astronomers to detect the faintest of optical signals from distant stars, and are designed for work underwater at very low light levels. The most advanced devices are enhanced by tiny refrigeration units with cooling surfaces that attach directly to optoelectronic transducers. At subfreezing temperatures the thermal noise floor is lowered, and these sensitive CCD (charge-coupled device) microchips can detect even a few photons, the smallest measure of optical energy.

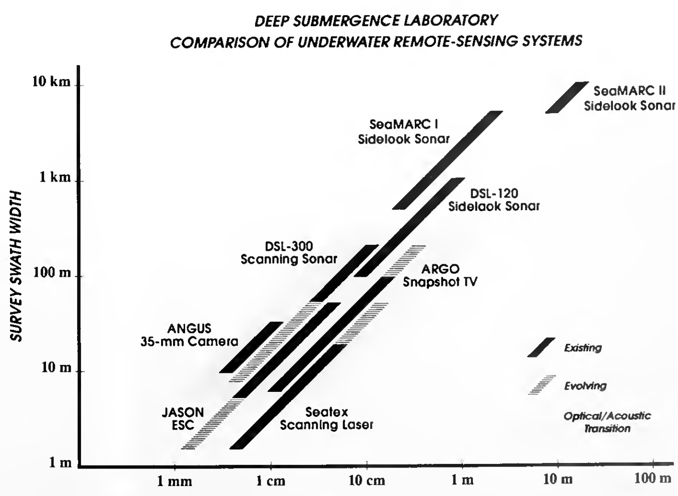
Range for Resolution: No Free Lunch

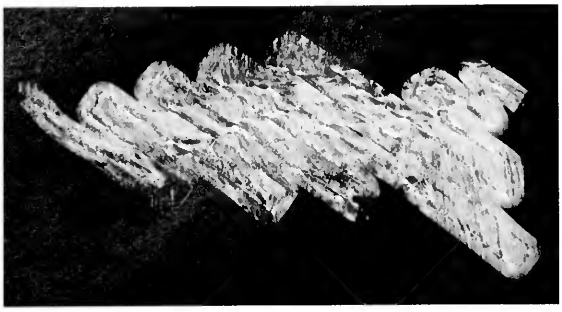
Despite our best efforts to design good remote sensors for underwater applications, the laws of physics are immutable. The most fundamental trade-off imposed on us is that of range for resolution. The determinants of resolution are more complex than the diagram below suggests, but some simplifying assumptions (and artistic license) have been invoked. The main point is that no single tool or sensing modality suffices for all needs; rather, we require a complete tool kit comprising low-frequency, wide-swath sonars for mapping large ocean areas at relatively coarse scales, and high-frequency acoustic and optical systems to provide detail in regions of particular interest.

As shown schematically, a hierarchy of optical and acoustic remote-sensing tools is at our disposal.

At the top right in the figure, the SeaMARC II sonar is somewhat out of place: It is a near-surface-towed system, incapable of achieving the higher resolution of the other systems shown. This statement does not in any way diminish the importance of SeaMARC II or of other sonars in its class, but rather illustrates the differences between lower and higher resolution sensors. The 12-kilohertz sonar, operated by the Hawaii Institute for Geophysics, is a community workhorse and is responsible for much of our current understanding of large-scale geological processes.

Two acoustic "images" created at DSL from SeaMARC II data are illustrated on page 16. The wide-swath, split-beam sonar (so called





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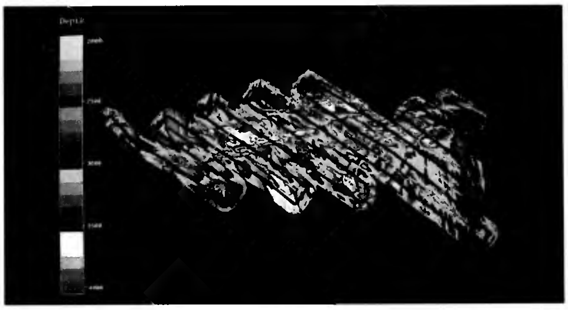


B

These acoustic images of the Siqueiros Transform were created from SeaMARC II data. The acoustic imagery reveals fine structure (A); bathymetry yields less detail, but provides quantitative shape formation (B).

because its dual receivers and twin sonar beams on each side extract acoustic phase differences for measuring bathymetry) can cover large areas at economic rates. The region shown is part of the Siqueiros Transform, a site where the Pacific plates are separating and sliding past one another. The acoustic imagery (**A**, above) is created by measuring the intensity (amplitude) of sound echoing back from the seafloor. Like a huge fax machine, the sonar's narrow horizontal beams, directed to either side, sweep out an image of the seafloor 10 kilometers at a time. The serpentine track covers a 135-kilometer region in the east-west (right-left) extent, and requires about two weeks of expensive ship time to survey. Here, the back-scattered sound contains information and constitutes the signal we wish to detect. This should not be confused with the "uninteresting" forms of back-scatter described earlier.

Acoustic-intensity images are like optical photographs. Though they contain high-resolution detail and provide information about finer-scale geologic structure, they do not represent shape directly. Our interpretation of shape comes from a brain evolved for complex visual processing and adept at pattern analysis. Two-dimensional projections of a three-dimensional world can be very misleading, though, as optical illusions confirm. Acoustic imagery can be still more difficult to fathom, even for an experienced marine geologist with eyes and brain accustomed to the task. SeaMARC II bathymetry (**B**, above), however, offers geologists and geophysicists direct measurements of seafloor morphology, adding another dimension to the information available to them in their quest for understanding tectonic activity.

Raw acoustic data are not nearly as useful as the final maps shown. Besides the corruption from noise sources described earlier, geometric distortions are also present. The raw data of SeaMARC I (30 kilohertz) are shown in unprocessed form (**A**, right). What seems to be a 5-kilometer wide, straight-line swath becomes the sinuous track of shown (**B**, right) when the data are digitally corrected for navigation and tow-fish heading (towed platforms are often referred to as "fish"). With the use of several DSL techniques for acoustic enhancement to remove noise and bring out more detail in the processed image, the volcanic mounds, lava flows, and cracks in this portion of the Galapagos rift (another site of ongoing tectonic activity) become more apparent to marine scientists.

The SeaMARC I is an older sidelook sonar system once owned and operated by DSL (now resting on the rugged seafloor off Puerto Rico; such are the vagaries of near-bottom towing in "interesting" terrain).

Without the more sophisticated split-beam design, systems of this class can only produce imagery such as that shown below. Acoustic shadows, clearly seen along the right edge of the image, are caused by protruding features that interrupt the returned signal. The mechanism is identical to that causing optical shadows, and can be used by the trained eye to infer relief. However, low-intensity regions of an acoustic image also result from the lesser scattering strength of different materials—mud or sand, for example, when contrasted with coarse gravel or rough volcanic debris. Without the benefit of bathymetric information, intensity variations caused by relief cannot be reliably distinguished from those caused by variations in back-scattering strength.

Acoustic scattering strength depends not only on material type but also on frequency and angle of incidence. In spite of this apparent complexity, the situation is familiar and comfortable in our world of optical sensing (or vision). Materials reflect or scatter light of different frequencies (or colors) in different ways. As light strikes surfaces at varying incidences (or grazing angles), the intensities vary between light and dark. Smooth, specular surfaces reflect light away from the source; if you shine a flashlight at a mirror angled away from you, little light is reflected back. Rougher, matte surfaces scatter incident light in all directions, and a portion is back-scattered toward the source. Smooth surfaces also reflect more acoustic energy away from the sonar, and appear as low-intensity regions that are easily confused with acoustic shadows.

There are two points here. First, although the laws of physics governing optical and acoustic remote sensing are quite different, the information ultimately extracted from the raw signals must be interpreted with similar regard to material properties, surface shape, and lighting (ensonification) geometry. Second, shape and intensity information together are more useful than either alone, and can help to better identify physical properties of interest. They can also be used in a complementary visual way. For example, "draping" higher-resolution SeaMARC I data over a three-dimensional perspective view derived from coarser, 13 kilohertz acoustic bathymetry yields a detailed image that provides shape cues to assist in geological interpretation. The whole is greater than the sum of its parts.

This SeaMARC I imagery from the Clipperton Transform compares unprocessed data (A) with geometrically corrected and radiometrically enhanced results (B).

A

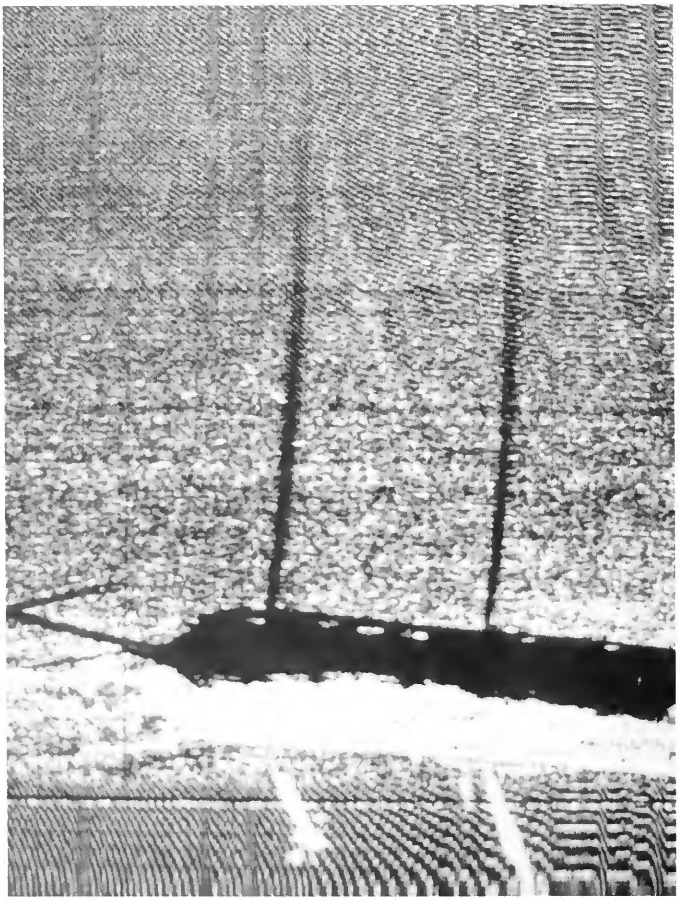
B

A New Tool Kit for Underwater Archaeologists

Archaeology presents one of the greatest challenges to remote sensing underwater. Not only does an archaeologist need images of the highest quality and resolution, but quantitative spatial measurements are fundamental to the field. In the past, this has meant sending divers to the bottom with tape measures and hand-held cameras; a terrestrial archaeologist's tools and techniques were augmented only by a scuba tank. Time on the bottom was limited, deeper sites were out of reach, and efforts were painstakingly slow. Low visibility, strong currents, and other vagaries of working underwater made this an arduous, often hazardous undertaking.

With improvements in sensors, platforms, and techniques for marine exploration has come a new approach to underwater archaeology. From depths prohibitive to human divers, ROVs now send back acoustic and optical data to archaeologists safe and comfortable aboard ship. Sonars give the "big picture," and acoustic data can be processed to extract spatial information including shape and relative placement of any artifacts. Still cameras and video document the fine-scale features, allowing an archaeologist to identify and date underwater relics. These are facilitated by new computational and graphics technologies that afford scientists and engineers a visual means of digesting the massive information flow from state-of-the-art sensors and platforms.

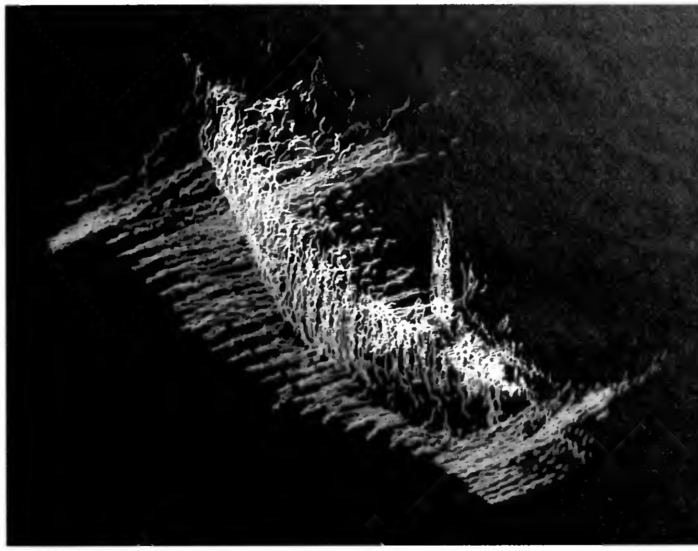
A two-dimensional sidelook-sonar image of USS Scourge *reveals the acoustic shadow.*



The sidelook sonar image of the USS *Scourge* at left was generated by the DSL-200 system during the course of a two-week archaeological survey with the ROV *Jason*. *Scourge* and her sister ship *Hamilton*, merchant ships converted to US gunboats during the War of 1812, were capsized by a sudden squall and now lie nearly upright at a depth of 90 meters, not far from Niagara Falls, New York. The wrecks remain in pristine condition, preserved by the frigid, low-oxygen bottom water of Lake Ontario. In this image, the prominent feature is an acoustic shadow; the bright region at the bottom is the ship itself, saturated by strong returns from below the vehicle. Outlined by the acoustic source, *Scourge's* two masts, bowsprit, and a dangling spar are visible; bright rectangles along the top rail are acoustic returns through the open gun ports.

For better definition of three-dimensional shape, a 675-kilohertz scanning sonar gives quantitative results. The wire-frame projection opposite was produced on-site in near-real time, with only 20 minutes of survey data.

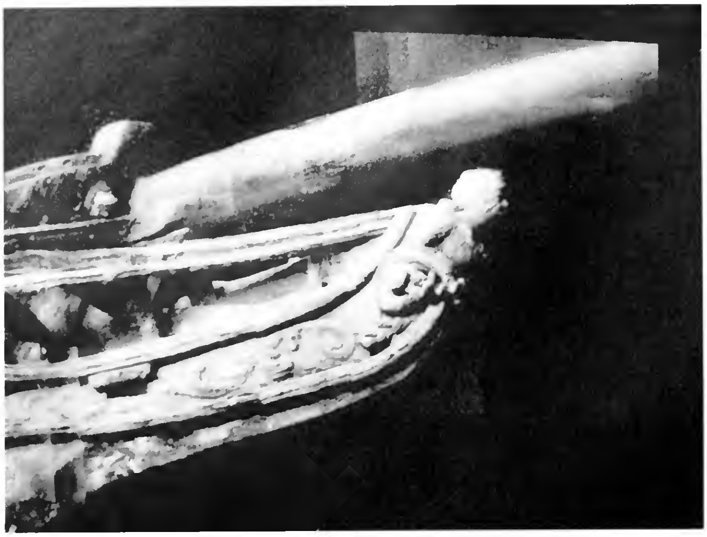
The view was generated during repeated traverses along *Scourge's* starboard side, clearly delineating the forward mast, bowsprit, and spar seen in the sidelook image. Such real-time visualization techniques should become an important part of an underwater archaeologist's tool kit, allowing scientists and engineers to develop strategies on-site, based on remote-sensing results, and to make more efficient use of costly survey time.



A more refined three-dimensional model (below right) of USS *Monitor*, the sunken Civil War ironclad, was created from data generated by the same scanning sonar during an earlier survey. More sophisticated processing has been applied to give a better representation of the wreck. After capsizing and sinking in a storm, *Monitor* lies upside down, its port side resting on the cylindrical gun turret (just visible at upper left). The prominent feature skirting the hull on the left is a massive, 1-meter-thick armor belt, which retained its shape after corrosion took its toll on the ironclad ship. The stern has broken away and the starboard side lies partly buried in the sand. An animated "swim-around," a technique that creates an impression of flying through the terrain, has also been produced from the three-dimensional data to give archaeologists a better overall picture of *Monitor's* condition.

The three-dimensional scanning-sonar view of USS Scourge *(top) was created in near-real time. A three-dimensional perspective of Civil War ironclad USS* Monitor *(bottom) was also created with data from scanning sonar; processing methods were then applied to yield a better picture of the wreck.*

Despite the increasing amount of information that sonars now provide, optical sensors will always surpass their capabilities in terms of resolution. A photomosaic of USS *Hamilton* (next page) illustrates how electronic still camera (ESC) images can be digitally combined to produce a more complete picture of the wreck, while an archaeological survey is still underway. A custom application was developed at DSL to enhance the raw images before interactively combining them on a computer screen. Similar to using a light table, a new image is selected (by pointing with a computer mouse), dragged smoothly around the display, panned, zoomed, then blended with the composite image. Contrast this efficient shipboard process with earlier efforts to produce a *Monitor* photomosaic, a laborious six man-month effort that required considerable skill with an enlarger to remove distortion, repetitive trips to the darkroom, and much cutting and pasting.



The Optical Imaging Revolution

Optical imaging (underwater photography) has long been a mainstay of detailed seafloor investigations. However, advances in cameras, image processing, and, especially, direct digital transmission and picture manipulation are revolutionizing our approach to remote sensing using light in the sea.

Early vehicles operated by DSL, such as ANGUS (Acoustically Navigated Geological Underwater Survey), were battery operated, with no power or communications links to the support ship above. Onboard film cameras recorded still frames at preprogrammed intervals as the vehicle was towed blindly over a region of suspected interest. When the film ran out, the fish was winched to the surface, brought aboard ship, and its film magazine removed for onboard development (in later years) in a complex, chemical processing facility. The crew waited with breaths held to see if anything of interest had been recorded or if, in fact, the camera had worked at all. Despite these limitations, ANGUS was instrumental in helping scientists uncover surprises from the deep, such as the hydrothermal vent communities shown below.

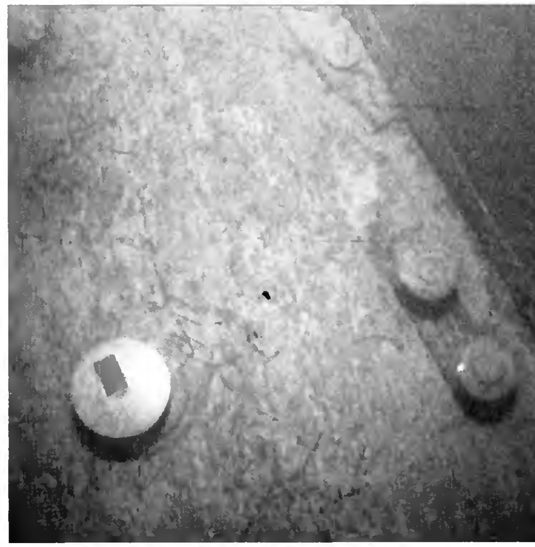
USS Hamilton *is recreated in this electronic-still-camera (ESC) photomosaic.*

The successor to ANGUS, the Argo towed platform, could send back live video images at depths of up to 6,000 meters. An image of the sunken *Titanic* recorded from Argo's sensitive video SIT (silicon-intensified target) camera is shown opposite. Instead of waiting a day or longer to view ANGUS footage, scientists and engineers could now be alerted as soon as a target was located, and the ship could be maneuvered to bring Argo around for a better view. Despite this major advance, Argo's low-bandwidth communications link limited surface viewing to relatively low-resolution, black-and-white images.

ANGUS captured this hydrothermal vent site, complete with tube worms and clams.

Argo was also equipped with the first-generation ESC and could send back digital images, though at a much slower rate than video. The additional advantage is that digital images, still subject to poor underwater lighting and other sources of noise, could now be fed directly to a computer for digital enhancement. The ESC images of a sunken helicopter (facing page) give an example of how such enhancement takes place. The raw image has typical low-contrast characteristics. Histogram equalization brings out more detail in the image by "stretching" the intensity values over a greater dynamic range; adaptive histogram equalization brings out even more detail, and lessens the effects of uneven lighting by optimizing the contrast within local regions. Finally, the image can be digitally cropped, enlarged, and rotated to provide the most information to users aboard ship. These images can then be combined to yield a more complete picture of the subject.

More recently, the real-time communications logjam has been broken by the advent of new fiber-optic cables and laser communications links. Equipped with this new high technology, the ROV *Jason* and its support vehicle *Medea* can now transmit back several channels of live, broadcast-quality color video from different camera views, along with high-bandwidth, digital sonar data and information from other sensors at the same time. Over the last two years, this remote-sensor view of undersea operations has also been transmitted live over satellite communications links to 14 sites in North America. By sponsoring such programs, the JASON Foundation for Education hopes to reach millions of students and share with them the excitement of exploring our ocean planet.



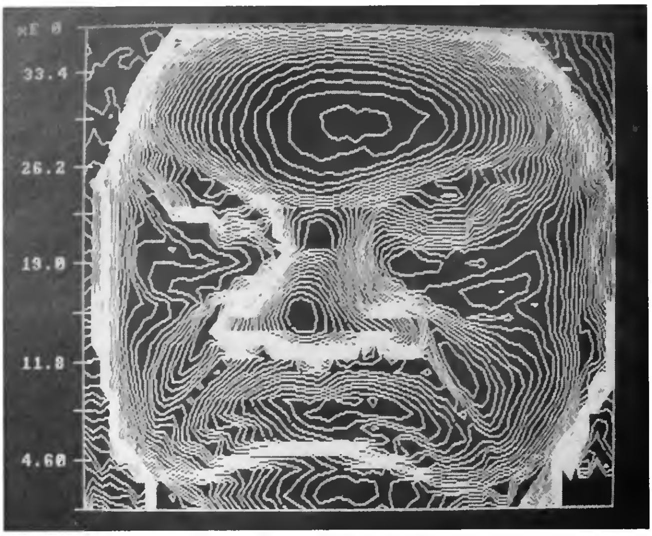
The Argo SIT camera recorded this image of the Titanic *bow, located at a depth of 13,000 feet.*

The Future

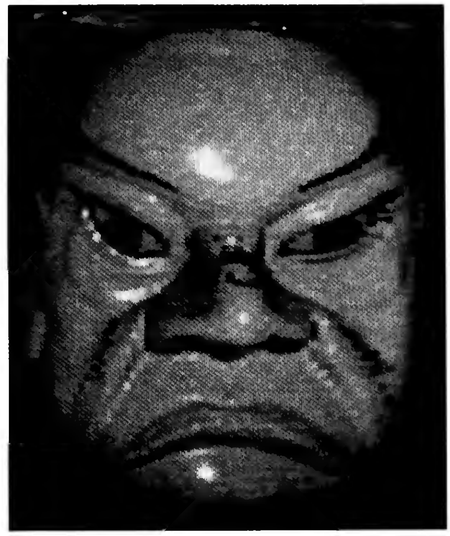
For marine geologists, archaeologists, and other consumers of underwater remote-sensing and visualization technologies, the outlook is rosy. New platforms, AUVs as well as ROVs, are under continuous development, promising cheaper, more flexible sensor deployment. Existing sensors, or newer cousins, are increasing in range, resolution, and bandwidth, pushing physical limits in many cases. Scanning lasers now available for underwater applications are capable of higher angular resolution and faster scanning than sonars. They can also generate monochromatic imagery combined with precision range maps, as shown by the figures on page 22.

Real-time capabilities are expanding, bringing the benefits of operational feedback that afford an opportunity to modify search-and-survey strategy in accordance with results. In view of the high cost of

Several Argo ESC images were combined to form a photomosaic of a sunken Navy helicopter.



A



B

A scanning laser image of a Chinese mask is shown above in two forms: (A) a contour map, and (B) monochrome imagery. (Courtesy of Seatex A/S.)

at-sea operations, this is an important factor in making more efficient use of expensive shipboard resources. In particular, a viable approach is to conduct a "coarse-to-fine" multiscale survey in which wide-swath, low-resolution sensors first identify features of interest for investigation at increasing resolutions in more tightly focused regions. Also, more processing can now be undertaken at sea, reducing cost and delay and allowing results to be disseminated more quickly. A goal of many is to provide the scientist a finished product to carry off the ship. (For the operator of an ROV, all the accoutrements of "virtual reality" systems may also become useful in easing the pilot's load.)

At the same time, rapidly evolving computer, graphics, and video technologies are having a profound effect on the way underwater science and engineering are being conducted. Analytically and conceptually, they extend our reach and yield more timely and more complete feedback, reducing cost and delay. As these new visualization tools are put into the hands of the end users themselves, scientists and engineers benefit from directly controlling the form of the products of their data and of their imaginations. And with the new information technologies, interesting results and techniques will be communicated more quickly, widely, and effectively.

Acknowledgements: Hamilton and *Scourge* data came from a field survey conducted under auspices of the JASON Foundation for Education and the Corporation of the City of Hamilton, Ontario, Canada.

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SOFAR Floats Give a New View of Ocean Eddies

Philip L. Richardson

There is something wonderful about a subsurface float trajectory. It provides a visualization of water parcel movement in the interior of the ocean that is available from no other technology. Sound Fixing And Ranging (SOFAR) floats are freely drifting, acoustically tracked subsurface floats. During the last 18 years, American scientists have obtained 230 SOFAR float trajectories in the North Atlantic. Most trajectories are so convoluted, however, that it is difficult to see patterns, and we must calculate statistics of the velocity field and plot maps of mean velocity and eddy kinetic energy to obtain an overview. These maps tend to obscure individual eddies and other details of the flow field, and we must return to the plots of individual floats to see them.

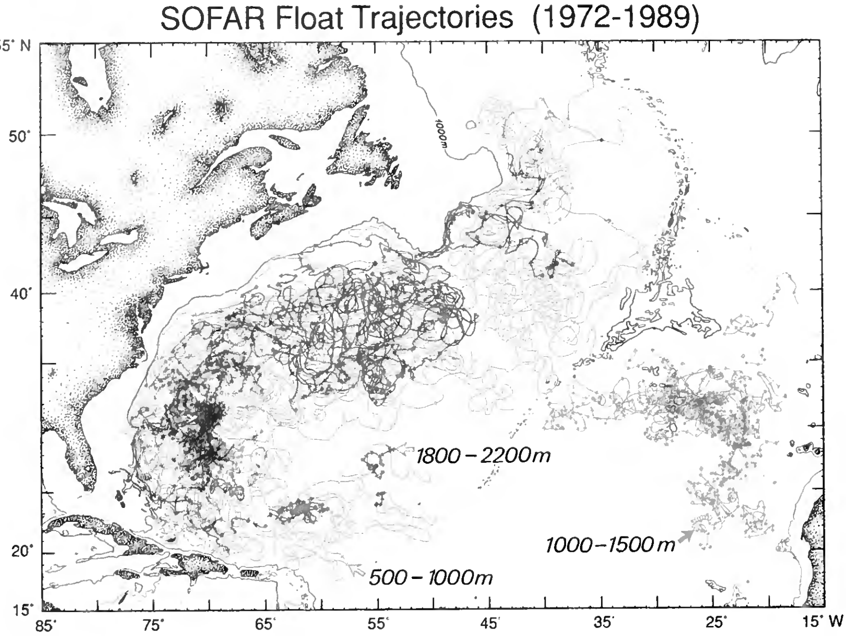
Recently I have explored the float data set to learn about discrete eddies in the ocean, in particular their distribution, number, paths, interactions, sizes, and speeds. Because the float data are so numerous, we can piece together eddy patterns at different depths over a large part of the North Atlantic. Some striking patterns emerge.

Parcels of water move in very complex patterns that must be seen to be believed.

Float Trajectories

Beginning in the early 1970s, SOFAR floats were used in a series of experiments to explore and study specific ocean features, regions, and depths. Over the years the lifetime of the average float has increased, from a few days to a current world record of nine years. At present there are over 240 SOFAR float-years of data in the North Atlantic at depths from 700 to 2,000 meters. Additional data sets being recorded continuously at an accelerated rate are a truly great resource for ocean circulation studies.

A summary figure on the next page showing the accumulated float trajectories reveals where the data were measured and conveys some idea of regional differences and the complexities of water movement. Details of the flow field are difficult to see in the figure because of the tangled appearance, which is a measure of the time variations of the ocean, or, more simply, ocean eddies. Parcels of water move in very complex patterns that must be seen to be believed. Colors represent

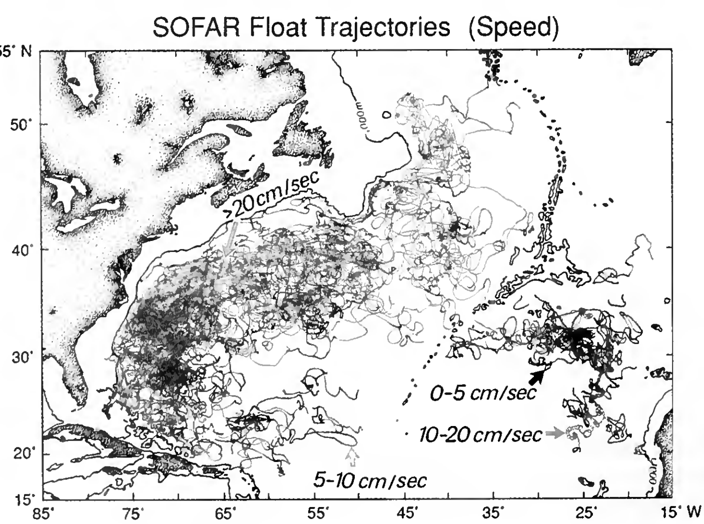


North Atlantic SOFAR float trajectories are easily recognized using color coding to signify float depths. Red denotes floats near 700 meters; green, near 1,300 meters; and blue, near 2,000 meters. Arrowheads indicate 30-day intervals along the trajectories. Most trajectories exist in and south of the Gulf Stream.

velocities in the figure below: Red indicates the fast-moving Gulf Stream, Gulf Stream rings, and the Stream's fast extension into the Newfoundland Basin. Blue and black identify the slow-moving waters of the Sargasso Sea. Float velocities recorded in eddies tend to be faster than those in nearby background floats.

Discrete Eddies

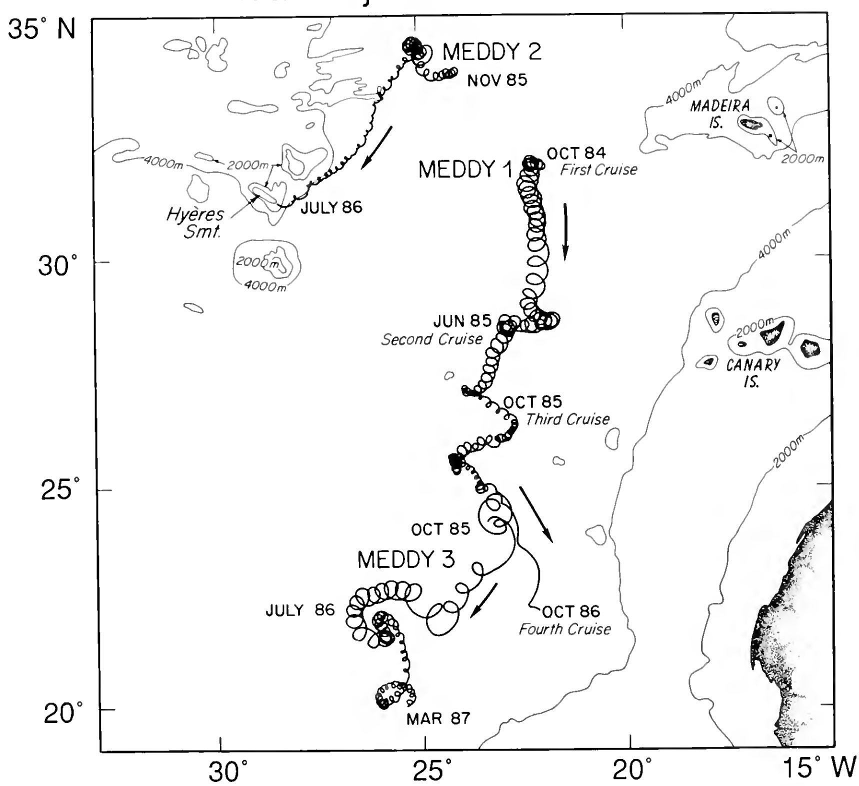
Eddies can be thought of as ocean weather; they are analogous to the atmospheric high- and low-pressure cells seen in daily weather maps. The diameter of discrete ocean eddies is typically a few hundred kilometers. The current swirling around eddy centers reaches several knots, and



In this summary of SOFAR float trajectories, colors signify float velocities. Red shows floats drifting faster than 25 centimeters per second; green, 10 to 25 centimeters per second; blue, 5 to 10 centimeters per second; and black, less than 5 centimeters per second. One knot equals approximately 50 centimeters per second. The color patterns reveal the fast-moving (red) Gulf Stream, its rings on either side, and its extension into the Newfoundland Basin. Slowest moving waters (blue-black) are in the Sargasso Sea near 25°N, 50°W.

is usually much larger than average currents. Eddies are important to study because they give clues to ocean dynamics and help identify sources and sinks of energy. They are thought to be dynamically significant in driving the mean flow in regions of high eddy energy. Although the presence of discrete subsurface ocean eddies has been known for many years, detailed information about eddy life cycles and movement through the ocean has remained elusive because of the difficulty in measuring continuously flowing eddies.

Float Trajectories in Meddies

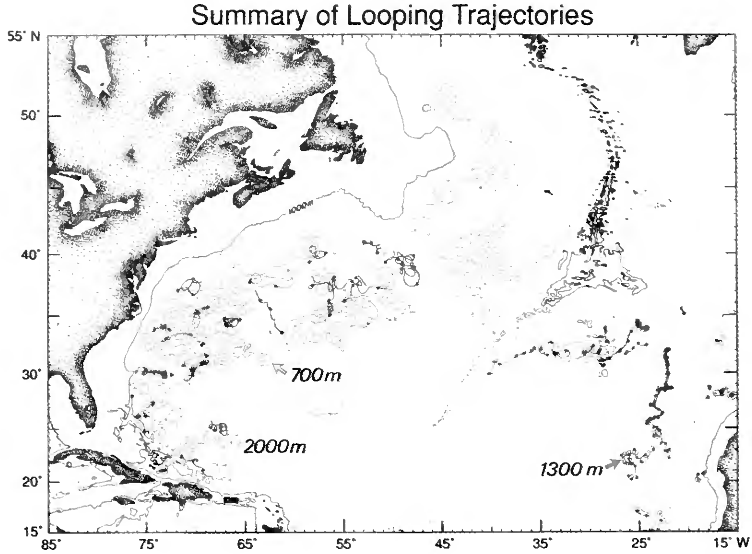


The paths of three salty Mediterranean water eddies (Meddies) in the Canary Basin are illustrated by the SOFAR float trajectories. Meddy 1 was tracked for over two years during 1984 to 1986 with five floats as it drifted 1,090 kilometers southward with a mean velocity of 1.8 centimeters per second. Four shipboard surveys revealed the nearly total decay of Meddy 1 by gradual mixing processes. Meddy 2 drifted 530 kilometers southwestward with a mean velocity of 2.3 centimeters per second until it collided with Hyeres Seamount (when the two floats in it abruptly stopped looping). Meddy 3 drifted 500 kilometers southwestward for a year and a half at 1.1 centimeters per second. The float loops are clockwise, and reveal solid-body rotation rates of four to six days for these Meddies.

Many floats were trapped in the strong flow around discrete eddies and looped around the eddy centers as the eddies moved through the ocean. Some of these floats looped long enough to reveal interesting eddy trajectories and eddy properties, such as rotation direction and rate. This unique float information provides a new picture of the behavior of subsurface eddies in the ocean.

Three Mediterranean water eddies (Meddies) were tracked in the Eastern Atlantic for long time periods. One float tracked an eddy for 114 loops over 821 days. This long-lasting eddy was measured by ship (with conductivity/temperature/depth or CTD profiles) several times during its life as it drifted southward and slowly decayed. This Meddy can be seen in the figure above located near 22°W between 22° and 32°N. Another of these Meddies was observed to crash into some tall undersea mountains where it disintegrated (near 31°N, 28°W). The third Meddy drifted southwestward for a year and a half.

Float trajectories that consist of two or more consecutive loops in the same direction imply the presence of discrete eddies. Overall, 15 percent of float trajectories are loopers. Higher percentages exist at 700 meters in the Newfoundland Basin (47 percent), and in and south of the Gulf Stream (20 percent). A low percentage (about 4 percent) occurs at 2,000 meters and in the southern Sargasso Sea.

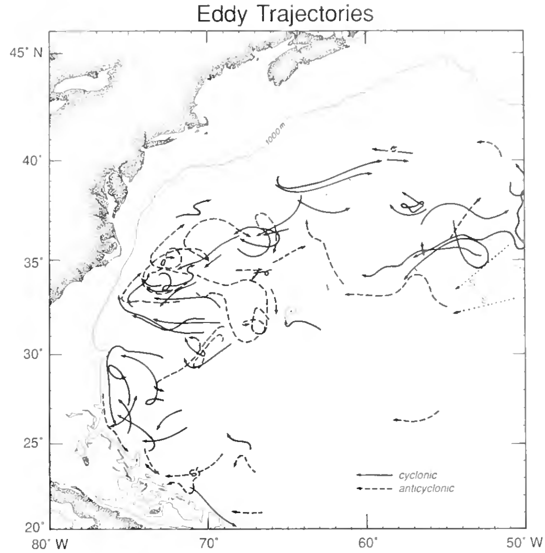


To learn more about ocean eddies, I systematically studied all looping trajectories (loopers) looking for patterns. The first task was to look carefully at each float trajectory and identify looping portions within discrete eddies. I defined loopers as floats making at least two consecutive loops and identified 119 separate ones. Occasionally an eddy trapped more than one float, which reduced the number of different eddies involved to 104.

The highest density of loopers occurred at 700 meters in the Newfoundland Basin and south of the Gulf Stream. In the Newfoundland Basin approximately half (47 percent) of all possible trajectories are loopers, implying that half of that area consists of closely packed eddies. This was reinforced by the individual float trajectories observed there; floats seemed to jump from one eddy into another with little time between. One float looped there for 560 days in seven different eddies, the most sampled by any float. In the Gulf Stream region approximately 20 percent of the trajectories were loopers. The percentage of loopers decreased dramatically with depth to around 4 percent at 2,000 meters in the vicinity of the Stream.

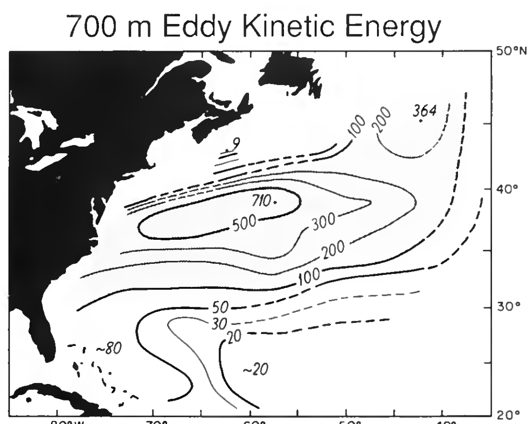
It is interesting that overall nearly 50 percent of the loopers rotated clockwise and 50 percent rotated counterclockwise. However, the distribution of rotation direction varied enormously in the North Atlantic. Almost all loopers in the East Atlantic at 1,100 meters rotated clockwise, presumably because they were all formed in a similar way from the salty tongue of Mediterranean water emanating from the Straits of Gibraltar. The best examples are the Meddies, but three other slower-rotating eddies were also observed. Offshore of the Gulf Stream and in the Newfoundland Basin only one out of three or four loopers rotated clockwise. This was probably due to the many strong counterclockwise-rotating eddies or rings that pinch off there from Gulf Stream meanders.

Trajectories of the eddies were visually estimated from the looping float trajectories and are summarized in the top figure on page 27. Eddies generally (but not always) drift southwestward at a rate of 1 to 3 kilometers per day. This seems to hold true for eddies in the East Atlantic, in the interior Newfoundland Basin, and south of the Gulf Stream. A noticeable exception is in or very close to the Stream, and its northward extension in the Newfoundland Basin, where eddies appear to be advected downstream in the Stream. A second exception is close to the western boundary (south of 30°N), where several eddies drifted southward, presumably advected by a southward boundary current there.



Trajectories of discrete eddies may be inferred visually from looping floats in the western North Atlantic (shown in the previous figure). Two record holders for length of time tracked are a warm core eddy (A) tracked for 431 days (over 40 loops) by two different floats, and a cold core Gulf Stream ring (B) tracked for 361 days (26 loops). Solid lines indicate counterclockwise (cyclonic) eddies, dashed lines are clockwise eddies.

These discrete eddies identified in float trajectories are being studied in greater detail to learn more about their characteristics and their role in the general ocean circulation. A clearer view of the complex patterns of ocean motion is revealed by the float data. Statistical summaries of mean velocity and eddy kinetic energy are used to help describe the flow field and create and improve models of the general circulation. The float data, combined with current meter records and hydrographic profiles, help us determine the mean circulation in the Gulf Stream system.



This contoured map of eddy kinetic energy at 700 meters is based on grouping individual velocity measurements in 2° latitude by 5° longitude boxes. Dashed contours indicate gaps in the 2-by-5 grid. High values greater than 500 centimeters squared per second squared (centimeters^2/second^2) are centered in the Gulf Stream, with an extension into the Newfoundland Basin. Relatively high values of 80 centimeters^2/second^2 are located along the western boundary south of 30°N. Values around 20 centimeters^2/second^2 are centered in the region surrounding 25°N, 50°W, the eddy desert.

Present and Future Float Experiments

Presently the "float group"* at the Woods Hole Oceanographic Institution (WHOI) is doing two experiments. One is a feasibility study of float tracking in the Arctic under ice. Ice reduces tracking range, and there are very few current measurements for this area. We intend to measure the general circulation. The other is a study of cross-equatorial water exchange between the North and South Atlantic. We obtain float trajectories to investigate the large-scale meridional transport of water, northward across the equator in the upper 1,000 meters, and southward in the North Atlantic deep water. We seek to measure, for the first time, paths of water in the vicinity of the equator, and to observe the extent to which water can freely cross the equator in swift, deep, western-boundary currents. We have recently obtained the first data and are processing them to plot the first subsurface trajectories in the Tropical Atlantic. Preliminary trajectories of 1,800-meter floats reveal a narrow (100-kilometer-wide) current flowing swiftly (25 centimeters per second) southward, adjacent to the continental slope off north Brazil.

Future studies of the float group will include using Bobber floats during 1991 to 1993 to measure characteristics of newly formed and subducted water in the Canary Basin, and also to measure horizontal dispersion in the thermocline as part of the World Ocean Circulation Experiment (WOCE) Tracer Release Experiment. Also during WOCE, a detailed study of the deep circulation in the Brazil Basin will be made using RAFOS floats (SOFAR spelled backwards). Work in the Mediterranean Outflow to identify how it disperses in the Atlantic, and further studies in the Tropical Atlantic are planned.

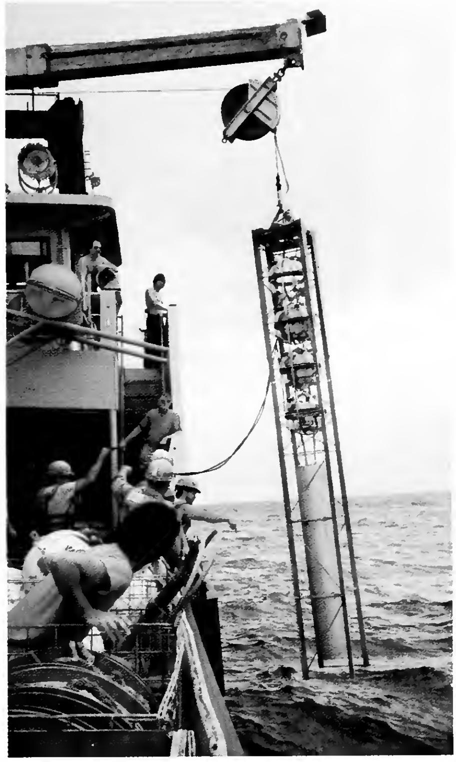
The next 10 years will be a very exciting time for ocean scientists. We expect some big surprises.

Float groups at other institutions are also active.** American scientists are obtaining and studying float trajectories in the Gulf Stream, the South Pacific, east of the Bahama Islands, and in the Circumpolar Current. French scientists are obtaining trajectories of the Arctic, and also tracking floats in the Gulf Stream extension over the Mid-Atlantic Ridge. British scientists have measured deep trajectories in the Canary and Iberian Basins. German scientists are beginning float experiments in the Mediterranean water off Iberia, and Japanese scientists have begun a new program to obtain trajectories in the Philippine Sea. As these groups continue to collect and pool exploratory float data, we will be able to create worldwide maps of trajectories, mean velocities, and eddy statistics. The next 10 years will be a very exciting time for ocean scientists. We expect some big surprises.

Early SOFAR Float Development

Starting 25 years ago SOFAR floats were developed by Doug Webb, at WHOI, and Tom Rossby, originally at Massachusetts Institute of Technology, and later at Yale University. Two major difficulties needed to be overcome: putting sufficient sound into the ocean for long-range signaling, and extracting the sound from the ocean, for tracking. A neutrally buoyant float capable of transmitting large amounts of acoustic energy and operating unattended for long periods of time at great pressures was required. Gaining access to military listening stations, extracting the received signals, and triangulating on the float were other problems that had to be solved. Webb led the float development, and Rossby planned the tracking. The result was the SOFAR float.

Modern SOFAR floats are neutrally buoyant aluminum or glass pressure housings that are ballasted to drift deep within the ocean. Some of the floats that drift the deepest (greater than 3,000 meters) are constructed from glass spheres. The floats emit a low-frequency acoustic signal (250 hertz) that sounds like a boat whistle. The sound travels horizontally through the ocean in an acoustic waveguide where the speed of sound is minimal (typically near 1,000 meters in the Sargasso Sea), and is received by undersea listening stations at ranges of a few thousand kilometers. Differences in the signal arrival times at the stations are used to calculate distances and to triangulate the float positions.

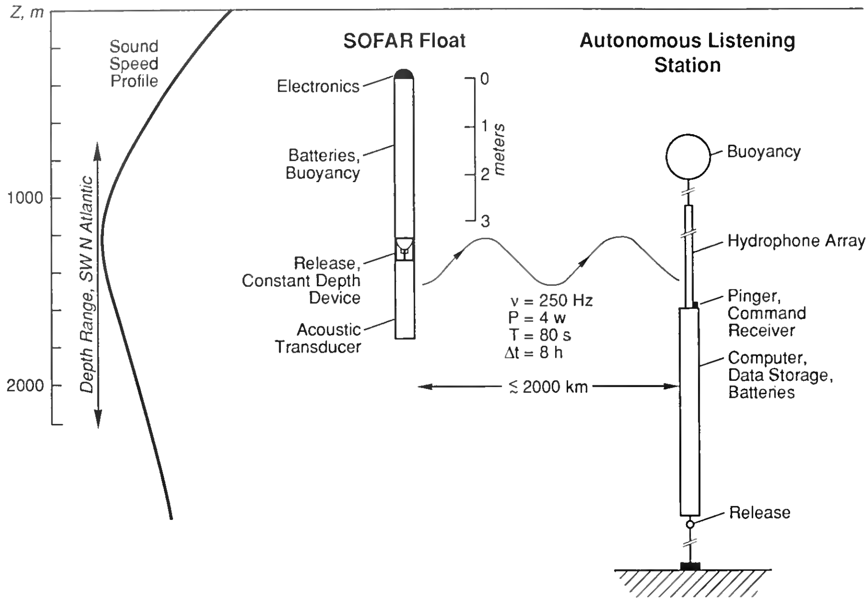


A 3,500 meter SOFAR float was launched from R/V Oceanus in January 1989 on the Atlantic equator. Glass spheres (pressure housings) contain electronics and batteries, and can withstand the enormous pressure of a 3,500 meter depth. The aluminum tube is the acoustic resonator, which produces a 250 Hertz signal once per day for tracking. The float is released from its rigid cage after it is lowered below the sea surface. This is one of the 48 floats, some aluminum and some glass, launched in the Tropical Atlantic to measure cross-equatorial currents. An array of six moored listening stations is recording data from these floats over a four-year period.

Recent Float Developments

Over the years, new developments have radically changed some aspects of subsurface acoustic floats, adding new capabilities. Early floats were tracked with landbased Military Impact Landing Stations, which precluded studying trajectories in the Gulf Stream and other areas far from shore. In 1977, the Autonomous Listening Station was developed at WHOI by Al Bradley and Jim Valdes. These stations, which can be moored anywhere in the ocean, made float tracking possible worldwide, at least wherever a deep sound channel occurs. We are still using some of the original autonomous listening stations, which have worked remarkably well (with over a 90 percent success rate). New autonomous listening station versions that are smaller, lighter, and easier to use have been incorporated in freely drifting tracking stations and mobile ice stations in the Arctic. These listening stations telemeter data back to us via orbiting satellites allowing us to receive the data in real time. The moored versions remain submerged, recording data for as long as two years. This moored system is cost effective, but makes us wait for what seems like an extremely long time to see float trajectories and to diagnose problems.

SOFAR floats have been greatly improved with microprocessors, better clocks, louder signals, and automatic ballasting control. Float lifetimes of four to five years are almost routine now. A new version, the SOFAR Bobber float, developed by Doug Webb (now at Webb Research Corporation) and Jim Price (at WHOI), repeatedly oscillates or bobs between selected isotherms to follow a specific layer of water. These will soon be used in the Subduction and WOCE Tracer Release Experiments. In 1984 Tom Rossby developed the RAFOS float, a smaller, less expensive float that "listens" to moored sound sources and at the end of its drift, surfaces and reports data back home or to the lab via satellite. A newer version of the RAFOS float developed by Rossby is being tested at WHOI by Breck Owens and Jim Valdes for use in WOCE. Modifications of this float are in progress at the University of Rhode Island and WHOI to make it rise periodically to the surface, report data back, and then return to its prescribed depth and continue its mission. Louder and more



A neutrally buoyant, freely drifting SOFAR float and a moored autonomous listening station is illustrated schematically. The floats transmit acoustic signals that are received and recorded by the listening stations. Tracking consists of triangulating on the position of a float, using the time delays of the signals received at several listening stations. RAFOS floats reverse the process by receiving the signals transmitted by moored sound sources. At the end of their missions these floats surface and radio their data to orbiting satellites. (Courtesy of Jim Price.)

powerful sound sources to further increase tracking range are also being developed by Tom Rossby.

Russ Davis of the Scripps Institution of Oceanography (SIO) and Doug Webb have recently developed a multiple "pop-up" float called the Autonomous LAgrangian Circulation Explorer (ALACE) that is not acoustically tracked. This float drifts at a preselected depth and periodically pops up to the surface where its position is calculated by orbiting satellites. Approximately 50 surfacings over a lifetime of five years are projected. The first few trajectories from ALACE floats are now being received from the Southern Ocean. ALACE floats present a good option for use where maintaining an acoustic tracking array is logistically difficult and, therefore, too expensive.

A remarkably innovative development by Doug Webb will make possible a smart and much more active float than we have seen before. Named after Joshua Slocum, the first person to sail singlehanded around the world, the new device, called Slocum, is actually a self-propelled undersea vehicle (see *Oceanus*, Winter 1989). Six times a day, it harnesses the thermal stratification of the ocean to dive to a preselected depth, return to the surface, report its findings, and receive new instructions by satellite. A Slocum glides horizontally both on the way down and up, and it can control its own direction. If the Slocum is successful, a fleet of these devices could one day monitor the ocean as weather balloons now monitor the atmosphere. On April 24, 1995, the 100th anniversary of the start of Joshua Slocum's voyage, we hope to send the first Slocum vehicle off on a world-circling trip of its own. It will not follow the same route, however, because the Straits of Magellan and other shallow passages would be impossible for the Slocum vehicle to negotiate.

Technical Difficulties

The successes we have had with floats have been accompanied by many serious problems that continually jeopardized our studies. Since most SOFAR floats are left to drift passively and are not recovered, it is difficult to diagnose their problems. Frequently we recovered data and saw problems in one batch of floats many years after they were launched and, sad to say, after even more of the same type of float had been launched. Problems have included failed transducers, vibration-induced electronic failures as power was increased, changed (degraded) electronic components, leaky batteries that caused electrochemical fires and explosions, and more recently, now that microprocessors are in use, slight but disastrous glitches in software that resulted in curtailed or failed missions. Thoroughly checking each float and sound source seems to be the obvious solution, but testing for the typical multiyear float lifetime is very expensive and time consuming. When funds to build instruments come late, thereby setting back delivery times and reducing time to prepare floats to meet inflexible ship schedules (especially for studies where different research groups work together on a joint experiment), checking each float becomes impossible. The more advanced and complicated the floats and the larger the experiments, the more difficult it is to adequately test the floats—and the more we worry. Another recent problem is obtaining necessary clearances to launch floats and moorings within the national waters of other countries. Long lead times required for clearance applications and the imposition of inflexible conditions make working within 200 miles of land a real headache. However, as we look back over the last 20 years and review the wonderful collection of ocean current trajectories, the successes more than outweigh the failures and difficulties.

One of the biggest problems we now have is attracting bright graduate students to the field.

It may seem surprising, but one of the biggest problems we now have is attracting bright graduate students to the field, to analyze the new float data in innovative ways and extract a better understanding of dynamic ocean processes. Fruitful analysis of float data is not easy, and new techniques need to be developed. I think the rich data sets we are obtaining will attract creative new scientists and we will start to see the data used in exciting new ways. I expect we will find that our present analyses have only scratched the surface of our SOFAR float data set.

Philip L. Richardson is a Senior Scientist in the Department of Physical Oceanography, Woods Hole Oceanographic Institution. He is director of the center of derelict drifters and phantom floats (Phil calls it CODDAPHT).

*The WHOI float group consists of five scientists: Amy Bower, Breck Owens, Jim Price, Phil Richardson, and Bill Schmitz, who work together on a variety of scientific problems and share resources.

**Tom Rossby (University of Rhode Island) recently obtained float trajectories in the upper layer of the Gulf Stream, and with Steve Riser (University of Washington) has obtained deep float trajectories in the South Pacific. Keavin Leaman (University of Miami) obtained trajectories east of the Bahama Islands, and Russ Davis (Scripps Institution of Oceanography) has launched ALACE floats in the Circumpolar Current.

Robotic Undersea Technology

Dana R. Yoerger

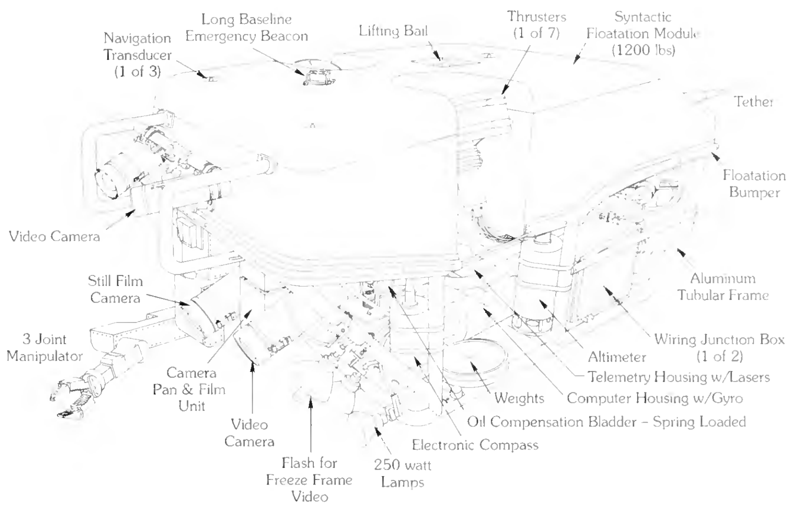
Robotic vehicles increase our ability to work underwater. Recent technological progress has made these robotic vehicles more capable, less expensive, and easier to use. They range from large, expensive work systems weighing many tons to lightweight, low-cost vehicles that can be carried in a car's trunk. Underwater robotic devices have traditionally been used by the offshore oil and gas industry and the military. However, they are now being applied to a wide range of tasks including hazardous waste cleanup, dam and bridge inspections, and environmental surveys. At the Woods Hole Oceanographic Institution (WHOI), we are applying underwater robotics to deep ocean science.

What is a Robot?

Most underwater vehicles in operation today are not true robots, rather they are teleoperators, remotely operated devices controlled directly by people. A few underwater vehicle and manipulator systems qualify as telerobots, where people and automated systems work together. A few fully autonomous robots that operate with no human control are in engineering development and may be operational soon.

The original teleoperators were mechanical manipulators that permitted people to handle radioactive material safely. A typical system consisted of two identical arm-and-gripper mechanisms; one was manipulated by a human operator, and the other handled the hazardous material. The two arm mechanisms were connected by cables and pulleys that forced the remote or "slave" arm to follow the "master" arm moved by the person. Later, the cables and pulleys were replaced by electric servomotors, permitting higher performance and larger separation between master and slave.

These early teleoperators are similar to many of today's underwater vehicles and manipulators. Present-day remotely operated vehicles (ROVs) are completely reliant on continuous human control, but allow people to work at a distance. Advanced teleoperator systems, some of which are planned for underwater use, will utilize complex, high-quality sensor and actuation systems to couple the human operator to the remote environment. Technologies such as head-coupled stereo television (a stereoscopic camera, usually worn on a helmet, that pans and tilts along with the movements of the wearer's head) and force-reflecting



ROV Jason *is a telerobotic vehicle capable of carrying a wide variety of sensors and manipulators for operation at depths to 20,000 feet.*

master-slave manipulators create an artificial presence, permitting the operator to feel he or she is actually present in the remote environment.

A telerobotic device uses a combination of human and computer skills to perform work. For example, ROV *Jason* can maintain heading and depth, follow precise track lines, and hover automatically under the pilot's supervision. Likewise, *Jason's* manipulator arm automatically reacts to contact forces to grasp objects firmly yet without damage. In a telerobot, the control task is apportioned between the human pilot and the automatic systems, although the human is always in charge.

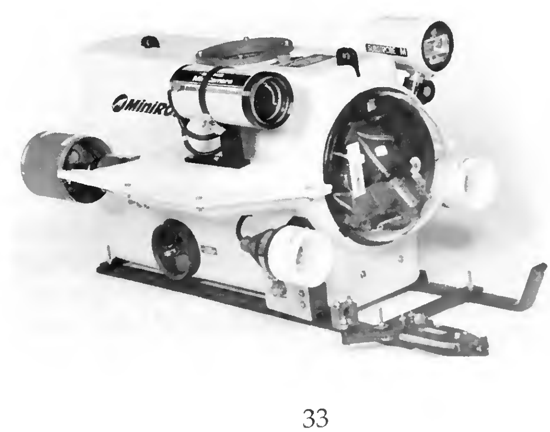
A true robotic system is autonomous, flexible, and able to deal with unexpected circumstances. For example, proposed untethered robotic submersibles may be able to survey large areas of the seafloor without direct support from a surface vessel. Such vehicles must carry all power on board, function reliably for extended periods, and deal with unexpected changes in the vehicle, environment, or mission without human intervention.

Tethered Vehicles

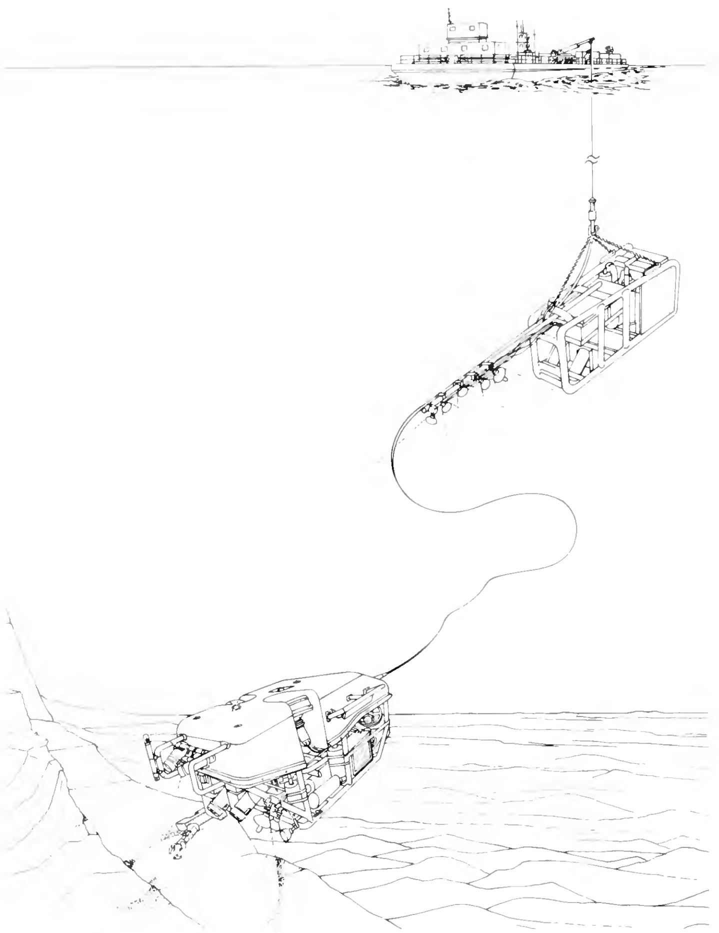
The most common type of underwater vehicle in operation today is a teleoperated or telerobotic device connected to the surface by a cable that carries both power and data. Despite the hydrodynamic drag and danger of entanglement, the simplicity, endurance, and excellent feedback provided by a tethered system are quite useful. Shallow-water ROVs are relatively inexpensive (around 30,000 dollars), weigh about 50 pounds, and can be operated and maintained with modest training. An example is the Benthos *MiniRover*. This vehicle is capable of transmitting video images from depths of several hundred feet and can be fitted with a simple grabber arm.

Benthos MiniRover *is an inexpensive shallow-water ROV that can operate to depths of several hundred feet.*

At the other end of the spectrum are full-ocean-depth tethered vehicles, such as *Jason*, which weighs nearly 3,000 pounds and can operate to depths of 20,000 feet. A second vehicle called *Medea* provides sufficient weight at the end of the long cable to isolate *Jason* from the ship-induced motions on the cable. *Jason* can carry a variety of sonars, video systems, and film cameras; additional cameras on *Medea* provide complementary views.



Illustrated by E. Paul Oberlander



Two tethered robotic vehicles are suspended from the ship: Medea *(top vehicle) isolates ROV* Jason *from much ship-induced motion.*

Jason demonstrates many of the strengths of tethered vehicles. The fiber optic cable and telemetry system permits tremendous amounts of data to be transmitted. This allows simultaneous viewing of up to four high-quality color video channels and up to 100 million bits per second of data from sonars, electronic cameras, and manipulators. *Jason* can remain on station (at the bottom) for extended time periods and has logged over 60 continuous hours at depths over 18,000 feet. *Jason* has sufficient payload, power, and telemetry capacity to carry a variety of specialized sensors for science.

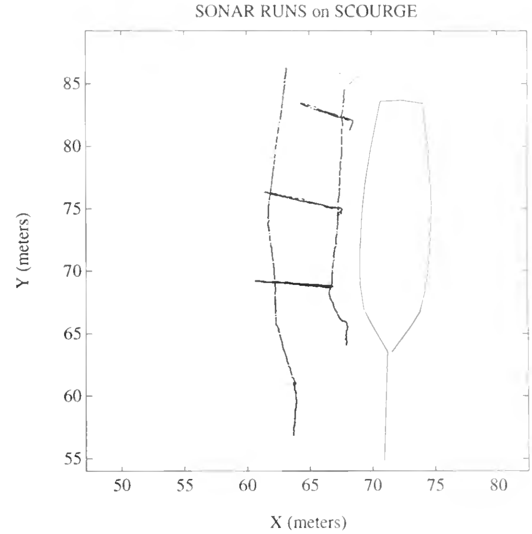
One view of ROVs is that they are replacements for manned submersibles, with advantages in terms of endurance, safety, and cost. While these are certainly strong points for ROVs, *Jason* was not intended strictly to replace manned submersibles. It was designed to perform a variety of functions, many of which complement rather than duplicate the strong points of a manned vehicle. For example, manned submersibles are rarely used for sonar survey, due in part to problems of storing or processing data in small spaces with limited manpower. *Jason's* high-bandwidth telemetry system and precise control capabilities make it a very effective sonar platform.

A precisely navigated and controlled platform, *Jason* can survey and sample the seafloor using a variety of techniques. It is an excellent platform for high-resolution sonars, electronic photography, and video. These functions require a combination of good navigation, precise control, and high-tether bandwidth.

Years of operational experience indicate that ROVs are poor sidescan-sonar platforms due to the lack of natural heading stability found in the streamlined sonar "fish" that are towed behind a ship. *Jason* can typically hold its heading to better than 1 degree, which is at least as good as most towfish. Additionally, *Jason's* ability to precisely follow prescribed tracks allows a scientist to choose a track that will yield the best image, and repeat the track exactly or with desired variation. If the track lines are chosen well, the resulting images contain more information and require less processing than equivalent data from a towed system.

These concepts were recently demonstrated on an archaeological survey of the War of 1812 vessels *Hamilton* and *Scourge*, which lay on the bottom of Lake Ontario at a depth of about 90 meters.* Hard-wired 300 kilohertz transceivers were used to track the surface support barge and *Jason*.

In one of *Jason's* telerobotic operating modes, vehicle speed and direction are specified by moving the joystick, and then executed by the computer control system. Rather than signifying "thrust right," a rightward deflection of the joystick moves the commanded vehicle to the right at a speed proportional to the amount of the joystick deflection. This allows the pilot to make the vehicle move in a straight track with constant heading and depth, with continuous control over speed and track direction. As seen at right, on the Lake Ontario dives the pilot occasionally made small changes in the heading setpoint to alter the track direction in order to maintain a constant distance from the hull.



Track lines of Jason *during a sector-scanning sonar survey of the starboard side of* Scourge *at the bottom of Lake Ontario. These track lines were executed using* Jason's *telerobotic capabilities.*

The closed-loop control capability proved useful during a variety of other types of survey operations. Because of its precise navigation and control, *Jason* was able to move over the deck of both *Hamilton* and *Scourge* for electronic still camera (ESC) survey runs under conditions of very poor visibility. Sometimes, the standard continuous video cameras were unable to image the ship's deck very well at the optimum altitude for the ESC. The pilot could not fly using the ESC, as it provided images only once every 20 seconds, but precise navigation and interactive closed-loop control allowed the 1.5 ton *Jason* vehicle to be maneuvered through the cluttered environment with confidence.

Jason is equipped with a manipulator that also works according to telerobotic principles. By a combination of its basic mechanical design and the implementation of its control system, *Jason's* manipulator can be configured to react in different ways when an object is touched. Using a principle called active compliance, the manipulator arm can be configured (through software) to respond to contact like a network of well-damped springs. The arm can be made very stiff in some directions and very compliant in others, and the grasping force can be finely controlled.

In the summer of 1989, *Jason* and its manipulator excavated the remains of an ancient Roman shipwreck at a depth of 2,500 feet in the Mediterranean Sea. Under supervision of an archaeologist, over 50 objects were recovered, including large terra-cotta jars, drinking cups, an oil lamp, and a cooking pot. The computer-controlled compliance of *Jason's* arm enabled recovery of these delicate objects without damage. Due to the fragility of the site, *Jason* could not rest on the bottom, but had to perform all manipulations "on the fly." Despite residual vehicle motions and unintended misalignment of the manipulator hand (the gripper), the resulting contact forces were kept low. Contact forces were managed by the manipulator and its control system as specified by the pilot, not directly by the pilot, as would be the case for a teleoperated device. The telerobotic system provides for high performance with relative simplicity while significantly reducing the pilot's work load.

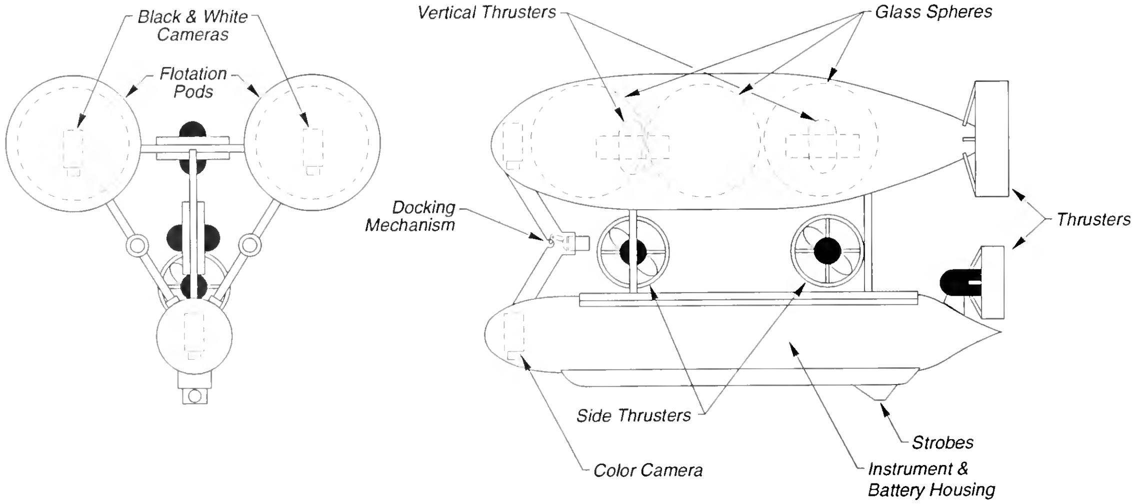
Untethered Vehicles

Untethered vehicles are able to move without the restrictions of a cable. Examples include the operational *Epaulard* vehicle developed by the French oceanographic agency IFREMER, the Experimental Autonomous VEhicle (EAVE) under development at the University of New Hampshire, and the Advanced Underwater Search System (AUSS) developed at the Naval Ocean Systems Center. *Epaulard* and AUSS operate in a telerobotic mode, with their activity supervised by shipboard operators through an acoustic communications link. The EAVE vehicles have completely autonomous capabilities for search and survey tasks.

At WHOI, we are building a robotic vehicle called the Autonomous Benthic Explorer (ABE), shown below. ABE is designed to perform surveys in deep-sea hydrothermal vent areas independently of a surface vessel. These vents, located at depths of several thousand meters, are extremely dynamic. Flows of hot, chemical-laden water and volcanic activity occur unpredictably. Traditional submersible or ROV expeditions cannot remain on station long enough to observe many of these changes. ABE will remain on the bottom for extended periods of time, mostly in a low-power "sleep" mode, eventually as long as one year. Periodically ABE will repeat video surveys and measure oceanographic parameters such as water temperature, salinity, and optical properties. ABE will complement other vent-studying techniques. While ABE's observations will not be as high in quality as *Jason's* or *Alvin's* (see *Oceanus*, Winter 1988), ABE is designed to make observations when these traditional vehicles cannot be on station. Likewise, through its mobility ABE will complement fixed instruments.

ABE is an untethered robotic vehicle designed to remain on station for longe periods of time, at depths up to several thousand meters.

Initially, ABE will perform preplanned tasks, such as repeated video surveys on a fixed trajectory. Although the vehicle path and schedule will be predetermined, a significant amount of uncertainty still exists. The environment can be unpredictable, especially in terms of currents. ABE itself will be the primary source of uncertainty, and the vehicle must be able to withstand subsystem degradation or even failure.



Illustrated by Jayne H. Doucette

ABE could make superior observations in later implementations by reacting to data as it is gathered, such as mapping out hydrothermal plumes by sensing temperature and water properties. Based on the observations, ABE will be able to alter its path and thereby map the plume more quickly (and more densely) than the vehicle could by executing a preplanned grid. Similarly, ABE might be programmed to react to data from other seafloor sensors; for example, an ocean bottom seismometer (OBS) could inform ABE of seismic activity via an acoustic link, after which ABE could search for changes in hydrothermal activity.

A number of other ambitious autonomous vehicles are in the planning stage. In the UK, two long-range autonomous vehicles are being planned, one for geological survey (DOGGIE, or Deep Ocean Geological and Geophysical Instrumented Explorer) and the other to survey the water column (DOLPHIN, or Deep Ocean Long Path Hydrographic Instrumentation). The potential traveling distance for DOGGIE will be about 500 miles, and DOLPHIN will be able to travel several thousand miles. The vehicles will take many years and tens of millions of dollars to develop. In Japan, plans are under way to build a diesel-powered full-ocean-depth autonomous submersible (R1) to survey the Mid-Ocean Ridge.

A number of other ambitious autonomous vehicles are in the planning stage.

In all cases, these long-range vehicles will require significant advances in technology. New levels of performance in drag reduction and power technology are essential for successful development of DOGGIE, DOLPHIN, and R1. A system like ABE will need fewer technical breakthroughs, although making such a system reliable and economic for the long run remains a significant challenge. An autonomous vehicle that can perform manipulation is still far away.

Underwater vehicle and manipulator systems are evolving in several directions, making them more useful for a variety of work. Some vehicles are getting smaller, cheaper, and easier to operate; others are growing in sophistication and capability. The majority of systems currently available are teleoperators, controlled continuously by people with little help from automation. Increasingly, systems with telerobotic qualities are appearing, supporting and augmenting human skills with low-level automated processes. Finally, fully autonomous robotic vehicles are beginning to appear and are useful for certain types of survey tasks.

Dana R. Yoerger is an Associate Scientist in the Department of Applied Ocean Physics and Engineering at the Woods Hole Oceanographic Institution. He is a principal in the design of Jason *and ABE, and has participated in many scientific cruises with the* Jason *system.*

*Exploration of the *Hamilton* and *Scourge* sites and work on the Roman shipwreck were undertaken for the JASON Project, an educational program that uses telepresence to bring live exploration via satellite transmission to a network of receiving sites across North America.

A Telescope at the Bottom of the Sea

DUMAND is a deep-sea telescope we can use to create a picture of our galaxy as seen by the "light" of neutrinos.

George Wilkins, John Learned, and Dan O'Connor

What happens when you join an enthusiastic ensemble of astrophysicists, oceanographers, high-energy physicists, marine biologists, and cosmologists in uninhibited discussion, spike the punch of their interactions with a high-proof sampling of the engineering professions, and then challenge them to devise an experiment that will push all of their disciplines to or beyond the known limits? We tried this once in Hawaii. The result was DUMAND, a Deep Underwater Muon And Neutrino Detector that may become the most exciting ocean science experiment of this century. Today, after more than 15 years of planning, modeling, engineering design studies, and technology development, the program has been formally funded by the US Department of Energy and government agencies in Japan, Germany, and Switzerland.

What is DUMAND? As sketched on page 41, it is a giant, three-dimensional array of optical sensors placed at a 4,800-meter ocean depth, then buoyed to 350 meters above the seabed. It is designed to detect and characterize ultra-high-energy neutrinos as they enter the Earth from deep space. In effect, DUMAND is a deep-sea telescope we can use to create a picture of our galaxy as seen by the "light" of neutrinos.

The Neutrino as a Tool

The neutrino was first postulated in the 1930s as a necessary outcome of particle decay, for example, the radioactive conversion of a neutron into a proton by electron emission. Conservation of both energy and momentum in this process required that another particle, originally called a little neutron or a neutrino, be emitted. Neutrinos were experimentally observed in the 1950s. They are believed to be massless, have no electric charge, travel at (almost?) the speed of light, and exist in three types or (in particle physics jargon) "flavors:" muon, electron, and tau. Flavor determines what type of particle is created when a neutrino, at some unpredictable stage in its very long life, finally interacts with matter. The DUMAND experiment is designed to detect the muon neutrino, that is, the neutrino that, when transformed, produces a muon. A muon is a charged particle with a mass intermediate between that of an electron and a proton.

Theoretically speaking, neutrinos should be the most numerous of all subnuclear particles, since they are a necessary outcome of almost all high-energy radiation events and since they interact so rarely with matter. At the ultra-high-energy levels to be investigated by DUMAND (more than a TEV, or a trillion electron volts, or the rest mass energy of a thousand hydrogen atoms), a typical neutrino will pass through the Earth as though it were a clear window. Our hopes to detect such high-energy neutrinos are based primarily on the fact that there are so very, very many of them.

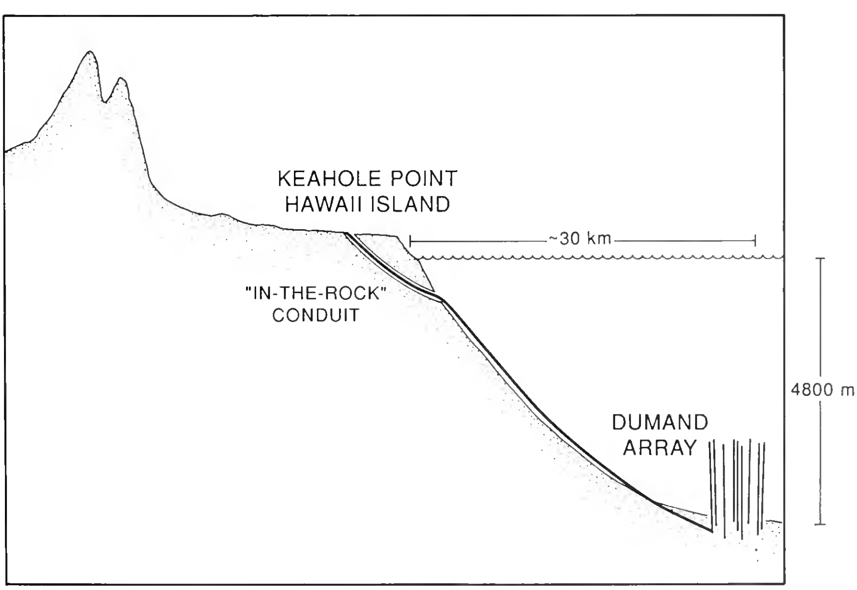
Its penetrating power is precisely what makes the neutrino an outstanding tool for probing our corner of the universe. Neutrinos should suffer no scattering and little absorption as they pass through the dense clouds that separate us from the center of our galaxy. If DUMAND can detect enough of these neutrinos and determine their origins to within a fraction of a degree, then we will be able to map the structure of the galactic center. This might allow us to determine both the existence and nature of the massive black hole we believe is lurking in that center.

DUMAND may become the most exciting ocean science experiment of this century.

How will we detect these neutrinos? That question forms the heart of DUMAND and is the primary reason why we gathered such a broad range of science and engineering talent for our study. It is also why our experiment must be located at a rather unique site, at the bottom of a very deep ocean. But, before plunging into that part of the story, let's examine DUMAND and how it works.

A Profile: The DUMAND Array

The DUMAND array will be located at a depth of 4,800 meters about 30 kilometers seaward of Keahole Point, near the western tip of Hawaii. Array power and telemetry will be supported by a 36-kilometer electro-optical shore cable that will connect ashore at the Natural Energy Laboratory Hawaii (NELH). The land-based portion of the cable will run



A global view of the DUMAND array.

beneath the shoreline, through an in-the-rock conduit that breaks through the seafloor at a 15-meter depth. We will drill and case the conduit this summer, as part of a state demonstration program. The ultimate goal of the drilling program is to show that very large (greater than 3-meter diameter) shafts can be drilled and curved through lava and coral formations, with seafloor breakouts at depths approaching 1,000 meters. Such shafts could be used to bring up deep, cold, nutrient-rich seawater to support aquaculture and ocean thermal energy conversion (recovering the energy from temperature differences between warm surface water and cold deep-sea water).

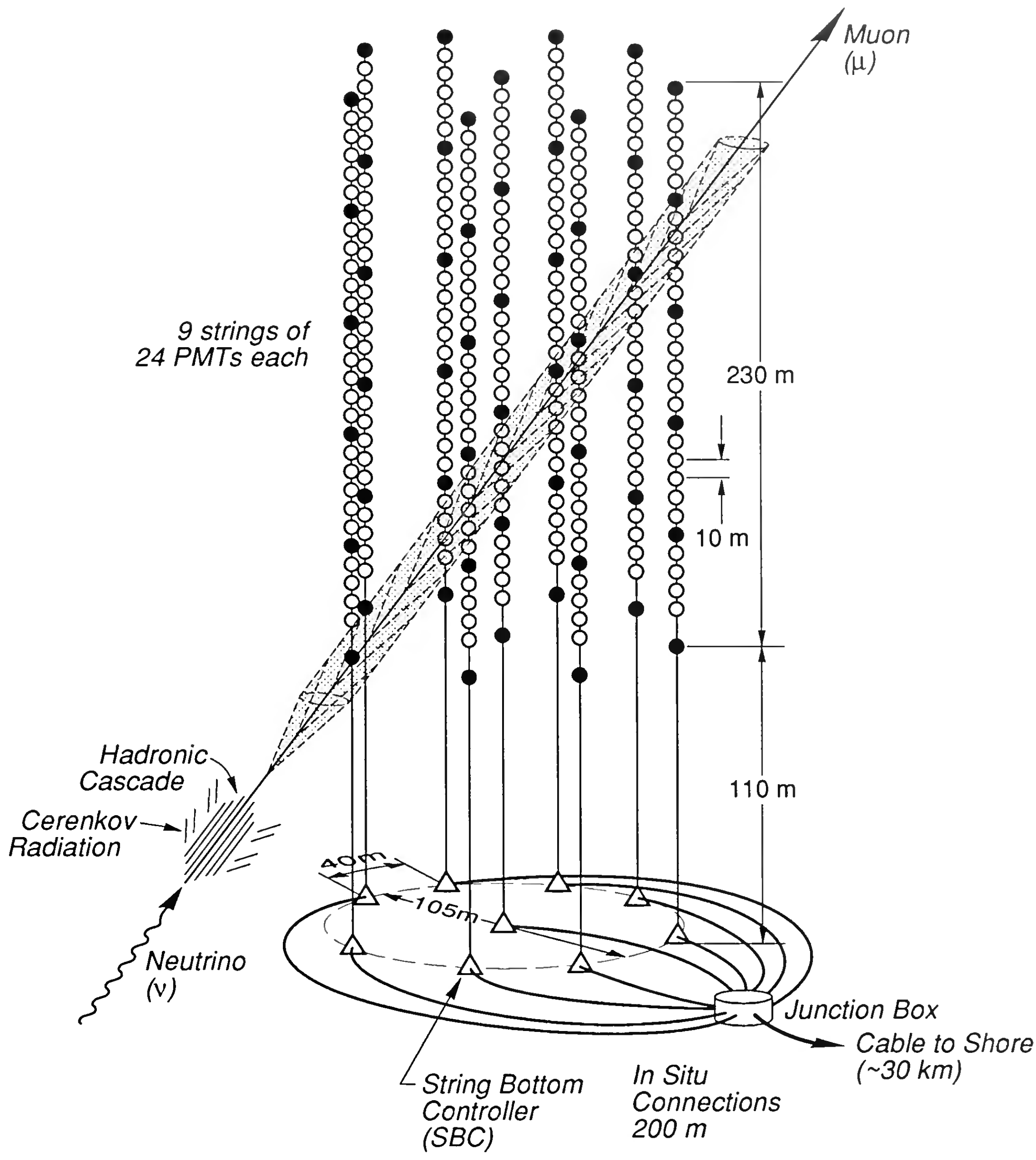
The DUMAND double-steel-armored shore cable will be 12 millimeters in diameter, and will contain 12 single-mode optical fibers and a single direct-current conductor. Operating with a seawater return, the cable will be able to supply at least 5,500 watts of power to the array. Command signals will be sent to the array from shore on nine of these fibers at 1,300-nanometers wavelength. The same nine fibers will also transmit array telemetry to shore in a full duplex mode at 1,550 nanometers. A tenth fiber will be used for telemetry of environmental data, including a television monitor at the end of the shore cable. Two fibers will be reserved for use as spares. The total array data rate will be approximately 5,600 megabits per second—about five times higher than the rate of today's commercial, transoceanic, fiber-optic cables.

The DUMAND array is octagonal, with eight sensor strings placed symmetrically around a central sensor string. The array's optical sensors will be carried by electro-optical cables to 350 meters above the seabed, but only the upper 230 meters of the array will be instrumented. The 110-meter lower array section will exist as a standoff or tare height, to ensure that all instruments are kept safely above any nepheloid (or scattering) layer, where stirred-up bottom sediments make visibility poor.

Mechanisms for Operation

Each of the nine sensor strings, or risers, is actually two identical electro-optical cables, separated every 10 meters by a 40-centimeter-diameter Benthos glass sphere that (barely) contains a giant photomultiplier tube (PMT). The risers can be thought of as ladders, with the glass spheres serving as rungs. The riser string will support 24 PMTs, with eight additional power or data channels reserved for additional instruments, including optical calibration units, environmental sensors, and hydrophones. The array will be outfitted with 45 high frequency (50 kilohertz) hydrophones distributed throughout the strings to support precise monitoring of string shapes and their responses to currents.

The schematic illustrates the array telemetry operation. At the top is a PMT in a glass sphere. If an output pulse exceeds a threshold value, the pulse is amplified and processed to preserve its intensity and the time of its leading edge. These data are sent through a dedicated fiber to the string bottom controller (SBC) at the string anchor. At the SBC, pulses from all sensors are digitized by a specially designed large-scale integrated (LSI) chip. These data are then launched for unrepeatered telemetry to shore (each array string is supported by a dedicated fiber to shore). En route, the optical signals pass through the



Illustrated by Jayne H. Doucette

The DUMAND has an octagonal array. The junction box and shore cable are clearly illustrated .

junction box (the functions of this box will be described later).

Now let's assume that an intense, beamlike pulse of light passes through the array and illuminates a small fraction of the PMTs along the way. Assume we have no advance knowledge of the beam's direction or brightness. Some of the PMTs will be illuminated by the beam. The ones of interest to us will produce an output signal greater than some predetermined detection threshold. For example, we may have instructed the sensor modules in the array to respond only to signals for which two or three photoelectrons entered the PMTs within a given sampling interval. (This level can be changed from shore.) All signals that pass the thresholding process to reach shore are analyzed for a space-time pattern that matches a beam passing through the array at the speed of light in seawater. This fit must include the beam's direction of travel. Once the correlation is found, all associated signal data will be stored and analyzed off-line. We should be able to reconstruct the beam direction to within a fraction of a degree, and beam intensity to within 50 percent.

The neutrino's energy is converted into a hadronic cascade: a needlelike shower of highly relativistic subnuclear particles.

Detecting a neutrino is similar. Imagine that a multi-TEV neutrino transforms to a muon as it approaches the array. First, the neutrino's energy is converted into a hadronic cascade: a needlelike shower of highly relativistic subnuclear particles. These particles move through the seawater at a speed greater than the speed of light in water (but less than the absolute speed of light). Quantum physics allows this, but imposes the penalty that the particles must radiate energy, a symmetric cone of blue-green light known as Cerenkov radiation. If this radiation occurs within the DUMAND array, it will be detected, but probably not by enough PMTs to support a meaningful determination of neutrino direction or energy. The cascade will lose its energy to the environment within a few meters. Second, the neutrino we are looking for produces a relatively long-lived muon that continues for hundreds to thousands of meters, nearly parallel to the original neutrino's track. The muon is also moving faster than light can travel in seawater, so it must also radiate a cone of Cerenkov light. This light should be detected by a dozen or so PMTs along the muon's track.

The DUMAND array will react to optical radiation from the muon the same way it did to the more conventional light beam. We can determine the muon's flight direction by measuring the relative intensities of the PMT pulses and the times when they occur. From measured pulse intensities we can reconstruct the muon's energy-loss rate and, from that, determine the muon and neutrino energies.

Predicting the Effects of Noise

The preceding events will not occur in a noise-free environment. The major noise sources are expected to be cosmic rays, radiation from potassium-40 decay, and bioluminescence. Noise from cosmic rays is reduced by a factor of 10 for each kilometer of array depth, thereby explaining our need to place the DUMAND array at the greatest depth possible. Low-intensity photon noise due to potassium-40 is relatively independent of depth, and will initiate about 40,000 counts per second in each optical sensor. Deep-sea bioluminescence is a unique problem when measuring signal levels that are variable and difficult to predict. During a 1987 deployment of a prototype string to a 4,000-meter depth, we monitored one deep-sea animal as it swam along a row of seven sensors, shining its bioluminescent photophores into each PMT aperture in turn, and saturating each of the sensors. We will record data from events of this type for marine biologists. We are sensitive (and responsive) to the plea of one Soviet marine biologist who asked the DUMAND team, "Please! Remember that your noise is my science."

From other tethered and moored experiments here and in the USSR, we know that background light for moored detectors at 4.8-kilometer depths will not be significantly more intense than the levels already noted for potassium-40, and so will not constitute a major noise source. Our prototype deployment proved that such rates are not a serious problem for DUMAND.

Location and Orientation Constraints

To maximize the array's neutrino detection ability, the direction of primary sensitivity will not be upward into space, but downward into the solid angle that lies near and below the horizon, through the Earth, and out into space on the other side. Why? Because no cosmic rays come from that solid angle, and the Earth barely attenuates neutrinos. In effect, DUMAND will use the enormous mass of the Earth as a noise filter.

The direction of greatest array sensitivity will occur at least 80° away from the local zenith. This sensitivity will rotate with the Earth at Hawaii's 20°N latitude. In any 24-hour period, only a cone of a 10° half angle around the North Pole will remain uninvestigated. All other celestial regions can be viewed and monitored by the DUMAND array.

In effect, DUMAND will use the enormous mass of the Earth as a noise filter.

The DUMAND experiment places very special constraints on the nearly 2 million cubic meters of whatever material is chosen to fill its instrumented volume. First, the material must be provided with a thick cover to screen out cosmic rays. Second, it must be extremely transparent so that optical signals can propagate far enough to activate several detectors. Third, it must be cheap, very cheap. DUMAND cannot even afford the cost of 2 million cubic meters of tap water. Finally, it must be close enough to shore to allow power and data support without massive cables and optical repeaters. Our best candidate—in fact our only candidate—was deep seawater.

More than 100 candidate DUMAND sites were investigated, but the only one that satisfied all of these requirements was Keahole Point. Water clarity at the array site corresponds to an attenuation length of 40 meters, with little or no nepheloid layer present.

Deployment

The conceptual problem of array deployment plagued the DUMAND design team for many years. When introduced to the program in 1976, one scientist commented that deploying the DUMAND could easily become "...a direct short across the national budget." For showing such insight, he was immediately chosen to head the deployment development team.

As a huge, monolithic, and hard-wired structure, the array would require conventional deployment techniques involving several ships working in impossibly close and precise coordination, in unpredictable weather. Within the past three years, two new technological elements have simplified the array structure, profoundly reducing the complexity and risk of its deployment. In the new approach, the three-dimensional array is designed, assembled, and deployed as a series of independent linear elements. After deployment, these elements are electrically and optically connected on the deep seafloor.

We decided that the technology for deep-sea, make-and-break, electrical and single-mode optical connectors was sufficiently mature and reliable that it could be used to assemble the DUMAND array, and that manipulator systems aboard existing manned and unmanned submersibles were suitable to carry out this mating operation.

Intensive investigations and testing of such systems revealed that a relatively crude, one-handed, deep-sea manipulator system could reliably open and close an optical connector. This led the DUMAND group to devise the following deployment sequence.

1) *Shore Cable.* The cable is laid in a seaward direction after a 300-meter length has been passed to shore through the in-the-rock conduit already described. AT&T's ship operations division has offered to furnish a cable ship for this task.

Recovery can be commanded from shore at any time during the planned 10-year life of the array.

2) *Junction Box.* This unit is permanently attached to the sea end of the shore cable, and lowered to the seafloor as a continuation of the cable laying operation. Make-and-break connector halves, corresponding to the two electrical leads and one optical fiber needed to support each riser string, will be permanently mounted to the junction-box top. The point where the junction box touches the seafloor defines the location of the DUMAND array. The box will be outfitted with environmental monitors, an acoustic transponder, a television camera, and lights that are all electrically and optically tied to shore. The transponder will query and monitor several conventional deep ocean transponders (DOTs) to establish a local navigation network.

3) *Riser Deployment.* We will use the US Navy's semisubmersible SWATH (Small WAterplane Twin Hull) ship *Kaimalino* to deploy the riser strings. As these are lowered through the ship's center well, a synchronous pinger in each string anchor will interrogate the navigation transponders to determine and update the anchor's X-Y-Z position. These coordinates will be compared to the planned touchdown coordinates so that adjustments can be made in the ship and anchor positions. We plan to allow as much as 24 hours for lowering and position adjustment. Finally, the string anchor will be set on the seafloor and the lowering line disconnected. During the descent, batteries will power diagnostic circuits in the SBC, which will then send periodic acoustic signals to verify proper string operation.

Interconnection of the Array

A manned submersible or cable-controlled vehicle will descend to the DUMAND array. Approaching in turn each of the string anchors, it will detach a harness-cable reel from the anchor structure and carry the reel 50 to 150 meters to the junction box. There it will join harness-cable make-and-break connectors with their mating halves on the junction box. When this occurs, the sensor string will become powered, monitored, and commanded from shore.

Once proper string operation has been verified, the submersible will continue to the next string. In the worst-case scenario of string operational failure, the submersible will cut part of the anchor loose, so that the string becomes positively buoyant (but bottom heavy); the string will then float to the surface for pickup, repair, and redeployment. This recovery can be commanded from shore at any time during the planned 10-year life of the array.

We plan to install three of the DUMAND strings in 1992 and begin obtaining basic physics data at that time. The last six strings should be deployed and operating by late 1993. We believe that this approach, deployment in simple linear elements followed by in situ connection, will allow for installation of a variety of complex and highly instrumented structures on the deep seafloor.

In fact, some of us are already involved at the University of Hawaii in another (National Science Foundation-funded) experiment of this type. We hope to deploy, wire, and operate a network of chemical, physical, and biological sensors on the summit of Loihi Seamount, a 1,000-meter-deep, active volcano that is steadily rising toward the ocean surface about 30 kilometers south of Hawaii.

We believe that the DUMAND telescope and the Loihi geophysical observatory point the way to a whole new generation of sophisticated deep-sea experiments. These will be based on the three-dimensional sensor arrays on or near the seafloor, and the arrays can be as complex as the associated science dictates. They will be assembled in situ from logically simple, linear elements. Assembly will be carried out by tethered vehicles or manned submersibles. Experimental data will be sent to shore or the ocean surface by fiber-optic telemetry—at data rates that dwarf those used today to connect the continents. The only practical limits to the scientific application of these new technologies will be those imposed by our ability to dream.

The only practical limits to these new technologies will be those imposed by our ability to dream.

George Wilkins is a Research Associate with the Hawaii Institute of Geophysics, and is responsible for the DUMAND optical telemetry and array deployment. He is also Principal Investigator for the drilling demonstration.

John Learned is a Professor of Physics at the University of Hawaii and is the DUMAND Scientific Director.

Dan O'Connor recently obtained a Ph.D. in Physics for his work on the DUMAND, and continues with the experiment as a Post-doctoral Fellow.

University members of the DUMAND collaboration include:
Boston, California, Hawaii, Vanderbilt, Washington, and Wisconsin in the US; Kinki, Kobe, Okayama, Tokoku, and Tokyo in Japan; Aachen and Kiel in Germany; and Bern in Switzerland.

ON THE COVER: The cover image represents the vast amounts of data available to modern scientists trying to understand the Earth and its processes. The topography of the western hemisphere was generated from a digital data base of land and seafloor elevations. The gridded data varies from true 5-minute for the ocean floors, the US, Europe, Japan, and Australia, to 1 degree in data-deficient parts of Asia, South America, northern Canada, and Africa. Data sources for ocean areas are: US Naval Oceanographic Office-US, Western Europe, Japan/Korea; US Defense Mapping Agency-Australia; Bureau of Mineral Resources-Australia, New Zealand; Department of Industrial and Scientific Research-New Zealand. Source for the balance of world land masses is US Navy Fleet Numerical Oceanographic Center. Numerous data collection methods were employed, such as bathymetry, soundings from surface ships, aerial surface surveys, and theodolite surveys. This image is one of 14 different vantage points available in slide form, including rectangular views showing continental plate boundaries. Slides or further information may be obtained from Peter Sloss at the Marine and Geophysics Division, National Geophysical Data Center, 325 Broadway, Boulder, Colorado, 80303-3328.

Ocean Data Telemetry: New Methods for Real-Time Ocean Observation

Telemetry allows the information collected to be used immediately.

Daniel E. Frye, W. Brechner Owens, and James R. Valdes

Oceanographic observational capabilities expanded significantly in the 1960s with the advent of modern electronic instrumentation. Instead of collecting brief snapshots of ocean conditions at a single point from instruments lowered from a research vessel, oceanographers were now able to install internally recording instruments that operated autonomously for periods of months to years. When these instruments were retrieved, their long time series of data could be used to investigate the dynamics of ocean variability. What they have not been able to do is provide data in real time. In fact, as instrumentation has improved and ship time has become more expensive, the trend has been to extend internally recording instrument deployments to one or two years. The disadvantages are the long time delay between data collection and use, and the risk that the instruments will be lost or damaged (along with their data) prior to retrieval.

Telemetry of data from in situ instrumentation solves these problems and allows the information collected to be used immediately, the way weather data is used to make forecasts and define existing conditions. This capability is important in a variety of applications such as vessel traffic management, deep-water remotely operated vehicle (ROV) operations, underwater construction, ocean prediction and modeling, and naval operations.

Ocean data telemetry refers to the "real-time" collection and transmission of information from sensors deployed beneath the sea. It is a related but different topic from remote sensing of the ocean surface. Remote sensing uses various wavelengths of emitted or reflected electromagnetic radiation to measure oceanic conditions such as surface temperature, wave height, wind speed, and chlorophyll concentration. Satellite remote sensing has totally changed our ability to observe the ocean surface both synoptically and in real time. Ocean data telemetry offers a means to extend this capability beneath the surface layer. The main difficulty in developing reliable methods for ocean data telemetry is seawater's opacity to all but the lowest frequencies of radio waves.

The primary motivations for developing ocean data telemetry are:

1) The need for real-time data on subsurface conditions for operational purposes and forecasting.

2) An improved ability to retrieve data collected by instruments deployed in high-risk environments such as the arctic ice pack, where instrument retrieval is difficult.

3) A need to reduce the time between instrument deployment and data analysis so that scientific hypotheses can be tested prior to instrument retrieval.

4) The need to reduce costs of scientific research. (For example, in some situations instrument retrieval costs exceed instrument replacement costs. Thus, data telemetry from expendable instruments may prove cost effective.)

5) Performance monitoring to ensure that high-quality data are being collected.

6) Adaptive instrument control allowing scientists to alter sampling schemes and initiate actions based on measured data.

In some situations instrument retrieval costs exceed instrument replacement costs.

The Surface Link

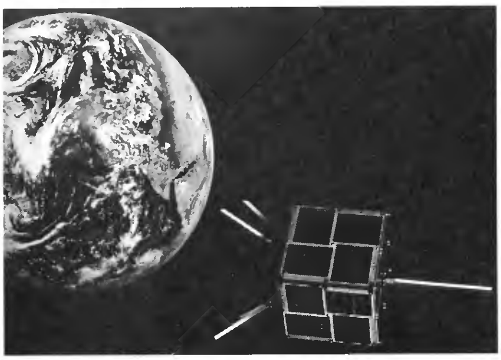
Since the mid-1970s, several satellite relay systems have been available for linking offshore buoys to laboratories ashore. They have usually been installed and maintained by government agencies expressly for the collection and dissemination of low-data-rate environmental information. The table shows some of the links available to oceanographers and their important specifications and capabilities. The most widely used systems are the Argos Data Collection System and the GOES (Geostationary Operational Environmental Satellite) Data Collection System.

The Argos system employs two polar-orbiting satellites that circle the Earth every 105 minutes at an altitude of about 900 kilometers and provide worldwide coverage. They have an instantaneous field of view of about 3 percent of the Earth's surface. A given point on the ocean is in view of a satellite for 10 to 15 minutes, six or more times per day, depending on latitude (more passes at the poles, fewer at the equator). Data are transmitted to the satellites from small, low-power radios operating at 400 megahertz using omnidirectional antennas. The amount of data on a single transmission is limited to 32 bytes and transmissions are allowed about once per minute. The satellite down-links this information to one of several ground stations where the position of the transmitter is computed based on the Doppler shift of the transmitter frequency.

The GOES system provides data-forwarding services for the Western Hemisphere, exclusive of the poles, using high-altitude geostationary satellites. Since they remain in the same location with respect to the Earth, terrestrial transmitters can be equipped with directional antennas, which are more energy efficient than omnidirectional antennas. GOES transmitters can also be used on offshore buoys by increasing their power output and using omnidirectional antennas. Data capacity is typically 500 bytes every 3 hours. The satellite is always in view, but a single transmitter is usually assigned a 1-minute slot every 3 hours.

In the last several years commercial services such as Geostar and Standard-C have been become available and are being evaluated for oceanographic use. These newer systems offer increased data throughout and two-way communication, but because they have been designed for nonoceanographic applications, they have important limitations as oceanographic research tools, such as high power consumption or limited coverage over the ocean.

These 9-inch microsat satellites are covered with solar cells to generate the power necessary to run the electronics and relay data to Earth stations.



A promising newcomer to the world of oceanographic satellite data links is the microsat.These miniature polar-orbiting satellites are used as store-and-forward transponders for amateur radio enthusiasts. They offer the potential for full-ocean coverage at a spectacularly low cost and at data rates higher than existing systems. Problems with licensing, cost sharing, and system operation are yet to be solved, but the future for this technology is bright.

Another bright idea that, if realized, may revolutionize our ability to transfer data from ocean platforms to laboratories ashore is the newly announced Iridium system being pursued commercially by Motorola and others. It promises two-way communication from small, low-power radio transmitters located anywhere on the globe using a

TABLE 1.
Telemetry Tradeoffs for Oceanographic Measurements from Offshore Buoys

Telemetry Option	*Coverage*	*Typical Throughput*	*Power Requirement*	*Platform Location*	*Hardware* (Cost)	*Per M* (Cost)
ARGOS	Worldwide	0.02-0.2 bps	1-10 J/bit	± 1 km ± 1 km N/A	$2k	$820[b] 236[b] 102[b]
ATS	Hawaii to Azores, but non-polar	0.3-1.2 kbps	0.5-1 J/bit	N/A	6k	0
GOES/METEOSAT/ GMS/INSAT	Worldwide except polar regions	0.2-2 bps	1-2 J/bit	N/A	3k	0
VHF (Line-of-Sight)	10-50 km from receive station	0.3-1.2 kbps	0.02-0.1 J/bit	N/A	1-2k	0
Meteor Burst	2,000 km from master station	1-20 bps	0.2-1 J/bit	N/A	5-10k	0
HF Packet	Variable up to worldwide[d]	1-30 bps	1-10 J/bit	N/A	2k	0
Recent[f]						
Inmarsat Standard-C	Worldwide except polar regions	10-100 bps[g]	0.5-1 J/bit	N/A	5-10k	0
Geostar	Coastal US	0.1-10 bps[g]	0.01-0.1 J/bit[h]	± 7m	3k	45

NOTES:
(a) Not continuously: orbiting satellite.
(b) Basic charges are monthly: per bit charges are based on assumed data throughout. Many users get large (to 100%) discounts.
(c) Extra costs are required to obtain data via telephone or tape.
(d) Lower data rates, more power required at longer ranges.
(e) More receive
(f) Systems existi
(g) Estimates.
(h) Spread-spectr

constellation of 77 small polar-orbiting satellites. This system would provide instant communication between any two locations on the globe.

The Subsurface Link

While the surface telemetry link has a number of reliable solutions, the link between subsurface instrumentation and the satellite transmitters installed on surface buoys has still not been solved except in a few specialized applications. At the Woods Hole Oceanographic Institution (WHOI), we have been working for several years to develop a class of general solutions for deep-ocean data telemetry. These solutions include moorings with instrument arrays connected by electromechanical mooring lines, acoustic telemetry links, and inductive telemetry links. Related work at Charles Stark Draper Laboratories and at the University of New Hampshire (UNH) has focused on pop-up systems, moorings that have an occasional surface expression. These pop-up designs can be tethered (Draper design) or freely drifting (UNH design). The freely drifting version is referred to as a data capsule, a small expendable float that collects data over a period of time and is released at a scheduled interval from a subsurface instrument. After each capsule in the package is released, it floats to the surface and transmits data to a satellite as it drifts away.

The top figure on page 50 illustrates several of the subsurface links being developed. The simplest, conceptually, are the hard-wired links that use electromechanical cables to connect subsurface instruments to the surface buoy. Surface and subsurface moorings have been tested with some success, but they remain somewhat expensive and prone to failure. The special electromechanical cables and terminations are costly and labor intensive to test and install. Where they pass through the surface, the constant action of winds and waves shortens their life.

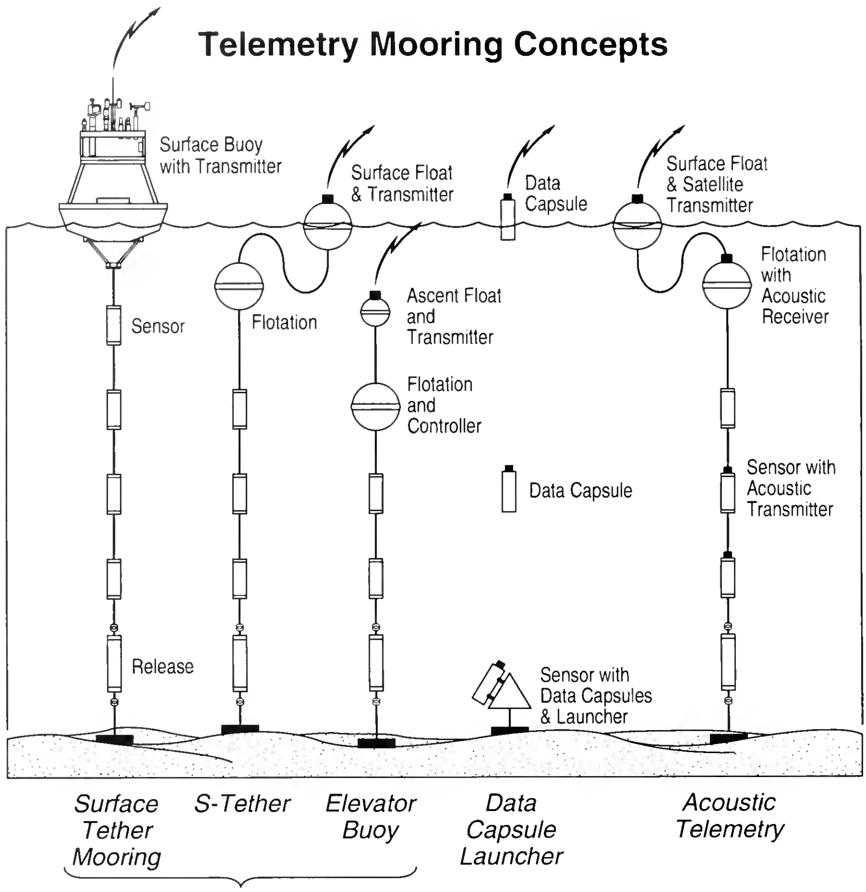
Two unique tethered pop-up systems have been designed, one by WHOI and one by Draper Laboratories, to deal with the reliability problem. The WHOI system, known as R-TEAM (Real Time Environmental Arctic Monitoring), was designed to operate in seas that are ice covered part of the year. In this system a large gas container in the subsurface module fills the surface module with carbon dioxide once per day causing it to ascend. If the waters are open, it transmits data to a polar orbiting satellite. If it encounters surface ice, the module transmits its data along the surface

---- Per Bit	*Long-Term Availability*	*Receive Station*
0.0014 0.0004 0.002	Yes	Not required, but available ($40k) with limited coverage
0	No	Not required, but available ($5k)
0[c]	Yes	Not required, but available ($40k)
0	Yes	Required ($5k)
0	Uncertain due to licensing	Required ($100k)
0	Yes	Required ($10k); may need several
0.00125[g]	Yes	Not required
0.00016	Not known	Not required

ıcreases efficiency.
988.

ɔlogy, hence low power requirement.

Several telemetry systems are being investigated to provide real-time data from subsurface instrumentation.



Illustrated by Jayne H. Doucette

This telemetry mooring station in the North Atlantic was equipped with instruments to monitor currents, winds, temperature, air pressure, and relative humidity.

of the ice via a low-frequency radio transmission. This signal is then detected by a shore station up to 100 kilometers from the site.

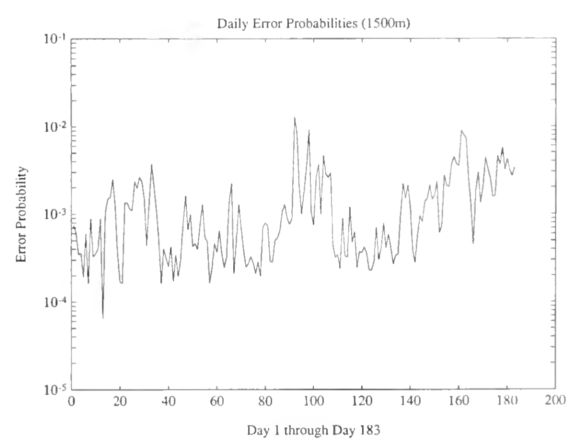
The Draper Laboratories design uses a compact winch to raise and lower a very small surface float equipped with a satellite transmitter to improve reliability and allow for telemetry in situations where a surface buoy may be at risk from fishing boats, ice, or other obstacles.

To reduce the cost and improve the reliability of electromechanical links, but take full advantage of the fact that a mechanical mooring line is required to support the instrumentation, WHOI has developed an inductively coupled modem to clamp on standard, mechanical mooring wire. Signals from the modem are amplified and passed through a toroid placed around the plastic-jacketed mooring wire. This toroid induces signals in the steel mooring line without any direct electrical connection. The signals are detected by a receiver in the surface buoy and passed to a satellite transmitter. This technique allows a single long wire to be used to suspend a number of small clamp-on sensors, thus reducing the cost of the entire array. Data rates of 1,200 bits per second at very low power output have been achieved.

The R-TEAM surface module has an umbilical attached to a subsurface flotation module 100 meters below the surface.

Use of acoustic signals is a third and very powerful technique for sending data through seawater. Because seawater transmits sound waves far better than air, signals can be sent very long distances through the ocean. Acoustic communication, unlike radio-frequency and hard-wired communication, is complicated by the complex and time-varying behavior of the ocean acoustic channel. While the channel supports communication, it introduces various distortions, noise sources, and attenuation factors that cause failures in many simple acoustic telemetry schemes. WHOI researchers are developing sophisticated techniques to send high-data-rate signals with low error-rate probabilities using very low power.

In most previous acoustic telemetry systems, two frequencies representing digital data (Os and 1s) were transmitted in sequence. This technique is limited by multipath considerations to modest data rates. In the WHOI system, up to 256 frequencies are transmitted simultaneously. These acoustic wave forms are decoded at the receiver using sophisticated digital signal processing (DSP) techniques originally developed for high-speed telephone and radio communication. Because the speed of sound in seawater is so much slower than the speed of electronic signals, processing time can be used by high-speed DSP chips to demodulate the incoming wave forms. As a result, data rates of 5,000 bits per second have been achieved with relatively low error rates. The figure at right illustrates the bit error rates recorded by an acoustic telemetry system tested at a 1,500 meter depth offshore of Bermuda for six months in 1990. Other applications for acoustic telemetry (beyond conventional ocean data telemetry) include communication with autonomous underwater vehicles (AUVs), submarines, bottom-mounted work platforms, as well as subsea instrumentation and control.



The bit error rate for an acoustic modem tested offshore of Bermuda and located 1,500 meters below the surface is illustrated graphically.

As we improve instrumentation reliability and attempt to reduce oceanographic research costs, ocean data telemetry will be an important area for technological improvement. Satellite bandwidth currently limits our ability to transfer large amounts of data, but the new systems being developed promise far more capacity in the near future.

Daniel E. Frye is a Research Specialist at the Woods Hole Oceanographic Institution (WHOI), where he manages the Advanced Engineering Laboratory. His current research interests are in acoustic telemetry, moored systems, and ocean instrumentation.

W. Brechner Owens is an Associate Scientist in the Physical Oceanography Department at WHOI. His current research focuses on measurements and modeling of the ocean circulation, particularly the Gulf Stream and the deep currents of the North Atlantic and Pacific oceans.

James R. Valdes is a Senior Engineer in the WHOI Physical Oceanography Department. His research interests include neutrally buoyant floats and satellite telemetry.

The Role of the Microcontroller in Ocean Research Instruments

Albert M. Bradley

Author's note: This article recounts the story of the microcomputer's invasion of ocean research. It is intended for those who have an interest in the history of technology and those who wonder just why these tiny computers are now so ubiquitous. It details some of the advantages—and handicaps—of living in the computer world.

Humans are tool-building animals, and our latest tool is the microcomputer. It is interesting to note that while we continue to develop increasingly powerful tools, we also seem to lose many of the tools we have had in the past. There are several reasons for this. The first is the limited time available for education. Today, for example, with all the new technology to learn about, few engineers know much about rotating alternating-current machinery, which was all the rage in the 1930s. A more subtle limitation is the evolution of parasitic structures that weaken previously successful ones. For example, many argue that we could not repeat the magnificent Apollo trips to the moon of the 1960s and 1970s because of the increased cost of doing business in today's litigious world. Like living systems, our technology seems to develop its own kinds of pathologies that limit its growth. But the microcomputer is here today, inexpensive, easy to design into anything one can imagine—and you don't need a license.

In the Beginning...

The first real, albeit rather limited, microcomputer, the Intel 4004, appeared in the early 1970s. It had just four integrated circuits, each about the size of your thumb. At that time most of us still punched data onto IBM cards and waited in line to submit our programs to the acolytes who tended the gigantic computing machines of the 1960s. We would look with envy at the few colleagues whose projects were flush enough to afford the new "mini" computers that could fit into a closet rather than taking a whole floor of the building.

The minis were a step in the right direction, but it was the micros that put computing in the hands of anyone who could imagine a use for them. Finally, we could think of including computers in our ocean instruments to control their behaviors and collect data.

One critical development was required before the microcomputer could invade oceanography. It was the complementary metal oxide on silicon (or CMOS) integrated circuit, developed at RCA in the late 1960s. This ingenious arrangement of transistors only expended electrical energy when it changed state, using almost no power at all while it waited for an input to change. This breakthrough permitted the design of computing elements that required very low power to operate. A microcomputer that previously required several watts could now make the same computations with only a few milliwatts. This was crucial for battery-operated instruments deployed in the ocean. Today, with incredible calculators that run for years on a few watch batteries, we rarely think of the days when instruments could run only a few hours between charges. In modern laptop computers, the disk drive's motors rather than the computer itself hog most of the power.

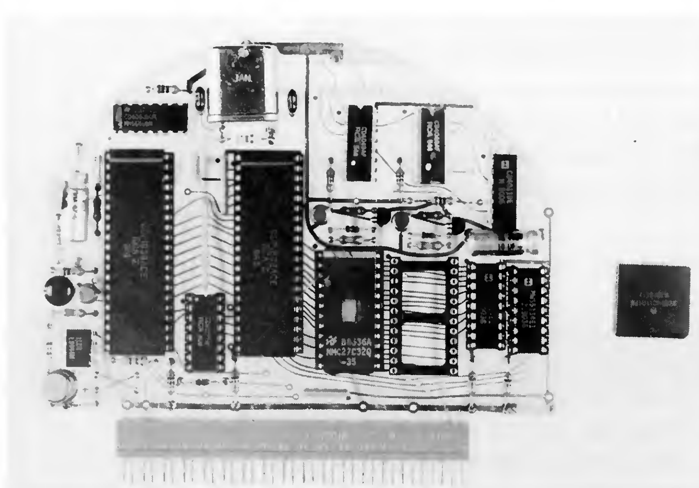
What is a "Micro," Anyway?

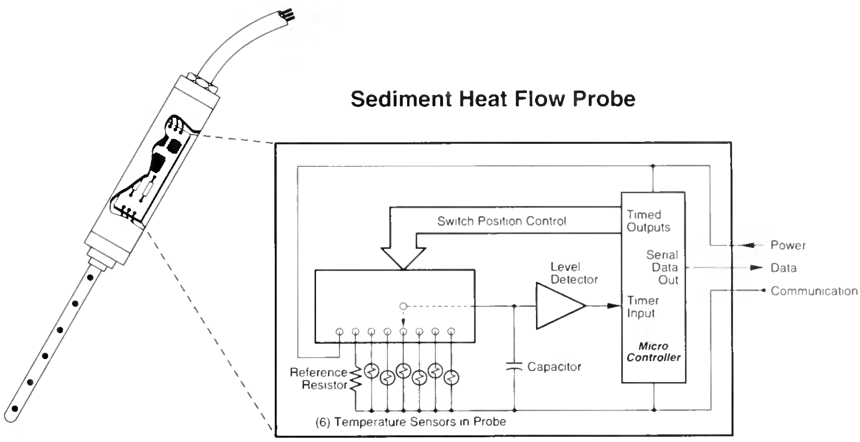
People argue about the exact differences between a microprocessor, a microcomputer, and a microcontroller. Often these terms are used loosely or interchangeably since, in many instances, the dividing line from one to the next is difficult to see clearly. In this article I'll ignore these fine points and just call them microcontrollers or "micros," but will emphasize the "controller" aspects.

Microcontrollers are either a single integrated circuit or a small group of integrated circuits that make up a computer. The micro contains a "program" in its memory, which is a specific list of directions done one at a time in sequence. In addition to the program memory, there's some additional memory for data and "scratch pad" uses. Micro memory sizes range from a few thousand to several million characters.

Microcomputers are used in a bewildering range of applications. The term "microcontroller," however, suggests that, rather than intensive computation, the application emphasizes measuring, timing, data formatting, and controlling the function of a system. The thermal conductivity sensor described below, a typical controller, clarifies this emphasis. By contrast, the acoustic telemetry systems discussed in this issue (see the telemetry article, page 46) use specialized microcomputing

The rapid evolution of the microcomputer is illustrated by these two examples. The integrated circuit on the right, available since 1989, has all the capability of the board on the left, designed in 1980.





A sediment heat flow probe is typical of today's microcontroller-based ocean instruments. Through clever exploitation of the capabilities of the micro, the circuitry is reduced to a minimum.

elements that emphasize rapid calculation at the expense of control.

A microcontroller often contains special input and output circuits to link it to the rest of the instrument. Examples would be simple on/off control lines, lines to read the state of external switches, and sophisticated timers to measure and control external devices with a precision of less then a microsecond.

A Typical Micro-Based Instrument

So why is the microcontroller so valuable for the average ocean research instrument? One reason is shown by the example of a specialized thermal conductivity sensor that geologists use to study the flow of heat up through the earth's mantle and overlying sediment into the ocean above. To measure the thermal conductivity of the sediment, they insert an 18-inch probe into the mud, briefly heat its tip electrically, then measure the temperature along the probe as the sediment cools back to normal. The figure above shows a block diagram of the circuit used by the instrument engineer to construct this probe with heater and temperature sensors. Notice that there isn't much beyond the sensors and the microcomputer itself!

But why use a computer at all? What exactly is it doing? The microcomputer we chose for this task has several additional circuits on its chip beyond the basic computer core, specifically, a number of input and output lines that can be either changed or sensed (depending on whether they're set to be inputs or outputs) at precisely known times. We use these with a bit of additional circuitry to make the precision temperature measurements.

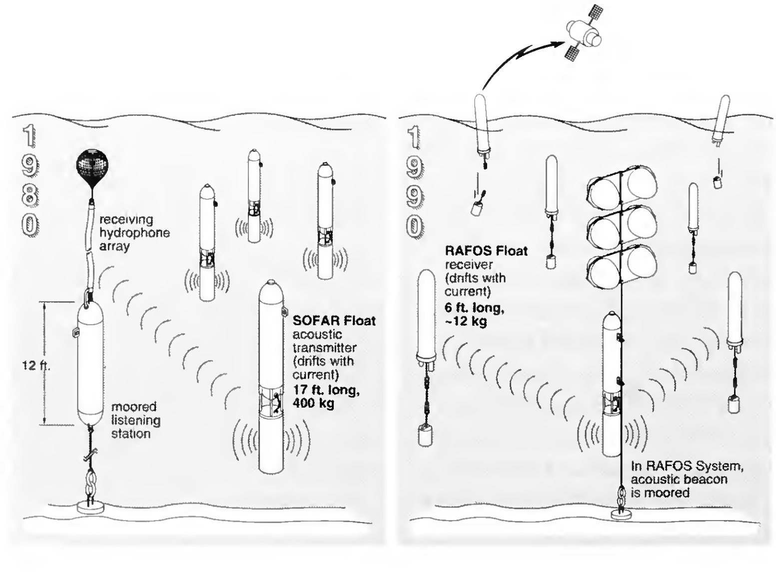
Here's how it happens. The temperature sensor is a tiny electrical component called a thermistor, whose electrical resistance varies with temperature. The job of the micro is to measure this resistance as precisely as possible. It does this by discharging a capacitor through the thermistor and measuring the time required to deplete the capacitor exactly half way. This is analogous to draining a cup of water through a small hole in the bottom of the cup. You can deduce the size of the hole in the cup (the resistance) by the time it takes the water to run out. The micro tells the circuit first to "fill the cup to the brim" (charge the capacitor) then to "open the leak" (connect the thermistor to the capacitor) and measure exactly how long it takes for the cup to empty half way.

In our case, we don't precisely know the size of the "cup," since capacitors are not as stable as we would like. The micro helps us get around this problem using a trick that would be awkward to accomplish without its help. We refill our cup and discharge it through another "hole." This time, instead of being a temperature-sensing thermistor, however, the "hole" is a precisely known reference resistor. This only requires a few more lines in the micro's program and, besides the extra resistor, requires no additional circuit components. Now we have two discharge times, one for the thermistor and one for the reference resistor. It turns out that you don't need to know the capacitor's size anymore. The ratio of the two discharge times is precisely the ratio of the two resistances involved. Not only is this method insensitive to the exact size of the cup, but since we're only looking at the ratio of two times, exactly how far we choose to "drain the cup" isn't important as long as we do it to exactly the same level each time. The microcomputer computes this ratio and stores it in its memory.

The micro's work isn't finished yet, however. The switch it controls (called a multiplexer) to select the discharge path for the capacitor comes with eight positions. One switch position is used for the thermistor, one for the reference resistor, and one is used to "fill the cup" by connecting the capacitor to the power supply. This leaves five additional switch positions to accommodate five more thermistors. With the micro, we can now measure a total of six separate temperatures with no additional circuitry. We just write the program to repeat the same timing measurement on all the channels and record the ratios associated with the six thermistors.

Finally, the micro is given the task of converting the ratios it has measured from its internal binary format to decimal characters, adding spaces between the six ratios to make the data easier to read and sending them out through what's known as an "asynchronous serial interface." I won't cover the details of this data interface, just mention that it is a direct descendent of the original telegraph system used since before the

The growth of the microcontroller has enabled scientists to plan more ambitious field experiments. Evolution from many powerful drifting acoustic sources and a few receivers to smaller but smarter drifting receivers and a few fixed sources has reduced the cost of tracking experiments.



Civil War to send data over wires. It is known formally as RS-232 and is today perhaps the most common means of passing data along a wire from one computer to the another. This serial data stream goes to the scientist, who views it on a laptop computer screen and records it on disk for later analysis.

In this example the micro's job is less that of a powerful mathematician than that of a very efficient manager with a good stopwatch. It spends its time measuring, transcribing, organizing, and arranging, with very little actual computation. This is typical of today's instruments.

The Evolution of the Micro in Oceanography

The history of the SOFAR float program at the Woods Hole Oceanographic Institution is another excellent illustration of the evolution of microcontrollers in ocean instruments (see Floats Give a New View of Ocean Eddies, page 23). Briefly, scientists needed to track the long-term motion of water masses in the interior of the world's oceans. Engineers led by Doug Webb (see also Henry Stommel's profile of Webb on page 104) developed freely drifting floats that sink to a preset depth, typically 1,000 meters, and drift forever with the current, emitting an acoustic signal that can be heard for several thousand kilometers with proper receiving equipment. Since sound takes many minutes to travel these distances, a careful measurement of the time of the sound's arrival at several locations reveals the location of the source.

We were finally free to follow our floats out into the central Atlantic.

Originally, the listening stations were hydrophones connected to shore with long (and expensive) cables. The drifting floats emitted an acoustic signal that started at 250 hertz and, over 80 seconds, slowly climbed to 251.625 hertz. The receivers' task was to recognize and record this unique signal in the midst of background noise. The first generation of receivers simply recorded the data on cassette tapes that were mailed once a week to a computing center at the University of Rhode Island where they were processed to find the float signals. By 1976, microprocessors were sufficiently advanced to allow us to deploy a signal-recognizing system in the field, and a small printer would type the exact time it received a signal from a float. We still had to merge the arrival times from a group of stations to locate the floats, but the volume of data was much reduced and easier to manage.

These early microprocessors still required about 10 watts to operate and couldn't run on batteries for very long, so we were still tied to the shore stations. In 1976, the first CMOS microcomputers appeared, and we were finally free of the wall plug. We soon developed a battery-powered listening station that could receive, recognize, and record float signals on tape for up to a year. The entire receiver ran on about .25 watt. These were large instruments with over 25 circuit cards and 600 pounds of D-cells, but we were finally free to follow our floats out into the central Atlantic.

Technology continued to improve, and, as more highly integrated components became available, we were able to shrink the size and cost of these receiving systems dramatically. In 1983 we were able to build a new version of the signal receiving and recognizing system on two cards only 8 inches long and 3 inches wide!

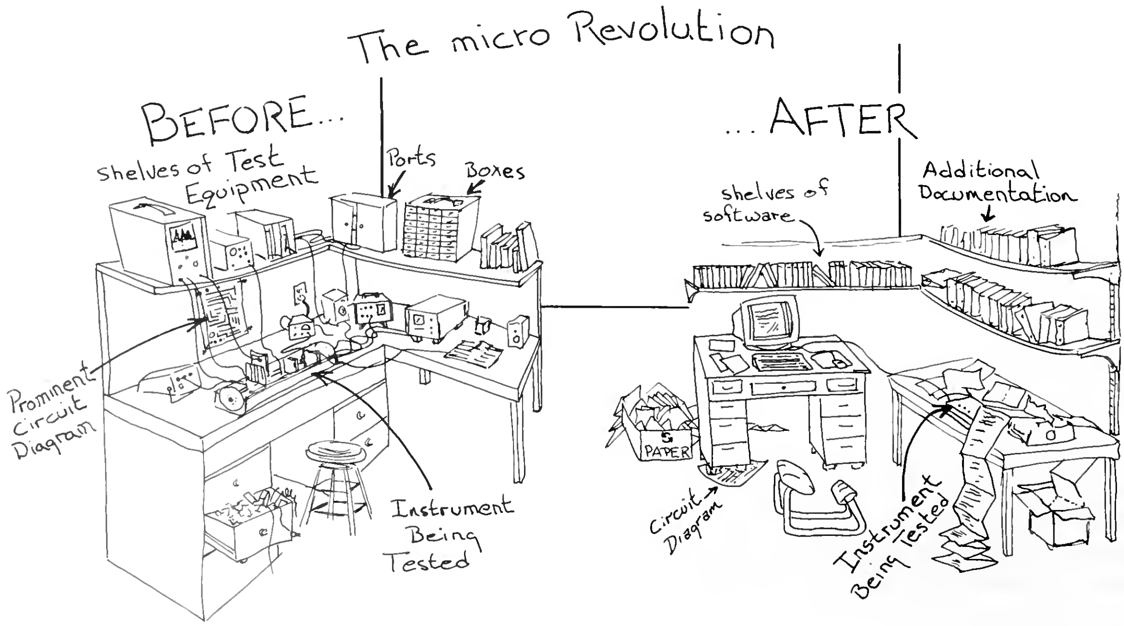
Engineers at the University of Rhode Island, however, saw the trend toward cheaper and smaller computers and decided to reverse the experiment. This team, led by Tom Rossby, recognized that the acoustic source, the floats, could not be easily reduced in size and cost because of the need to generate the 150-watt location signal, while every year they could imagine making the receivers smaller and cheaper. They therefore decided to moor the signal sources to the bottom and allow the receivers to drift, subsurface, with the current. This meant that the data (the arrival times of the acoustic signals from the now fixed beacons) were recorded in the memories of the drifting floats. At the end of its design life, each of these drifting receivers would drop a ballast weight, float to the surface, and tell the tale of its travels to a passing satellite.

This is an example of the how the evolving capability of microcomputers has changed our approach to instrument design. Originally, the micro was used to perform some crucial data processing task and most of our effort was focused on this component. Today, even the battery pack is often more expensive than the computer (particularly for a year-long deployment!) and the computer is exploited for every shortcut and economy we can think of. We no longer make elaborate control panels for any of our instruments, for example, but instead control them with a computer terminal through a simple serial interface.

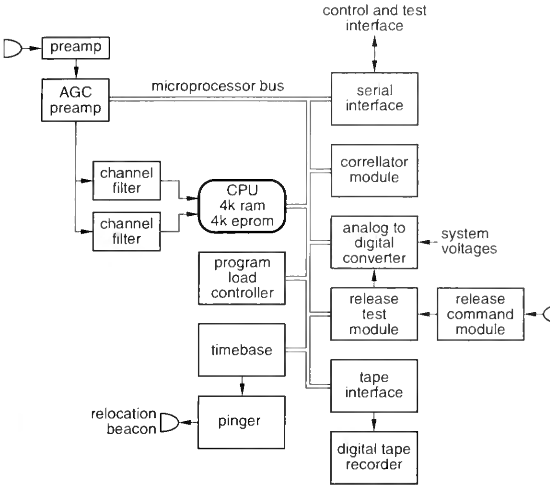
A Matter of Style

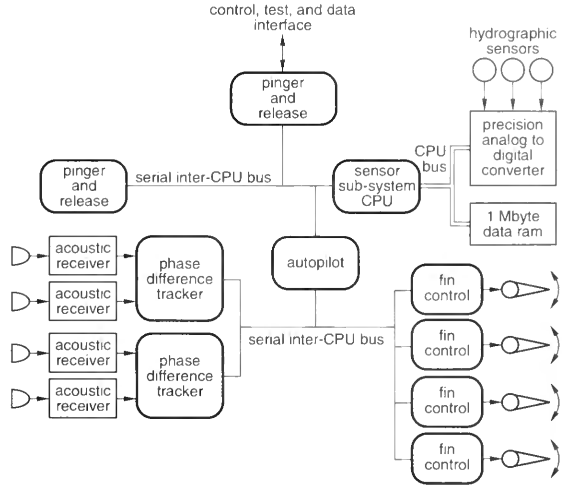
The work style of the instrument designer has also changed significantly with the switch to micro-based instruments. In the premicro days, the instrument designer was surrounded by all sorts of test equipment such as oscilloscopes, signal generators, and power supplies. Somewhere in the heart of a gigantic tangle of cables and probes would be the emerging prototype instrument. Nearby, almost hidden in the jumble, but certainly

Work Styles of Today and Yesterday



Illustrated by Albert Bradley and E. Paul Oberlander





on the top layer, would be the circuit diagram, usually with all sorts of scribbled notes around the edges.

Today, the typical picture is quite different. The instrument is smaller and the surrounding equipment sparse. Instead, there will be an attendant desktop computer with printer nearby, and long printouts of program listings will cover every available work surface. The circuit diagram is often buried deep in the pile. Clearly, the action is now in the program, not in the wires.

The approach to instrument design has changed drastically over the past decade. Ten years ago, a single-core computer controlled all the functions of an instrument. Today, single-chip computers are distributed throughout an instrument and work as a team.

There's a hidden danger in this evolution, however. We'll often spend hours searching a new program for some "bug" only to find that the prototype circuit really isn't working quite right and the program is not at fault! Then we have to find the buried circuit diagram, dust off the oscilloscope and do battle with the electrons as we did 20 years ago. We tell beginning engineers that there are never really any problems with digital systems. There's only "cockpit error" (you don't understand what's happening, which is a cruel, but accurate, way of describing a program bug) or old-fashioned analog problems. We then advise the neophyte to bone up on analog techniques so he or she will recognize this lurking menace in a misbehaving digital system.

Nonetheless, as our micros and their attendant software evolve, the trend from wires to paper continues. This in itself causes further problems. Twenty years ago, a careful study of a proper circuit diagram would tell a design engineer a lot about an instrument. Today, the circuit diagram only tells a small part of the story. Without knowing the details of the program in a micro, there's absolutely no way to distinguish the controller of an in situ water analysis instrument from that of a bread maker! Furthermore, while it might only take a few minutes to read and understand a circuit diagram, it can take from hours to weeks to study and understand a well documented, yet unfamiliar, program. This means that in the premicro days, a new engineer could step in and replace a member of a research team in a pinch without too much effort. Today, however, it is often easier to start over at the beginning than to take over a complicated and partially debugged program.

On large systems (a desktop computer in this context), software (the programs) is written in many modules by many people. First, these individual modules are carefully debugged (hopefully) to strict standards. Then the modules are interfaced to each other by strict rules. But, as with the micros, a not-quite-finished program module is nearly valueless if its author is not available.

Another trend is evident in the evolution of controllers for ocean instruments. In the early days of micros, the instrument was based on a single computer system with as many peripheral circuits as required to do the job. Today, in contrast, an instrument often has a large number of micros, each doing a part of the job and communicating with the others to pass data and commands. On page 59, this is illustrated in the figure contrasting the listening station designed in 1976 with a more recent instrument, the Fast Hydrographic Profiler. This new "distributed" architecture is the result of the growing capability of the available controller chips and offers several important advantages.

Even engineers find themselves fighting with the control panels of micro-controlled VCRs.

In the research world, we rarely build instruments in large numbers and the time available for documentation and instruction manuals is always less than we would like. With the centralized computer architecture, often only one "guru" knows how the system really works and modifications and upgrades are usually difficult or impossible without that person's help. A distributed architecture, on the other hand, has the advantage that one component may be replaced with a newer or more capable model, requiring only a fraction of the effort of modifying the whole system.

One could argue that if the centralized system is "properly" designed, its software can be easily upgraded a segment at a time. In practice this doesn't work out as smoothly as we would like. Often it's the central processor itself that is obsolete, thus limiting the performance of the system, and necessitating redoing the entire system.

Are We Ahead or Behind?

Even engineers find themselves fighting with the infamous inscrutable control panels of micro-controlled VCRs, and sometimes doubt that we're making any progress. Things have gotten so out of hand that you can buy a special remote-control box that explains your newspaper's television listings to your VCR when you can't figure out how to do it yourself. Most believe that these are only temporary aberrations and that the microcontroller is a definite step forward. We just have to be careful to avoid clumsy and confusing interfaces between the people and the machines. As with any art, good and bad examples abound, and we should be inspired by the best. As we attack the problems of studying the ocean, we find the micro a powerful ally if we use it wisely.

Albert M. Bradley was educated by his parents and a long series of exasperated teachers, including many at Cornell and MIT, where he finally received his Ph.D. from the Ocean Engineering Department in 1973. Since then he has taken refuge at the Woods Hole Oceanographic Institution, where the administration remains adamant in their refusal to change his title from Research Specialist to Toymaker.

The History of Salinometers and CTD Sensor Systems

Neil Brown

Prior to the introduction of conductivity-type salinometers in 1930, essentially all temperature and salinity data was obtained with reversing mercury thermometers and collection of Nansen-water-bottle samples for later laboratory measurements. The salinity was determined by titrating the chlorides using a method developed in 1901 by Martin Knudsen in Norway. Since chlorides are the major constituent of seawater and the relative proportions of dissolved solids are essentially constant, salinity was calculated directly from chlorinity. This method was very time-consuming and expensive, and required extreme care to achieve accuracies of 0.03 parts per thousand (ppt) in salinity.

Early Salinometers

The conductivity-type salinometer, introduced in 1930 by Frank Wenner of the US Coast Guard, directly measured the ratio of the conductivity of a sample to that of standard seawater, using two-electrode cells that were maintained at the same temperature. Salinity was calculated from the conductivity ratio. This instrument was at least as accurate as the Knudsen titration method, and much faster and easier to use.

Temperature has a large effect on seawater's conductivity. A .01°C temperature increase has the same effect on conductivity as a .01 ppt salinity increase. Modern oceanographers' need for accuracies of ±.003 ppt or better in the deep ocean led to the development of more precise instruments. For example, in 1956 Alvin Bradshaw and Karl Schleicher (Woods Hole Oceanographic Institution, or WHOI), and in 1958 Roland Cox (National Institute of Oceanography, UK), developed laboratory salinometers consisting of two-electrode conductivity cells in a thermostated oil bath along with the associated heaters, refrigeration, temperature-control electronics, and conductivity-bridge electronics. Salinity was determined by comparing the conductivity of a sample to the

Taken in 1958 aboard *Atlantis*, this photograph depicts Karl Schleicher operating a salinometer while Alvin Bradshaw looks on.

conductivity of standard seawater after both samples were equilibrated to the oil-bath temperature. These instruments were large, complex, heavy (in excess of 200 kilograms) and not commercially available, but they achieved the required accuracies of ±.003 ppt.

In 1961 Bruce Hamon and I, working at the fisheries and oceanography division of the Commonwealth Science and Industrial Research Organization in Australia, described a portable salinometer weighing approximately 15 kilograms. It used a thermistor and resistor network to precisely compensate for the large effect of temperature on conductivity, thus avoiding the need for a temperature-controlled oil bath. This instrument was manufactured in large numbers and achieved accuracies of ±.003 ppt. It used an inductively coupled sensor in a Plexiglas housing containing the sample and two thermistors. An impeller at the top of the housing provided rapid stirring. One thermistor was part of the temperature-compensation network; the other measured the sample temperature to an accuracy of ±.1°C and was then used to correct for the slight variation of temperature coefficient of conductivity with salinity. Using the inductively coupled conductivity sensor in this salinometer was intended to eliminate the drift problem in two-electrode cells. This drift was due to the inherent polarization impedance (similar to electrical resistance) that exists between each of the electrodes and the seawater. Drift was substantially reduced by using platinum electrodes coated with platinum dendrites (platinum black) to decrease the polarization impedance and, hence, the resulting drift. However the effect of drift was still significant and required that the cells be cleaned frequently and calibrated against standard seawater.

Inductively coupled conductivity sensors consist of two toroid-shaped transformers mounted close together with their center holes aligned one above the other. Seawater completely surrounds both transformers and fills the center holes so that the seawater forms a single-turn circuit common to both transformers. An alternating-current (AC) voltage applied to one transformer induces an electric current in the seawater circuit proportional to conductivity. The induced current is measured by the second transformer. Although these cells are more stable than two-electrode cells, the electrical resistance of the windings causes minor instability that must be compensated for by frequent recalibration.

In 1975 Tim Dauphinee (National Research Council of Canada in Ottawa) designed a laboratory salinometer (commercially available as the AUTOSAL) that is still widely used by oceanographers today. AUTOSAL uses a four-electrode cell immersed in a small thermostated bath as a means of avoiding the problem of drift caused by polarization. The four-electrode cell is exactly analogous to a four-terminal resistor. The conductance is defined as the ratio of the current through the two "current" electrodes to the

In this 1960 photograph, the author operates an early inductively coupled salinometer.

open-circuit voltage between the two "potential" electrodes: Defined this way, conductance is totally independent of the polarization impedance of any of the four electrodes.

Even though these salinometers satisfied the accuracy needs of most oceanographers, techniques for collecting samples for later salinometer analysis left much to desired. Samples were collected at relatively few preset depths, so that important details were often missed, salinity information was not available quickly enough to guide a cruise's progress, and sampling and analysis was time-consuming and expensive.

In Situ Systems

The limitations of collecting seawater samples and analyzing them onboard ship led to the development in 1948 of the first in situ system by A. W. Jacobsen working at the Bristol Corporation in Waterbury, Connecticut. Limited to 400 meters, this instrument used separate cables for mechanical support and electrical connection. The system was crude but pointed the way of the future in oceanography.

It showed more fine-scale structure in the ocean than traditional sample-collecting methods could reveal.

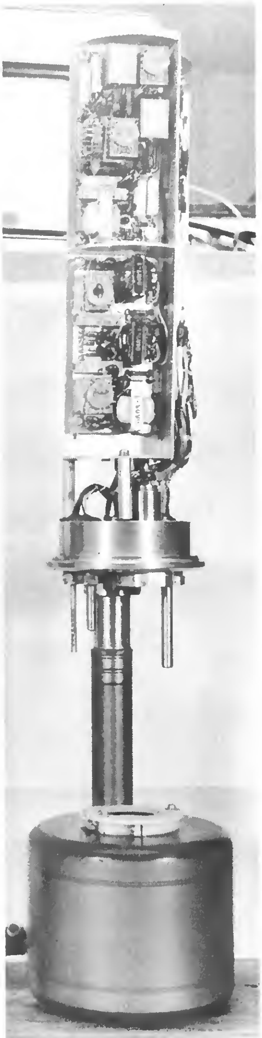
In 1958 in Australia, Bruce Hamon and I described an instrument designed for use to depths of 1,000 meters. It was the first use of a single-conductor armored cable for mechanical support, power to the instrument, and transmission of data to the surface. Its temperature accuracy was ±.15°C, and its salinity accuracy ±.05 ppt. Salinity was measured using a two-electrode conductivity cell and a thermistor-resistor circuit to compensate for the effect of temperature on conductivity. A simple phase-shift oscillator circuit converted the output of each sensor sequentially to a variable audio frequency. This signal was transmitted to the ship, converted to a direct-current (DC) voltage, then recorded on a strip-chart recorder. There was no compensation for the effect of pressure on conductivity: Recorded data had to be manually read from the strip chart recordings, then manually corrected for the pressure effect.

Hamon made the first determination of the effect of pressure on seawater's conductivity as a result of the development of this instrument. Bradshaw and Schleicher (WHOI) in 1965 made much more extensive and precise determinations of these pressure effects. Although this instrument needed constant cleaning and cell replatinization to maintain its accuracy, it clearly showed there was much more fine-scale structure in the ocean than traditional sample-collecting methods could reveal.

Development of the STD

In 1959, I came from Australia to WHOI to work with Bradshaw and Schleicher to develop what was hoped to be a more accurate in situ instrument. It used an inductively coupled conductivity sensor and a sealed compensating cell containing standard seawater. The compensating cell was intended to precisely compensate for the effects of both temperature and pressure; however, our attempt to make a cell that was both stable and rapidly responsive to temperature changes was unsuccessful and was abandoned.

I returned to Australia in 1961 and then in 1962 returned to the US to join the marine division of Bissett-Berman Corporation in San Diego, California, to continue the development started at WHOI. The STD (sa-



This STD was developed for Bissett-Berman between 1962 and 1964.

linity, temperature, depth) instrument resulting from this work was first sold commercially in 1964. At that time, computers and their peripherals were too expensive, unreliable, and difficult to use routinely at sea. Since it was essential that salinity data be available immediately, the complex relationships between salinity, temperature, pressure, and conductivity had to be emulated in an analog fashion in a salinity bridge. This bridge consisted of two platinum thermometers, three thermistors, two pressure transducers, and six transformers, as well as the inductively coupled conductivity sensor and a considerable amount of electronics. It required a complex, time-consuming series of adjustments for calibration.

The STD used a phase-shift oscillator (known commercially as the Paraloc Oscillator) developed from the design we used in Australia. Separate oscillators converted the output of the salinity, temperature, and pressure bridges to audio frequencies in three separate bands. Although it stretched analog technology to the limit, this complex and expensive instrument became the first profiling instrument to be routinely used: More than 700 were sold worldwide before they were made obsolete by the CTD (conductivity, temperature, depth) sensor system, starting in the early 1970s. The STD's accuracy was not adequate for depths much greater than 1,000 meters, and there was a severe "spiking" in the salinity data, due to the slow response of the temperature sensor relative to the conductivity sensors. Also, its accuracy was limited by systematic errors in the salinity bridge emulation of the salinity, pressure, temperature, and conductivity relationships.

Enter the CTD

These limitations, along with rapid evolution of the digital computer, prompted me to rejoin WHOI in 1969 to commence development of a digital instrument to address the limitations of the STD. Following publication of this work in 1974, I left WHOI to form Neil Brown Instrument Systems, Incorporated to manufacture the Mark III CTD. The Mark III's conductivity sensor was a miniature four-electrode sensor 3 centimeters long, fabricated from thin alumina ceramic. It measured temperature using a combination of a very stable platinum thermometer with a typical response time of 250 milliseconds and a thermistor with a response time of approximately of 50 milliseconds. The outputs of these two sensors were combined in an analog circuit that had the stability of the platinum thermometer and the speed of the thermistor with no sensitivity to the steady-state calibration errors in the thermistor. The combined output was digitized along with the pressure and conductivity sensors. Experience showed that due to the variability and complexity of the time response of these sensors, it was better to digitize their outputs separately and combine the outputs numerically in the computer. One key development in the CTD was the high resolution (16-bit) AC digitizer, which had a noise level of 0.1 microvolt at a rate of 100 samples per second.

In 1974 Nick Fofonoff, Stanley Hayes, and Robert Millard wrote in a WHOI Technical Report that with appropriate data processing and adequate at-sea calibration the "CTD gives data equal to or better than the best hydrography stations data." They claimed that for measurements below the main thermocline the accuracies were: temperature, ±.0015°C;

depth, ±1.5 decibars; and salinity, ±.003 ppt. Not all users of the CTD were able to achieve these accuracies; they required careful calibration immediately before and after each cruise with frequent checks against bottle samples during the cruise, adequate data acquisition, and good processing software.

There are two main sources of error in the Mark III CTD. The most serious one is the calibration drift of the conductivity cell, caused by contamination of the ceramic surface and the platinum electrodes by the deposition of oils or other organic matter on the electrodes or the formation of calcium or magnesium carbonate on the ceramic surfaces. The second source of error is the limited accuracy of the pressure measurement (±0.1 percent). At a depth of 6,000 meters, this pressure error results in an error of ±.004 ppt in salinity.


Photo by Peter Wiebe

A CTD is launched from R/V Atlantis II *in 1981. This water-sampling trial included 12 five-liter bottles mounted on a rosette, as shown.*

Since the early 1970s when the Mark III CTD was developed, microprocessor technology has undergone spectacular evolution. At the same time the demand for CTDs with custom modifications and additional sensors became the rule rather than the exception. As a result, the Mark V CTD was developed starting in 1987 to take advantage of microprocessor technology so that most custom modifications and calibration adjustments could be made in software rather than in hardware, thus simplifying the manufacturing process. Another important difference is the use of a six-electrode conductivity cell that promises substantially improved stability. It is sensitive to the external seawater at one end of the cell and not sensitive to seawater inside the cell. All six electrodes are inside the cell, remote from its sensitive area. However, the electronics necessary for this cell are inherently complex. The Mark V CTD uses a titanium pressure sensor that is about three times more accurate than the sensor used in the Mark III system.

Future Developments

The amount of oceanographic data that ships and personnel can collect using existing CTD systems limits the advance of oceanography and climatology. Possible alternative methods include mounting CTDs on autonomous vehicles and employing conventional and expendable moorings and ships of opportunity. Regardless of platform used, CTD sensors need to be less expensive, consume less power, be lighter and smaller, and, most important, have excellent long-term stability. Even the present shipboard methods would benefit considerably from such CTD systems. The design philosophy in both the Mark III and later the Mark V systems was to make each part of the system extremely stable and predictable in performance. This resulted in systems with the desired performance, but at the cost of high power consumption, complexity, and expense.

As my company grew to over 50 employees, I found that managing it was no longer fun. In 1982 my board of directors and I appointed a general manager to run the company so that I could get back to the design work I really enjoyed. After two years under his management, the company was acquired by EG&G. I remained with them for five years as a senior scientist; however, during this time I found very little opportunity to work on new developments, so at the end of the five years (in 1989) I was very happy to return to WHOI.

A new design I am presently developing uses very simple, compact, and inexpensive electronics. They are not necessarily stable but are dynamically calibrated in situ against ultra-stable resistance networks that accurately simulate the output of the sensors for known values of the measured parameters. An internal microprocessor then corrects for drift in the electronics.

One of the main objectives of the new development is to adapt this concept to long-term, battery-powered applications. A preliminary study shows that power consumption of 1 milliwatt per sensor can be achieved. This would mean that a sensor could be operated continuously for two years from two D-size lithium batteries. Marine fouling is the most serious problem for long-term deployment of any CTD system using electrode-type cells. Since the electrodes must be exposed directly to seawater, they cannot be reliably protected from marine fouling using any form of anti-fouling coating. The new development proposes to use an inductively coupled conductivity sensor with additional feedback winding and electronics to eliminate the errors of previous designs caused by the windings resistance. This will also eliminate the need for a pressure housing to protect the transformers, drastically reducing the size, cost, and thermal mass. Since there are no electrodes involved, conventional antifouling techniques can be used, greatly improving the chance of achieving long-term stability.

Over the years the conductivity sensors in salinometers and CTD systems have evolved from the simple two-electrode cell to the inductive cell, then to the four- and later the six-electrode cell, and finally back to the inductive cell. Use of the new inductive cell and dynamic calibration of the electronics using the power of the microprocessor now promises CTD systems that are small and inexpensive, and have excellent long-term stability.

Neil Brown is a Principal Engineer in the Department of Applied Ocean Physics and Engineering at the Woods Hole Oceanographic Institution. He has been instrumental in the development of modern CTDs since 1956; since then he has alternately worked for WHOI, Bissett-Berman Corporation, and his own company which he sold to EG&G in 1984. CTDs are currently produced by several US firms.

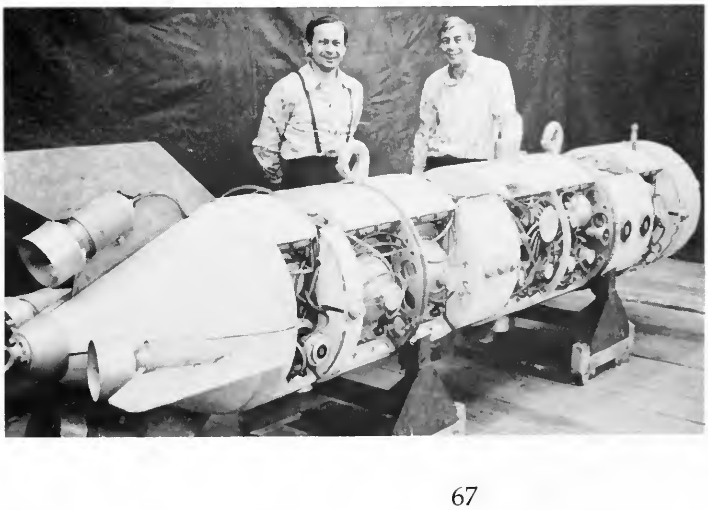
Underwater Technology in the USSR

Deam Given

For the Soviet Union and the rest of the world, 1989 was a momentous year. The Berlin Wall cracked open, suddenly freeing Eastern Europe from Moscow's bonds. A Soviet nuclear submarine sank in the Norwegian Sea losing 42 lives, followed by unprecedented criticism in the Soviet press about naval safety standards. Also in that year, Soviet engineers and scientists revealed some of their latest and previously covert underwater technology. *Glasnost* had arrived.

In March 1989, the Marine Technology Society's ROV (remotely operated vehicle) Committee held its annual subsea Intervention/ROV technical conference and exhibition in San Diego, California. Soviet scientists had attended this event before; however, this time they went to participate. Mikhail Ageev, director of the Institute of Marine Technology Problems in Vladivostok, presented a paper at the conference about how ocean current fluctuations can induce errors in underwater vehicle navigation. Nikolai Rimski-Korsakov (a great, great grandson of the composer), of the P.P. Shirshov Institute of Oceanology in Moscow, presented a paper on the Soviet *Zvuk* (sound) series of towed, sidescan sonar vehicles.

This early model autonomous underwater vehicle was built in the USSR in the early 1970s. Behind it are Mikhail Ageev (right) and a colleague.



During the conference, these gentlemen offered me materials for publication in the magazine *SubNotes* (now titled *WAVES*). Rimski-Korsakov provided mounds of photographs and data about the four *Zvuk* vehicles. Ageev's contribution was smaller, but far more eye-opening: A photograph of the *MT 88* (MT for *Morskaya Teknologiya* or Marine Technology; 88 for the year it was built), an autonomous underwater vehicle (AUV) that operates in ocean depths to 20,000 feet. Its chief sensors are sidescan sonar and photographic and television cameras. This tetherless vehicle is used to search the seafloor for manganese nodules, and also for geological surveys. The vehicle is 14 feet long and 2.3 feet in diameter, weighs 1 ton in air, and runs on silver-zinc batteries that provide a six-hour underwater endurance at 1.5 knots. It has made more than 100 operational dives to date. This was extraordinary news.

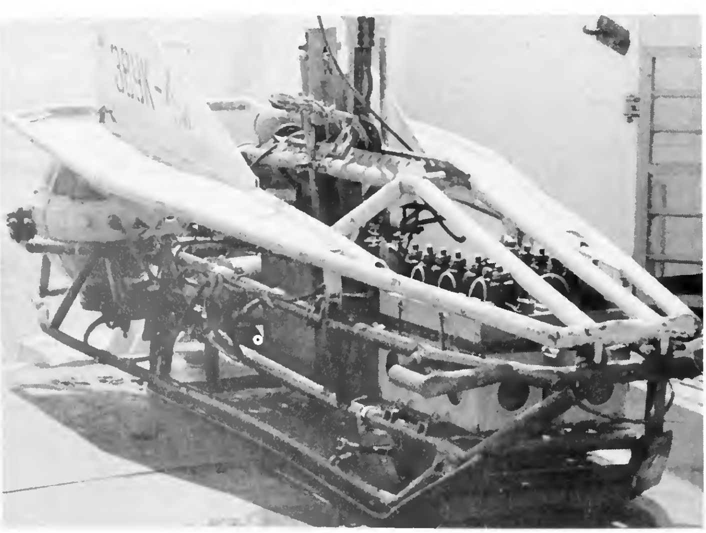
In the 1950s, to prevent the transfer of military technology to the USSR and Eastern bloc countries, the US and 16 other Western countries established the Coordinating Committee for Multilateral Export Controls (CoCom). These regulations, including a 1,000 foot depth limit for underwater-technology items, were aggressively enforced during the Reagan administration. Although it was assumed that the Soviets could design and build equipment for operations to 20,000 foot depths, it was not openly known that they had AUV systems and were routinely operating them at considerable ocean depths. Previously classified, the *MT 88* project was declassified just two months before the conference.

A Firsthand Look at a Soviet Research Institution

Upon publication of this information in *WAVES*, Ageev invited me to visit his institute in Vladivostok and informed me that he was now authorized to sell or lease these AUV systems through a joint venture. It is difficult to price the MT system in US dollars, chiefly because no one knows the true value of the ruble, but five million dollars is a good guess. I was asked to evaluate the marketability of *MT 88* technology and discuss the feasibility of a joint venture with a Western company. From "Top Secret" to "For Sale" in nine months indicates how fast things were changing in the USSR. Such an invitation could not be refused.

Vladivostok is a closed city, so I flew from Japan to Khabarovsk, a city 600 miles north of Vladivostok, where Ageev and two of his associates met me. The next morning we flew to Vladivostok aboard an Aeroflot Yak-40.

The Institute of Marine Technology Problems (IMTP) employs approximately 160 people in a dingy building on a hill overlooking the city's splendid harbor, known as the Golden Horn. Following staff introductions, I visited a laboratory where *MT 88* was undergoing maintenance following recent operations off Mexico. A new *MT 88* was nearing completion (to be called MT 89) for a Soviet Far Eastern geological institute. It was lost six months later in the Pacific, at a depth of 16,000 feet: The vehicle suffered electronics failure and the ballast plugs did not release. With no emergency pingers functioning, no attempt was made to recover it. The geological institute ordered a replacement.



The photo-television towed vehicle Zvuk-4M *is one of a series of four* Zvuk *vehicles.* Zvuk 4M *contains a monophoto camera system, normal television, echosounder, and an accumulator battery.*

Also in the laboratory I saw an earlier-built yet still operational AUV, merely called *Prototype 2*. It had numerous stars on its side, each designating 10 successful underwater missions. Although *Prototype 2* is about the same size and configuration as *MT 88*, it sported many more battle scars from deep ocean operations. It, too, is depth rated for 20,000 feet.

The Soviet MT-88 *is a very deep diving remotely operated vehicle.*

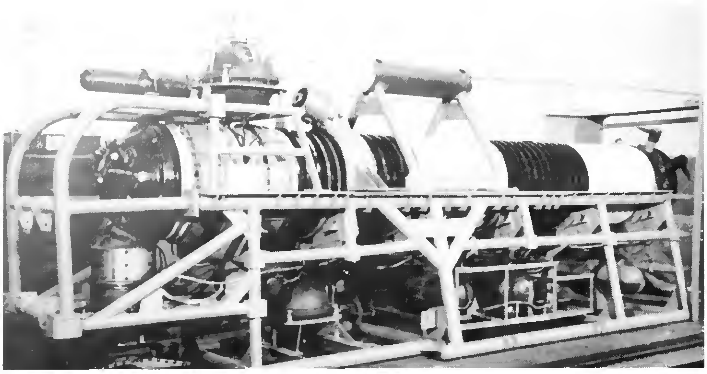
According to *Avtomaticheskie Podvodnye Apparaty* or *Autonomous Underwater Vehicles*, a book coauthored by Ageev, the Soviets have been developing AUV technology since the early 1970s. In conversation Ageev maintains the IMTP is the leading Soviet institute in this field, but the Krylov Shipbuilding Research Institute in Leningrad has done some AUV work as well.

Aside from scientific and deep-water minerals survey missions, Soviet AUVs have also been used for military operations, for example, to locate and survey the Soviet nuclear-powered, *Yankee*-class ballistic missile submarine (SSBN) that sank off Bermuda in October 1986 and the Soviet nuclear-powered *Mike*-class attack submarine (SSN) that sank in the northern Norwegian Sea in April 1989. AUVs were deployed to survey the wreck sites before deep-diving manned submersibles were sent down for more detailed investigations.

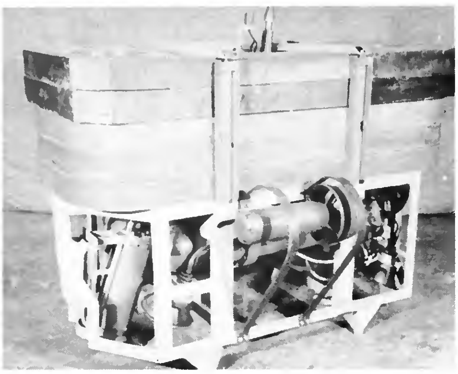
The deep water search for these submarines was conducted in three stages: First, preliminary hydrographic soundings were made and navigational transducers were placed, creating a long-baseline navigation system. Second, a sidescan sonar survey was made using the AUV, and finally, a detailed, fixed-run grid search of the whole area was performed, using the AUV's television and photographic cameras. For the *Yankee*-class operation, the AUV produced over 40,000 frames of bottom detail including 25,000 in the object search zone. Water depth during some 45 AUV dives was over 18,000 feet. It took just three days to find the *Mike*-class submarine and its emergency escape module in 6,500 feet of water. The AUV made 17 dives during this operation and took over 1,000 photos; 100 were targeted on specific areas of the submarine's hull. Ageev showed me several of these black-and-white prints and later gave me two, in addition to a videotape of *MT 88* operations in the Pacific during a deep-ocean manganese-nodule survey. Little wonder he asked his deputy to escort me from Vladivostok to Khabarovsk to ensure I would not be arrested for espionage at the airport!

The Soviets have the most operational experience with AUVs. They freeze a design, put it in the water, and learn how to make the next one better based on pragmatic experience. We certainly have AUV technology in the US, but we tend to design, engineer, and refine until we are certain that it will work at sea. Ours are streamlined and polished; theirs are bruised and bulky. But both sides have produced working systems.

Soviet engineers and technicians do not have the resources available to them that their Western counterparts take for granted. To obtain a



connector or wiring cable, for example, an American engineer simply opens a catalog and specifies a part number, while a Soviet engineer usually must design and build the part. Indeed, when a Soviet underwater specialist visited a Canadian ROV manufacturing company during the Intervention/ROV '90 trade show in Vancouver, BC, he was amazed at the availability of parts and subsystem components accessible from many outside sources.



The two-bodied ROV Uran 1 *was built in 1987. Module 1 (top) is a depressor fitted with several instruments. Module 2 (bottom) contains a television camera and a manipulator.*

One example of the ungainly Soviet systems is the ROV *Uran-1* (*Uran* for Uranus). It looks like it was fabricated with a sledgehammer. Five overlapping and ill-fitting buoyancy slabs are strapped together in a steel frame; two heavy iron bars protect each horizontal thruster. The television camera is stuffed into a large pressure housing and the underwater lights look like they came from a KGB interrogation room. Contrast this design with the Soviet Union's latest manned submersibles, *Mir 1* and *Mir 2* (*Mir* means "peace;" see *Oceanus*, Winter 1989). These superbly manufactured, nickel-steel subs reflect the latest in underwater technology. Each can take three people to 20,000 feet. American scientists and underwater specialists who have dived in them use superlatives to describe the subs. Built to Soviet specifications, the *Mirs* were designed and manufactured in Finland. According to a Soviet paper presented at Black Sea '90, a conference held in Varna, Bulgaria, the USSR has built over 20 ROV systems during the past 20 years. These include towed vehicles, such as the *Zvuk* series, standard tethered ROVs, and tethered "two-bodied" ROVs that can operate as a towed system or as a propelled vehicle.

The *Uran-1*, a two-bodied ROV, was designed and built in 1987 by Krylov Shipbuilding Research Institute. The first body or module serves as a depressor (a device to dampen ship motions created by a towed underwater vehicle) and is fitted with sidescan sonar, a magnetometer, and releasable acoustic transponders. The second body or vehicle (described above) employs a black-and-white television camera and a simple manipulator. *Uran-1* is towed at 1.5 to 2 knots at depths to 20,000 feet. When exploring a specific area in detail or inspecting and perhaps recovering an object, the first vehicle hovers while the second vehicle maneuvers (with its own thrusters) via a 300-foot neutrally buoyant cable attached to the first module. The depressor module is over 16 feet long, 5 feet wide, and 6 feet high, and weighs nearly 2.5 tons. The second module weighs just under 1 ton and is 6 feet long, 5 feet wide, and 4.5 feet high. The main power and data-transmitting load-bearing cable is 26,240 feet long. The main cable transport drum alone weighs 22 tons. The *Uran-1* cost six million rubles to develop and build.

But, according to another paper presented at Black Sea '90, all is not well with *Uran-1*. During Pacific Ocean sea trials at depths over 18,000 feet, the main umbilical twisted severely and the problem had not yet been solved. In addition to interfering with platform positioning on the ocean bottom, the twisting creates a hazard during recovery of the ROV, potentially damaging the main umbilical.

When I asked several US Navy underwater engineers and civilian contractors to review photos and specifications of both the *MT 88* and the *Uran-1*, they found the design technology to be 1970s in appearance, and nothing new or clever was apparent. They also noted a heavy-handed construction approach. However, all conceded that the systems appeared robust and probably worked satisfactorily. "We wouldn't design underwater vehicle systems that way," said one navy engineer, "but considering their resources and my observation of other Soviet-made equipment, I'm not surprised by the way they look." Another simply remarked, "Crude, but credible."

The USSR has built over 20 ROV systems during the past 20 years.

Yet, despite low marks in finesse, the technology works, is reliable, and produces results. But what incentives exist for Soviet engineers to build more refined systems? Their working conditions, while adequate, are certainly behind Western standards. Their living conditions are appalling. Primarily, I saw tiny, ill-furnished apartments in dreary, depressing buildings; pre-World War II kitchen appliances; brackish tap water that corrodes porcelain and rots teeth; people constantly searching for something to buy. The longest line I observed were people waiting not for meat or bread, but to buy gold on a rare day when its sale was authorized. In Vladivostok, boxy Soviet-made Fiats and filthy buses bounce over bumpy, potholed streets. Prefabricated concrete apartment buildings look as though they would crumble in a heap if given a vigorous shake. Upon seeing a newly constructed apartment building set out on a hill by itself with virtually no road leading to it, I asked my hosts if there was a central planning bureau in the city that made the decision to erect this particular structure in that awkward location. "Oh yes, there is a central planning bureau," one replied, "but it's in Leningrad." Shrugs and weary smiles shows they are only too aware of the absurdity of it all.

Coming in from a day-long fishing trip in the Sea of Japan, I saw the modern white fleet of well-equipped research ships in Vladivostok harbor. While in Varna attending the Black Sea '90 conference, I toured the Soviet R/V *Gelendzhik*, a newly completed oceanographic research vessel equipped with two towed sonar and survey vehicle systems capable of operations to 20,000 feet. One, a two-bodied vehicle system known as *Abyssal*, is a multipurpose mineral exploration system fitted with sidescan sonar, an acoustic profiler, a slowscan survey television camera, and mono and stereo photographic cameras. Upon seeing this impressive array of deep-ocean data collection systems plus rooms crammed with Hungarian-made computers and data processing equipment, a US Navy civilian commented that it was "overkill." He was convinced that the ship also had a military mission. Yet, I have often had the impression that Soviet ships conducting endless hydrographic surveys are sometimes used for calling in Western ports to load up with radios, cassette players, and other consumer goods more than for collecting data. The system just works that way.

The busy Vladivostok Harbor is the port of call for many modern research vessels.

The World's Largest Submarine Force

The USSR is a vast country that has difficulty in feeding and giving comfort to its people. It is also the country that has built the world's largest submarine force, with over 350 units spread over four fleet areas—and ever more rolling off the production lines each year like so many links of sausage. But it has been a case of quantity more than quality. Over the years there have been reports of radiation sickness (one Indian scientist has reportedly died from a radiation hazard on a nuclear training submarine that the Indian Navy is leasing from the Soviets), fires (one early class of submarines was referred to by Soviet crews as *zazhigalki*—"incendiary bombs"—based on their tendency to blow up at sea), and accidents attributed to poor quality-control in Soviet shipyards. There have even been operational complaints about the latest 26,500-ton class of *Typhoon* ballistic missile submarines.

Recent Technological Improvements

Nonetheless, Soviet engineers have made important strides in sound reduction, largely due to the illegal transfer of advanced propeller milling machinery and the Walker-Whitworth spy ring. Quieting of Soviet submarines, which have been described as "underwater freight trains" by British and American sonar specialists, is one improvement that worries the US Navy considerably (see *Oceanus*, Winter 1990). The IMTP is also developing a new integrated navigation system for AUVs, ROVs, and manned submersibles. Scheduled for completion in 1992, the inertial and long-baseline acoustic-navigation system boasts microprocessor controls.

Soviet shipyards continue to build submarine hulls entirely from titanium and to experiment with advanced technology such as drag-reduction techniques and air-independent (non-nuclear) propulsion. The Soviet Navy is anxious to recover the *Mike*-class SSN from the bottom of the Norwegian Sea: Its maximum operational depth is said to be 3,300 feet, yet it lies in 6,500 feet of water with its titanium inner hull apparently intact. Salvage operations by a Dutch consortium begin next year.

A US Navy team had an opportunity to board a *Victor* III-class SSN two years ago and was impressed with what they saw. Admiral William J. Crowe, Jr., then Chairman of the US Joint Chiefs of Staff and himself a submarine officer, commented "It was cramped—a lot of equipment put into a small space—but it was modern equipment. I was looking at a very fine weapon system, as well as an impressive man-of-war."

Let's hope the improved flow of nonsensitive information from Soviet marine and underwater sources continues.

Soviet underwater technology cannot be assessed as "good" or "bad." Commercial offshore contractors did not exactly leap from their seats when offered the opportunity to form a joint venture using Ageev's technology. Such a reaction was due partly to the market (AUVs have performed no commercial underwater operations), and partly due to skepticism because the vehicles are Soviet made. However, customers requiring underwater survey services, such as oil companies, don't care if the vehicle comes from Mars, as long as it produces results at a reasonable cost. For his part, Ageev remains optimistic that his AUV technology will find a hard-currency market and a willing joint-venture partner, pointing out that the Soviet government has initiated strong tax advantages to encourage such cooperative efforts.

IMTP plans to display its AUV technology from April 15 to 18 at the UNDERseaWORLD '91 exhibition and conference in San Diego, California. It will be the first time any Soviet organization has displayed its wares at an underwater technology show in North America. The AUV systems will be marketed under the name "Sea Lion."

Let's hope there will be no Soviet policy shift that steers *glasnost* from its present course, and that the improved flow of nonsensitive information from Soviet marine and underwater sources continues. This type of exchange benefits everyone: It is useful to know how other organizations approach ocean technology problems and enables us to conduct joint research, share data and conclusions, and, if Ageev prevails with his joint-venture proposal, make a little money at the same time.

Deam Given was a US Navy submariner and has worked on subsea technology programs with the Department of Defense and civilian aerospace and defense firms. For the past ten years, he has been Editor and Publisher of the trade magazine SubNotes that has been recently renamed WAVES.

Advanced Marine Technology for the Soviet Arctic

The Arctic Ocean has always been a challenging environment for ocean engineers. During the past four decades, Soviet and Finnish designers and engineers have been adapting a wide range of advanced marine technologies for Soviet Arctic transportation. Two polar icebreakers, Taymyr *and* Vaygach, *are striking examples of this state-of-the-art ship technology and ocean engineering. These nuclear, shallow-draft ships were added to the Murmansk Shipping Company polar fleet in 1989 and 1990. Both employ a unique combination of modern technologies to overcome the problems of sustained icebreaking operations in shallow Siberian rivers (primarily the Yenisey and Ob rivers, which are ice-covered for nine months each year) and along the Northern Sea Route.*

Press releases from the Finnish shipbuilder Wartsila (now Masa Yards) and Soviet technical journals (such as Morskoy flot, *a journal of the USSR Merchant Marine Ministry) reveal many details about these 150-meter icebreakers. The outboard ship profile and significant design features are illustrated. A key advantage is an 8-meter draft; the average 11-meter drafts of other large Soviet nuclear and diesel-electric icebreakers prohibit them from operating on the Siberian rivers.* Taymyr *and* Vaygach *can operate with depths of only 0.8 meter under the keel. Their underwater hulls have been extensively strengthened for such operations. As for icebreaking capability, tests indicate that both ships can continuously break 1.8 meters of level ice at a 2-knot speed. Thus, the new ships are ideally suited for icebreaking and escort duties in estuaries and shallow river mouths along the Siberian coast.*

Designing and building Taymyr *and* Vaygach *involved a complex collaboration between the USSR and Finland with the project lasting nearly a decade. Ice-model testing of hull forms began in Finland in 1981, and a formal construction contract was signed in 1984. Once the ships were completed in Wartsila's Helsinki Shipyard, each sailed (using an automatic boiler plant) to Leningrad's Baltic Shipyard for installation of nuclear reactors. Development of these two ships was a challenging and unprecedented merging of marine technologies, combining Soviet nuclear technology and Finnish shipbuilding expertise.*

The nuclear power option was chosen because refueling conventionally powered icebreakers in remote regions is difficult. The Kapitan Sorokin *class icebreakers currently operating on the rivers use nearly 100 tons of fuel per day. Fuel must be shipped from Murmansk, thereby reducing the cargo capacity of the Arctic freighters. The propulsion plant of the* Taymyr *class is an intricate blend of Soviet, Finnish, and German technologies. A single pressurized water reactor powers two steam turbines; all three components are Soviet built. The two turbines drive two German-built generators that in turn provide electricity to three Finnish-built alternating-current (AC) propeller motors. These newly designed motors use frequency converters, and are lighter, smaller, and more efficient than traditional direct-current (DC) motors found aboard many of the world's icebreakers. The ships' three fixed-pitch propellers can be replaced while the ship is in the ice, keeping with past Soviet practice. The power plant is controlled by a Finnish microprocessor-based system that monitors more than a thousand parameters and can remotely adjust valves and pumps throughout the plant. The normal plant output is 32,500 kilowatts (44,000 shaft horsepower or shp), and the maximum that can be generated is 35,500 kilowatts (48,000 shp). Only the nuclear* Arktika *class (at 75,000 shp) and the non-nuclear US* Polar *class (at 60,000 shp on gas tur bines) icebreakers have more power available for operations. A novel addition—three diesel generators for a standby diesel-electric propulsion plant—can provide a reserve source of* *electricity and power the ship if the nuclear steam-generating plant is shut down!*

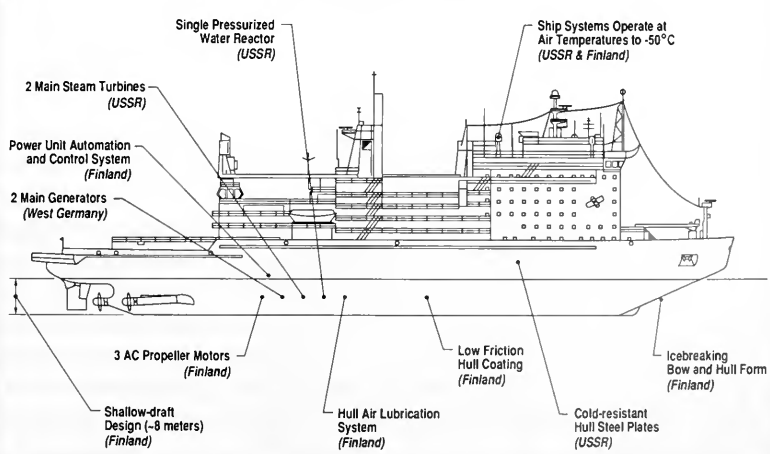
Much of the advanced technology aboard Taymyr *and* Vaygach *is specifically designed for the unique and often hostile operating conditions of the Soviet Arctic. Ship systems are designed to operate in temperatures to –50°C. An air lubrication system, developed by Finland's Wartsila engineers, pumps large volumes of low-pressure air and water around the hull to reduce the friction of both ice and snow. The underwater hull is also coated with a low-friction paint, to further enhance icebreaking performance. Special high-strength steels are used in the hull due to the extremely cold operating environment. The lines of the shallow-draft hull are designed to minimize the interaction of ice with the rudders and propellers. Two advanced all-weather helicopters, a large flight deck and aviation complex, extensive satellite communications systems, and several modern marine radars are provided to assist in the safe navigation of these ships in the Arctic Ocean.*

Both ships are designed to accommodate 138 people. A July 20, 1990, Pravda *article noted that Vaygach was sailing with a crew of 116, all quartered in one- and two-berth cabins. Finnish designers placed all living spaces above the main deck and included a library, cinema, gymnasium, swimming pool, sauna, and other recreational spaces. One special feature also found aboard other Soviet ships plying the Northern Sea Route is an artificially lighted, hydroponic "greenhouse" for growing fresh vegetables.*

It is interesting to note that the initial operation of the Taymyr *has not escaped criticism in the Soviet press. In the wake of the disaster at Chernobyl, many residents are concerned for their own well-being and environmental safety. There are many unanswered questions regarding the environmental effects these large, shallow-draft ships might have on the rivers—impacts on fish stocks and the sediment regime, effects of using large volumes of water, and concerns about the width of the icebreaker tracks. The assessment and discussion of these ships' travels in the Soviet North will be interesting to follow.*

—Lawson Brigham
Captain, US Coast Guard

Nuclear, Shallow-draft Polar Icebreaker
TAYMYR Class



Toward a Global Ocean Observing System

We know that the ocean plays a key role in global change, and to understand that role we must have global data collected over long time periods.

D. James Baker

We all admire nightly television weather forecasts with their striking graphics and predictions of global, regional, and local weather. The scope and immediacy of the weather patterns sweeping across the screen reveal the power of the international World Weather Watch and its associated data delivery system. The predictions are not always accurate, but this is a problem outside the capabilities of those who report the weather. In any case, the global data collected from this system are used for much more than just weather prediction, and the nightly forecasts are a good example of the advanced nature of the observing system in place for the atmosphere.

Why don't we have such a system for the ocean? Mainly because we live in the atmosphere and are subject to its changes. But today we know that the ocean plays a key role in global change, and to understand that role we must have global data collected over long time periods. From its very beginning oceanography has been global in scope. Still, our knowledge of the ocean and its coupling to atmosphere and land is rudimentary. Moreover, we do not yet have the necessary operational technology for and we have not yet brought the necessary resources to bear on developing and supporting long-term ocean measurements.

What would a global ocean observing system do? It would collect global, long-term systematic measurements of physical, chemical, and biological data to provide ocean nowcasts. The data would then be used to update and provide initial conditions for coupled global climate models. In a paper dated August 1990, Henry Stommel noted that by the year 2000 we could hope to maintain an updated "state of the dynamics of the ocean model" that could be used for predicting eddy events, El Niño, deep and intermediate water-formation anomalies, and pollutant spreading, as well as providing climate-model boundary conditions.

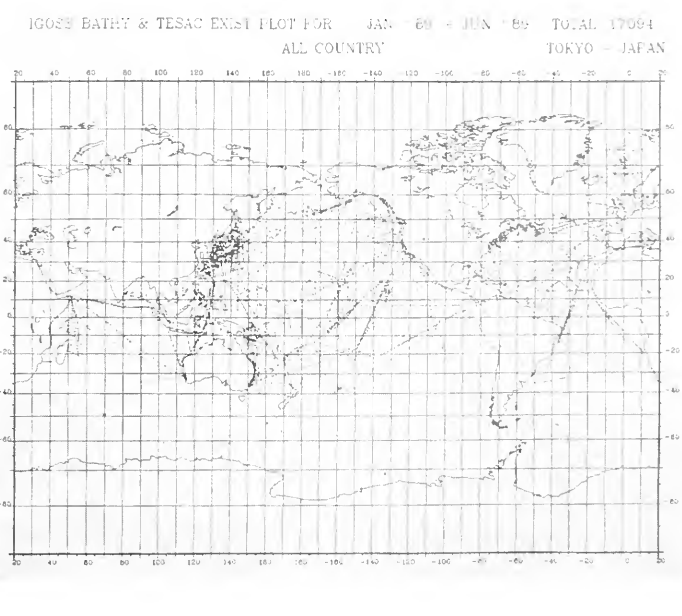
These days, while there is much talk about the greenhouse effect and long-term global warming, a global ocean observing system would provide measures at the full range of seasonal, interannual, decadal, and longer time scales. The variability is due to both natural fluctuations and anthropogenic effects from greenhouse gases. But because the Earth system dynamics are nonlinear, that is, effects are not simply additive, increasing greenhouse gases may have subtle effects beyond slow temperature change, for example, increasing the near-term variability of the system. The overriding objective is not only to detect the greenhouse effect, but also to understand how the coupled ocean-atmosphere system works in general. The specific greenhouse warming issue, only one of many important questions, can then be studied using the understanding of the coupled system and how it responds when perturbed.

Since the fluctuations in the ocean and the Earth system occur at a wide variety of time and space scales, designing a global observing system is not simple. Research to understand how the ocean works and new technology to provide cost-effective long-term measurements are both required for progress. Until we know how the Earth system works and how to measure relevant parameters accurately, there are important aspects of climate that we will not be able to document.

For observing the climate system, we will need to look at all the relevant parts: the atmosphere, the ocean, and the land. Probably the most viable part of existing systems is that for the atmosphere: the World Weather Watch (WWW). It has been in place since 1963 and provides an observation (satellite and in situ measurements) and data distribution system for global monitoring of the atmosphere. We are still far from having an equivalent of the World Weather Watch for the oceans, and, in fact, it is not clear that an exact analogy is appropriate. A global ocean observing system will contribute to and be driven by much more than any analog to weather, both in terms of science requirements and in funding. This additional complexity is one of the reasons that we do not yet have a global ocean observing system. (We do not have such a system for the land either, but that is a subject for a different article.)

There are some operational programs (that is, programs with an ongoing commitment to providing data for users on a regular basis) already in place for the ocean. The operational programs sponsored by NOAA and the US Navy, for example, provide global data sets for prediction of surface temperatures and ocean eddies. The Soviet "Sections" program, with massive deployment of ships for hydrographic measurements, has a similar goal: application of large-scale measurements to provide data for operational predictions. A coarse network of global scale operational measurements (sea level, expendable bathythermographs or XBTs, drifting buoys, etc.) is coordinated through the Intergovernmental Oceanographic Commission and the World Meteorological Organization (IOC/WMO) to provide real-time data to users.

Current operational programs do not produce an adequate global



These XBT and upper layer measurements of temperature, salinity, and currents were reported by the volunteer observing ship network of the IOC/WMO Integrated Global Ocean Station System for the first six months of 1989. Note the gaps in the southern hemisphere. (Courtesy of WMO.)

data base for monitoring and understanding the ocean, partly due to a lack of resources and partly because we do not yet know enough about the physics, chemistry, or biology of the ocean to deploy our resources sufficiently. To make progress, we need to define the major elements of a global observing system and implement them as soon as possible. This requires adequate funding of existing programs designed to describe and understand how the system works. We need to develop new technology for cost-effective observing. And we need to enhance the existing patchwork of measurements to a true global system by providing adequate funding and national commitments for long-term measurements.

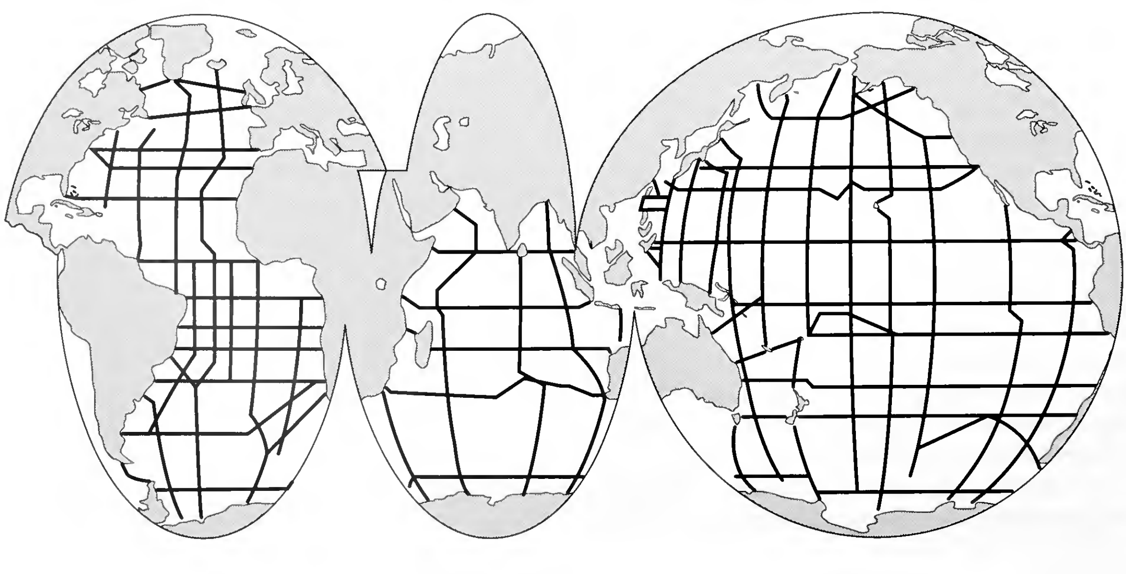
In the long term we look to a system that will provide real-time observations coupled to an information system that provides easy access and wide distribution. The data can then be used for real-time operations and predictive modeling.

Developing the Scientific Basis

A number of research programs and operational activities are working toward providing the information that we will need to decide where and what to measure. The large-scale research programs, Tropical Ocean and Global Atmosphere Programme (TOGA), World Ocean Circulation Experiment (WOCE), and Joint Global Ocean Flux Study (JGOFS), are aimed at providing much of the understanding and development of new measurement technology required on a global scale.

TOGA, WOCE, and JGOFS results will lead to identification of parameters for long-term monitoring. The first priority toward a global observing system must be to ensure full support for these research programs. Without the scientific basis they can provide, it makes little sense to try to build a global observing system. The research programs are aimed at understanding different parts of the system. TOGA will tell us where in the upper layers of the tropics we should concentrate resources for improving interannual climate predictions. WOCE will give us the first quasi-synoptic satellite/in situ description of the global ocean.

The World Ocean Circulation Experiment plans hydrographic, nutrient, and chemical tracer measurements along these track lines during 1990 to 1997. (Courtesy of WOCE International Programme Office.)



WOCE results will, for example, tell us the importance of indices such as basin-scale heat flux and how it can be monitored through western boundary currents and broad gyre flow. Chemical tracers will be used to monitor broad-scale flow, and the significance of eddies in transport of all kinds will be studied. JGOFS is carrying out a series of regional studies to identify the significant parameters of chemical and biological systems; global ocean color measurements by satellite will be an important part of JGOFS in the mid-1990s.

This is an artist's conception of the US/French TOPEX/Poseidon satellite designed for precision (to an accuracy of several centimeters) measurements of ocean surface topography during the period 1992 to 1995, and possibly longer. (Courtesy of NASA.)

Based on the scientific information we have today and the results anticipated from these research programs, it seems that a global ocean observing system would focus on measurements of surface fluxes, hydrography, heat and chemical fluxes, and biological processes such as primary production. The measurement categories would include upper-ocean monitoring, systematic deep-ocean measurements, and satellite observations of several types. The major coordinating elements would include numerical operational models, data and information management, and international coordination and oversight. Above all, the system must be capable of evolving as understanding improves and technical developments show new ways to accomplish the goals.

New Technology for Observations

Global studies of the ocean require techniques that adapt well to global measurements, but, in fact, most of our instruments are designed for local-property measurements. Some techniques, however, such as sea level measurements or accurate tracer chemistry, do provide local measurements that represent both local and global processes. The collective information from such data help to document global change in the ocean.

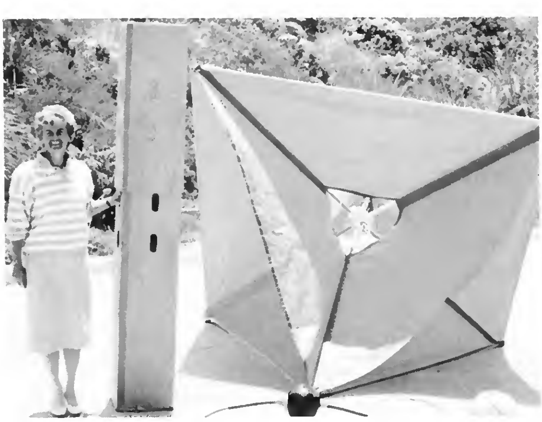
A global ocean observing system must consist of these local measurements but will also need devices that can provide either global synoptic (comprehensive at a point in time) pictures, or long-term data, or a combination of the two. New techniques are required. In 1982, Walter Munk and Carl Wunsch, writing about observing the ocean in the 1990s, pointed out the importance of acoustic tomography and satellite observations of sea surface topography and wind stress. Today, a number of missions are planned for providing satellite altimetry, scatterometry, and ocean color; an acoustic tomography program has been carried out in the Greenland Sea; and a pilot global acoustic-travel-time study was recently carried out with a sound source located at Heard Island in the Indian Ocean (see Box on page 6). Other new techniques include floats, autonomous vehicles, long-term moorings, and expendable temperature and salinity devices. Applying these new techniques is essential for a global observing system.

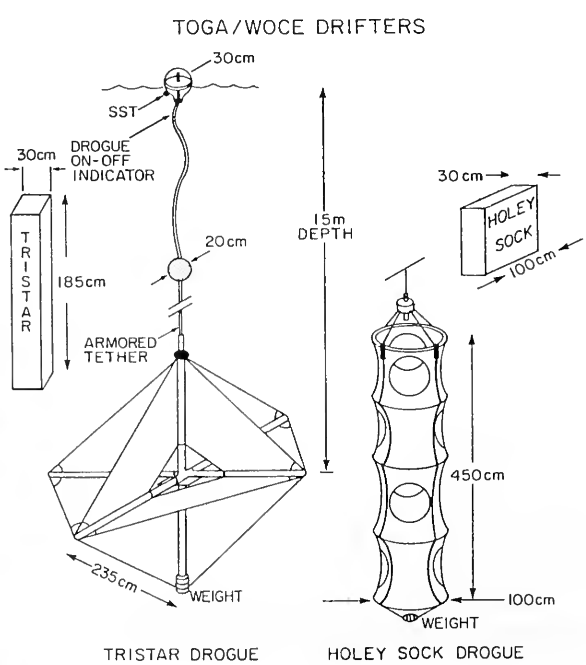
Floats and their next stage, autonomous vehicles, can carry instruments, make measurements, report data back through acoustics or satellites, and operate for a long time; they are a key element of any long-term ocean observing system. In 1989, Henry Stommel wrote evocatively about "The Slocum Mission" (see *Oceanus*, Winter 1989) in which he envisaged a time when unmanned vehicles in great numbers would roam the ocean making hydrographic and other measurements, reporting into a Mission Control on Nonamesset Island in Woods Hole. In 1990, the forerunner of such a system, Scripps' Autonomous LAgrangian Circulation Explorer (ALACE), began providing such measurements in the South Atlantic for WOCE (see below). British scientists are working on the Autosub Project, an unmanned-ship concept. Two missions are currently planned; the first uses DOLPHIN (Deep Ocean Long Path Hydrographic Instrument) and will also contribute to WOCE (see Robotic Undersea Technology, page 32).

As John Woods* has argued, it seems clear that a global ocean observing system, in order to be cost-effective, must rely on robotic observing systems, and the role of ships must be greatly diminished in any global long-term data collection system. Slow-moving and expensive in terms of cost per unit of data collected, today's oceanographic ships are best suited for research projects rather than as part of a global observing system. However, ships do play a key role as volunteer observing platforms and for periodic high-accuracy surveys. For example, periodic surveys of hydrographic, nutrient, chemical tracer, and biological properties of the ocean probably will continue to require precise shipboard instrumentation and teams of experts.

The main point is that we need to move our data collection from a predominantly research mode to a more operational mode. We need technology for collecting and transmitting data for long periods of time with minimal human interaction that also maintains adequate quality-control procedures. This requires operational rather than research

These surface drifters (right) were developed for WOCE and TOGA. (Courtesy of Peter Niiler.) Each Tristar Drogue (below) is compactly packaged in a cardboard box to be assembled on board the ship before being released into the ocean.





agencies for long-term commitment and development of new in situ and satellite techniques. Internationally, there are few agencies with operational oceanographic responsibilities; this is part of the problem we face.

Currently, our data is not easily transmitted among user groups that range from the research community to operational users. In general, any new schemes must provide information in real time; otherwise the operational use in models is diminished. New technology requires about a decade to progress from initial design to operational system, so technology development must proceed in parallel with research programs.

We need to move our data collection from a predominantly research mode to a more operational mode.

In TOGA a start has been made with sea level measurements with real-time satellite links, XBTs on voluntary observing ships, surface drifters, and the TOGA Tropical Atmosphere and Ocean (TAO) array that provides meteorological and upper-ocean real-time data. These techniques could well be the forerunners of a long-term observing scheme for tropical ocean predictive models.

In WOCE there has been a concerted effort to support development and testing of new technology for long-term global measurements. Satellite measurements together with in situ observations are key to meeting WOCE objectives: It is the only way we know to achieve global synoptic measurements of sea level, surface currents, and wind stress. Autonomous vehicles are another important element. As mentioned above, the WOCE program supported development of the ALACEs now working successfully in the South Atlantic Ocean. The ALACE floats are the first step toward a set of operational unpowered and powered floats that we hope will be able to replace ships for much data collection. The WOCE program also supports the development of improved meteorological packages for ships of opportunity and buoys. The new packages provide increased accuracy and reliability, and are another step toward a system that will provide global data for predictive models.

Sediment traps for measurements of chemical and biological fluxes and productivity have been developed for JGOFS. This program also aims at better understanding and quantitative interpretation of global satellite ocean color measurements. These developments will be important for the chemical and biological aspects of a global observing system.

Planning: The Next Steps

There is world-wide public interest in global change and increasing governmental support for global change research programs. The Second World Climate Conference, held in Geneva, Switzerland, in November 1990, formally called for the creation of a global climate observing system, including a global ocean observing system.

The first steps have been taken towards an operational predictive system, using data and models, with the TOGA predictions. We need to continue these with a series of operational oceanography pilot studies. The first of these could be considered to be the TOGA TAO array and modeling. Other candidates include the Heard Island global acoustic monitoring project, follow-ons to the Kuroshio and Gulf Stream monitoring of the 1980s, and use of voluntary observing ships to collect physical and biogeochemical data to study large-scale, long-term physical/chemical interactions.

The key element in a global observing system is the commitment of national agencies: This is the success of the World Weather Watch, and must be a part of the global ocean observing system. National agencies such as NOAA and its National Ocean Service in the US play a key role. The responsibilities for such measurements, including the coordination of satellite measurements, are focused on such agencies; otherwise, we will not have a set of viable national programs on which to build an international system.

The key element in a global observing system is the commitment of national agencies.

Some immediate steps could be taken now, particularly in regard to the existing operational programs. We need to evaluate the existing mechanisms of oversight and control to find a better mechanism for defining the operational goals in response to the scientific requirements of national and international research and operational programs. Existing mechanisms do not provide for adequate client or customer input and evaluation of the process. IOC should undertake an evaluation of the existing mechanisms of oversight and control with a view to improving the lines of communication between these programs and their customers.

An Ocean Observing System Development Panel (OOSDP) has been established to "formulate the design of a long-term systematic observing system in order to monitor, describe, and understand the physical and biogeochemical properties that determine ocean circulation and the seasonal to decadal climatic changes in the ocean, and to provide the observations needed for climate predictions." The Panel, chaired by Worth Nowlin (Texas A & M University), is fully engaged in that process now, and a final report is planned for 1994. Interim reports will also be issued. The Panel is cosponsored by the Committee on Climatic Changes and the Ocean, and the Joint Scientific Committee for the World Climate Research Program.

The OOSDP is being supported in that activity by the Committee on Ocean Processes and Climate (OPC) of the Intergovernmental Oceanographic Commission. The Ad Hoc Group of Experts on a Global Ocean Observing System of the OPC, chaired by Geoffrey Holland, has prepared a statement entitled "Toward a Global Ocean Observing System: A Strategy" that identifies a number of important immediate action items. Together, the OOSDP and the Ad Hoc Group will develop the necessary long-term action items.

It is clear, however, that committees can only go so far in designing and implementing a system. In order to ensure that adequate attention is given to this process, a planning office should be established, preferably at the IOC, where the ocean focus is paramount. However, close links should be maintained with WMO operations.

Support from a Broad Base

Today's patchwork observing system is funded with a series of different rationales: marine weather (e.g., sea surface temperature), local harbor and beach conditions (e.g., sea level and beach erosion), and biological and chemical effects (e.g., local pollution). In the end, we must find a way to synthesize the funding for an operational observing system based on these user needs. The funding support in oceanography for a global system will be different from that of atmospheric sciences because it will be more broadly based.

In my view, the funding for a global ocean observing system based on climate needs cannot be fundamentally decoupled from the system based on local needs—beaches, harbor tides, pollution, and fisheries. This means that the general views of coastal oceanography, fisheries, and the health of the ocean must be folded into the funding and rationale. Climate-related measurements might be piggy-backed onto fisheries, coastal, and pollution measurement systems, since that is where the local interest will be for many countries, developed and developing.

Climate-related measurements might be piggy-backed onto fisheries, coastal, and pollution measurement systems.

Since the scope of a global ocean observing system is international, the expertise and resources of international organizations such as the Intergovernmental Oceanographic Commission, the World Meteorological Organization, the United Nations Environment Programme, the Food and Agriculture Organization, and the International Maritime Organization will be essential to the success of the system.

The Opportunity

With a global ocean observing system we could do some very important things: update global weather and climate models on a periodic basis, monitor the health of the oceans, provide information for routing of ships at sea, and carry out scientific research. We should look to no less than this. Henry Stommel put it best when he said: "What a magnificent opportunity it can be for an enterprising nation to present a world ocean observing system to an environmentally distracted world!"

Acknowledgments: Thanks to R. Allyn Clarke, Worth Nowlin, Henry Stommel, John Woods, and Carl Wunsch for discussions on this subject.

D. James Baker is President of Joint Oceanographic Institutions Incorporated in Washington, DC, Chairman of the Committee on Ocean Processes and Climate of the Intergovernmental Oceanographic Commission, Co-chairman of the Scientific Steering Group of the World Ocean Circulation Experiment, and a member of the Joint Scientific Committee of the World Climate Research Program.

*John Woods is Director, Marine and Atmospheric Sciences Directorate, Natural Environment Research Council, UK.

Modernizing NOAA's Ocean Services

NOS undertakes scientific programs relating to the land and water environment of the US.

Virginia K. Tippie and John H. Cawley

The National Ocean Service (NOS), a component of the National Oceanic and Atmospheric Administration (NOAA), is the federal government's oldest scientific agency. Established in 1807, during Thomas Jefferson's presidency, to survey and chart the young republic's Atlantic coastal waters, NOS undertakes scientific programs relating to the land and water environment of the US, and is a major contributor of oceanographic data worldwide. NOS collects, analyzes, predicts, and disseminates environmental data to describe the earth system, to monitor and predict processes such as tides, currents, and water levels, and to assess the impact of human activity on the coastal environment. NOS is also a participant in the establishment of a Global Ocean Observing System (see Toward a Global Ocean Observing System, page 76).

To address the challenges of the 90s, NOS has embarked on an effort to modernize its ocean services. New technologies are now being applied to better describe the Earth's surface, chart the nation's waters, understand the coastal and ocean environments, and assess the human impact.

Describing the Earth's Surface

Continuing in the tradition of the original US Coast and Geodetic Survey, NOS provides accurate geodetic and bathymetric surveys. However, the labor-intensive surveying equipment of the past, such as lead lines, sextants, and Bilby Towers (tall instrument towers designed to overcome vertical obstructions like hills and trees), have largely been replaced by advanced data processing and instrumentation systems.The NOS Geodesy Program now provides a wide range of geodetic data, and establishes and maintains the national horizontal, vertical, and gravity networks that provide a basic geographic framework for mapping, charting, science, engineering, and defense operations.

During the past ten years, Geodesy has taken full advantage of new and advanced technologies including satellite altimetry, the Defense Department's NAVSTAR Global Positioning System (GPS), Very Long Baseline Interferometry (VLBI), and absolute gravity. This program is now international in scope, cooperating with many nations and international organizations.

Geodesy also uses these technologies to increase productivity and improve data quality to meet growing demands for high-precision data from surveyors, government agencies, and the military. For example, the National Geodetic Survey (NGS) recently computed a high-resolution geoid height model for the lower 48 United States. The geoid is a geodetic parameter that describes a sea-level surface extended continuously over the Earth's surface. The figure below is a colored contour map of the geoidal separation over the US. Since precise geoid separations are increasingly important to high-precision Earth science measurements, this model allows use of GPS to determine vertical heights above sea level to an accuracy of a few centimeters, with substantial savings over conventional survey methods.

Geodetic efforts are also closely tied to the NOAA Global Sea Level Program. Tide gauges at selected sites around the world measure the relative motion between the sea surface and the land. Since the land itself rises and subsides, the problem of relative motion must be solved for sea level data to be properly interpreted and used. Applying GPS, VLBI, and absolute gravity measurements creates an absolute geodetic reference framework linked to the tide gauge network. As a result, changes in sea level can be distinguished from land motion for an absolute measure of sea level in a global reference frame.

A computer-derived geoid surface is overlaid with an outline of the US. Color shading shows the difference between ellipsoidal heights obtained from GPS satellite measurements and orthometric heights above sea-level datum.

Charting the Nation's Waters

Nautical charts in both analog and digital formats are essential to safe navigation and prevention of oil spills and other coastal pollution. Maintenance of some 980 paper charts requires continual data revision for about 2,500 chart panels and publication of about 500 revised charts annually. The demand for digital products is increasing rapidly, and im-

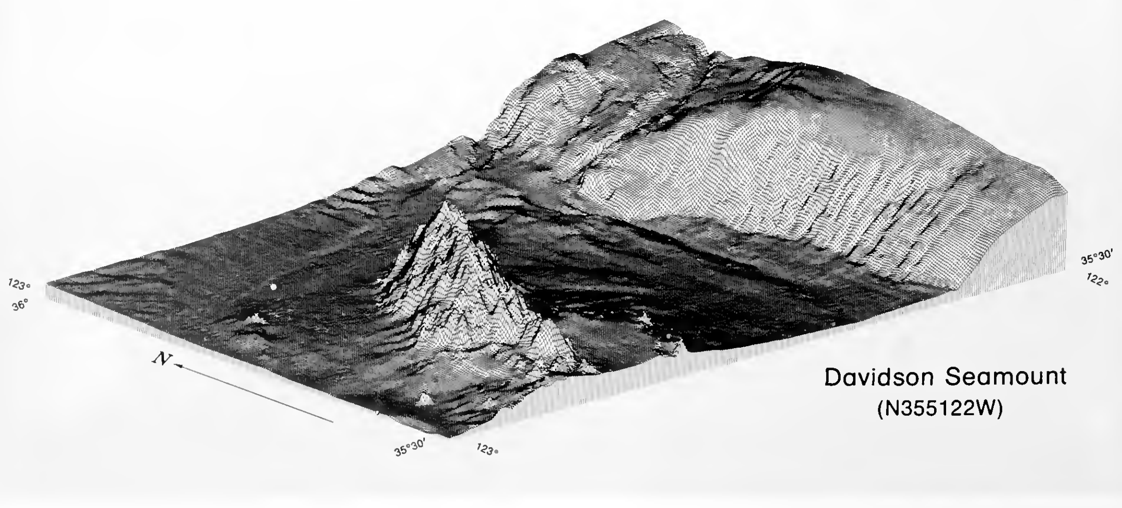
proved digital products are on the way. NOS initiated development of the Automated Nautical Charting System (ANCS II) in 1988, taking advantage of new technologies to provide digitally generated nautical charts and products. This system transfers most of the meticulous and judgmental tasks now performed by cartographers to 40 computer work stations where data evaluation and chart compilation can be performed automatically. The ANCS II system is being implemented in stages and is scheduled to be operational by mid-1992.

For many years, NOS has been a leader in automating hydrographic surveys, chart compilation, and data management. A combination of new multibeam and sidescan sonars, computer, and navigation technologies depicts the seafloor with a degree of resolution not possible just a few years ago. These technologies assure 100 percent bottom coverage and allow charting of rock pinnacles and other underwater obstructions that can elude the more conventional time-consuming single-beam sounding techniques.

Recently we have begun to use a revolutionary echo sounding system that covers wide swaths of the seafloor on both sides of a survey ship. By using GPS satellite navigation systems and overlapping swaths, images and bathymetric maps can now be compiled less expensively for much larger areas of the seafloor. NOAA and the US Geological Survey (USGS) have embarked on a long-term joint program to map the entire US Exclusive Economic Zone (EEZ) using this new technology. The products include 1:100,000-scale bathymetric maps and accompanying three-dimensional views of the seascape that provide greater detail in the small features than found on previous bathymetric maps (as shown below).

NOS is also responsible for locating and identifying submerged obstructions in US harbors and coastal areas. Traditionally, we have used wire-drag surveys: Each end of a long cable is attached to a survey ship, the two ships separate, then both move ahead slowly, dragging the loop of cable over the seafloor. When obstructions are found, a diver is sent to mark the location. Although positive identification of each obstruction is made, the method is cumbersome, slow, and costly.

Looking northeast at Davidson Seamount and the adjacent California continental slope, the vertical exaggeration is 6:1.



To improve the efficiency of these operations, NOS is developing a ship-towed, high-speed, high-resolution sidescan sonar, designed to detect a 20-centimeter-diameter target 100 meters away at towing speeds up to 10 knots. Prototype tests indicate that increasing operational survey speed by a factor of three to four and obstruction mapping production rates by a factor of two or more over the wire-drag method may be possible.

NOS uses aeronautical surveys to define coastlines, water-land boundaries, and near-shore underwater features, and to assess damage to coastal areas from severe storms. Present methods use overlapping stereo-camera photographs of the survey area. Accurate positioning of the aircraft is essential to each mission, and precise ground-control points must be surveyed and tied to the National Geodetic Reference System. To replace these time-consuming and expensive procedures, NOS is developing a positioning system known as Kinematic GPS to provide precise horizontal and vertical control of photogrammetric mapping. This new concept reduces photogrammetric project costs as much as 40 percent, and can provide positions for aerial cameras that are precise to about 5 centimeters in each coordinate. Proven operational in the fall of 1990, Kinematic GPS will become a part of NOS mapping and charting procedures when the constellation of GPS satellites is complete.

Oceanography has come a long way since the days of the Challenger Expedition, when data took months or years to analyze and disseminate.

Understanding the Coastal and Global Oceans

NOAA/NOS enjoys long-term partnerships with the Navy and other federal agencies, universities, and the private sector in collecting marine meteorological and oceanographic data from the world's oceans. Oceanography has come a long way since the days of the Challenger Expedition, when data took months or years to analyze and disseminate. Advances in science and technology in the past few years allow oceanographers to collect and transmit information in real time by satellite and conventional methods to central locations for processing and analysis.

Tides and Water Level. Since the mid-1800s, NOS and its predecessor organizations have been in the complex business of describing and predicting tides to improve navigation safety, determining datums and shore-line boundaries, and maintaining the International Great Lakes Datum (IGLD). The present tide measurement system, located at some 240 stations, uses a stainless-steel wire-and-float apparatus attached to an analog-to-digital recorder (ADR). The ADR system filters out all high-frequency energy from sea surface waves, while recording very long waves, weather perturbations, and tidal periods. However, the ADR system is prone to errors that can only be controlled with a great deal of care and time.

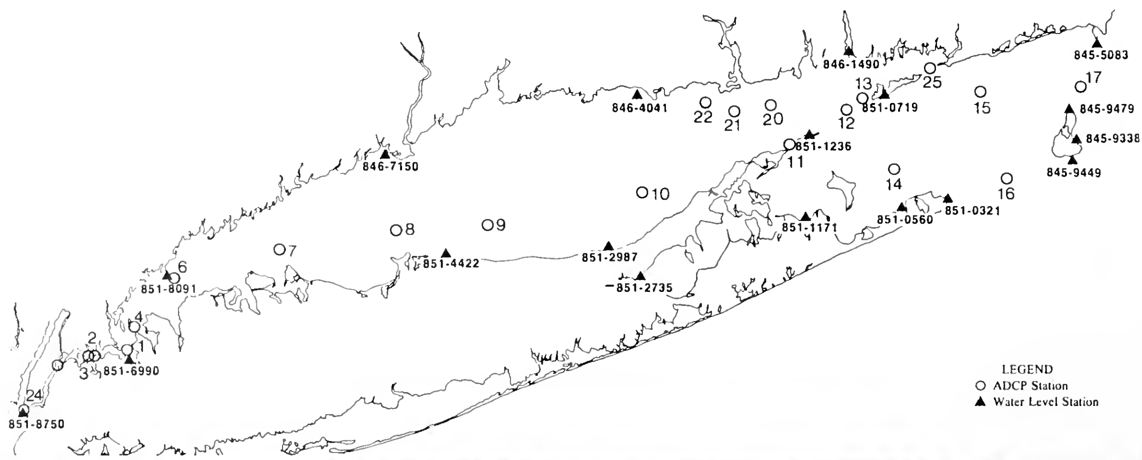
An improved and more reliable tide measurement system recently developed by NOS is called the Next Generation Water Level Measurement System (NGWLMS). This system has state-of-the-art capabilities: A nonmechanical acoustical sensor replaces the old wire and float, and microprocessor-based data collection and recording subsystems further improve data precision and quality. The water level measurement range is over 12 meters and the system resolution is ±1 millimeter. Data is generally transmitted via a Geostationary Operational Environmental Satellite (GOES) to NOS offices in Rockville, Maryland, and the telephone is used as an alternate means of data transmission. When the NGWLMS network is integrated with the VLBI network, we will be able to determine absolute values of sea level.

Coastal Circulation. Several of NOAA's programs are aimed at predicting coastal tides, currents, and coastal circulation, especially in relatively enclosed bays and harbors. Two tasks illustrate our coastal ocean modeling efforts: the Tampa Bay and Long Island Sound Oceanography Projects. The Tampa Bay Oceanography Project began in mid-1990 to illustrate the value of integrating oceanographic and meteorological information to improve navigation safety. A Physical Oceanographic Real-Time System (PORTS) allows a harbor pilot using a cellular telephone and/or a personal computer to receive real-time current, wind, and water level information that reflect actual conditions at multiple locations in Tampa Bay. Early reports on the system's performance are promising, and prototype installations may be considered for other US harbors.

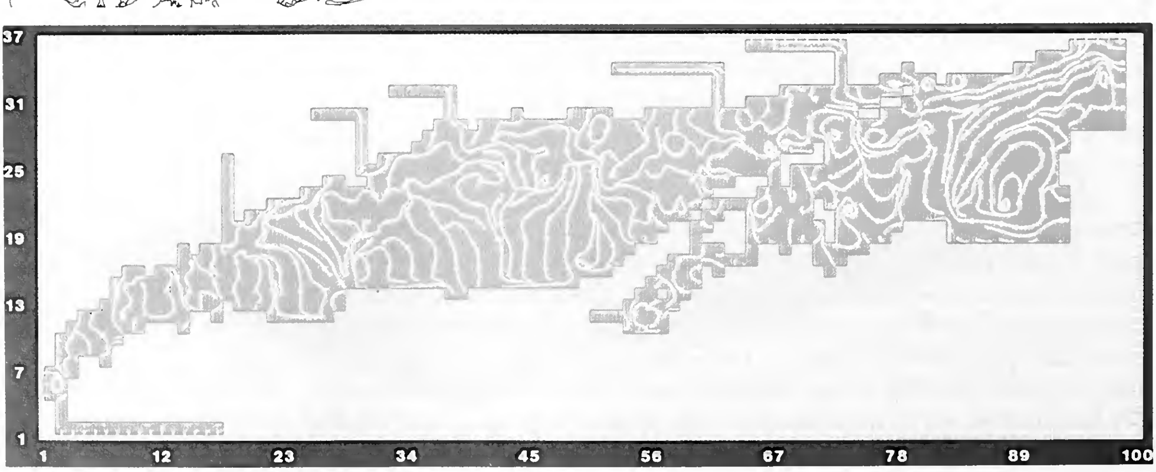
Through multiyear circulation current measurements and a numerical modeling and analysis effort, the NOS Long Island Sound Oceanography Project provides the Environmental Protection Agency (EPA) with tools for managing water quality problems in Long Island Sound. Our coastal ocean circulation program couples tidal current residual fields and temperature and salinity fields from a three-dimensional circulation model to a water-quality model developed by an EPA contractor. A com-

(A) The outline of Long Island Sound and locations of water level and acoustic Doppler current profile monitoring stations are shown schematically. (B) This computer-generated graph depicts Long Island Sound streamlines in the top layer (near surface waters) on September 1, 1988, as developed from the current velocity vectors.

A

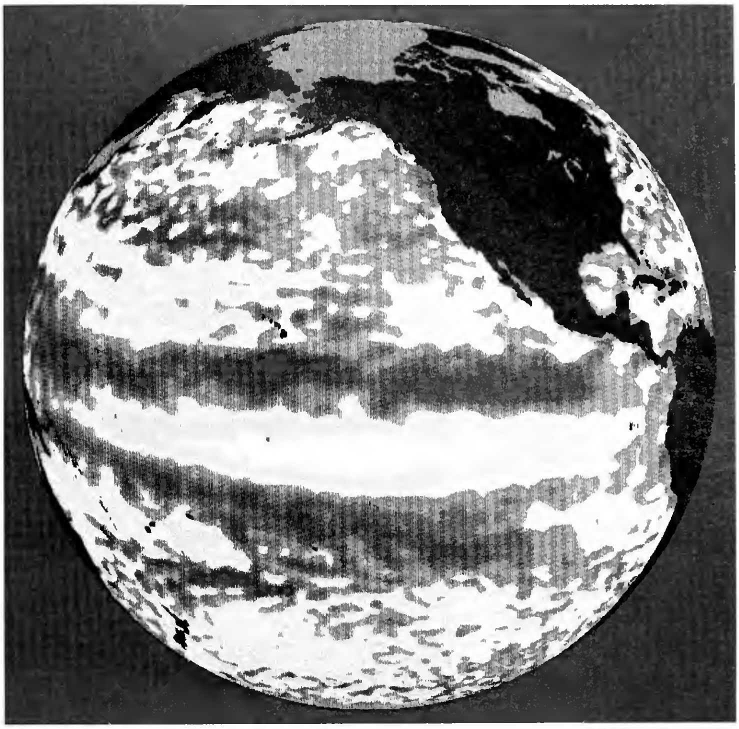


B



prehensive conservation management plan will also be developed by EPA and NOS to determine the role of circulation and transport processes on dissolved oxygen and nutrient distribution in the Sound, and to outline actions to aid EPA in the Sound cleanup.

Sea Surface Characteristics. NOAA's Global Sea Level Project is an integrated monitoring program involving satellite and in situ measurements of water level. In the satellite-based Geosat program just completed, sea level changes as small as 5 centimeters were detected, and the new sensors to be launched on satellites in the 1990s should be even more sensitive and precise, further improving our understanding of ocean dynamics. The figure above shows a Geosat altimeter view of sea levels in the Pacific Ocean on January 1, 1991, as compared with an annual mean sea level. Onset of the 1986-87 El Niño is indicated by the strong positive sea level along the equator. Smaller scale anomalies off the coast of Japan and the eastern US are created by the Kuroshio and Gulf Stream currents respectively.



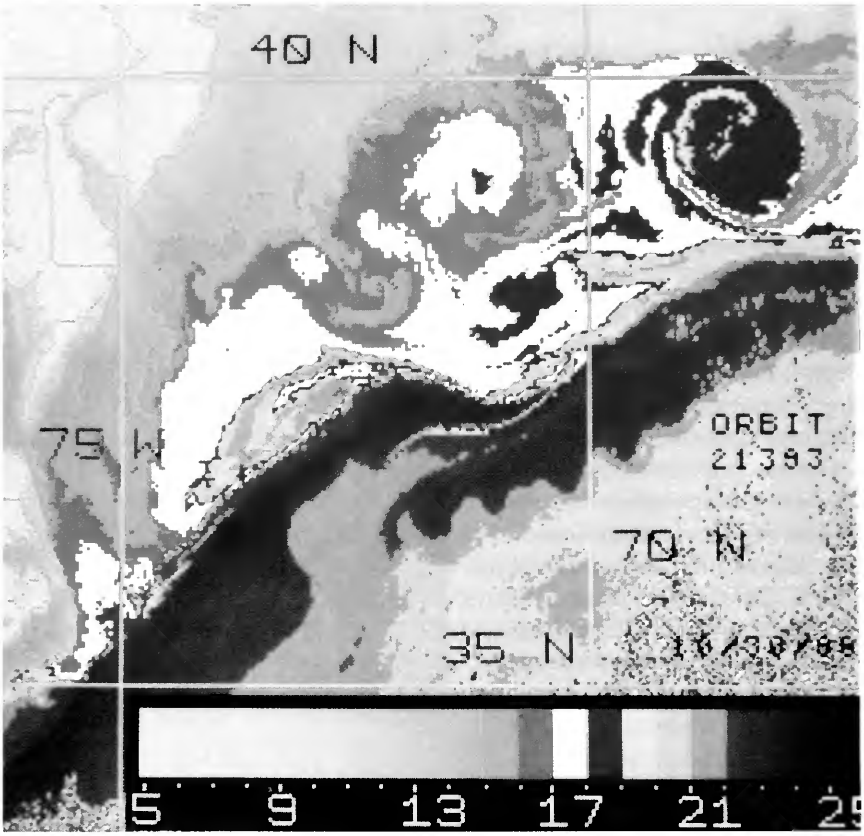
This view of sea levels in the Pacific Ocean compares the Geosat altimeter's view (on January 1, 1991) with the annual mean sea level. Blue indicates levels that are below the annual mean; yellow and red indicate levels above the annual mean. Levels varied by about 15 centimeters above and below mean sea level.

Satellite imagery is also remarkably useful for monitoring major ocean features, including ice formations in the Arctic and Antarctic oceans. NOS distributes daily ocean analyses of satellite images for US Atlantic coastal areas and the Gulf of Mexico. On October 30, 1990, the color enlargement on page 90 of a thermal infrared image was downloaded from the NOAA polar orbiting satellite.

The vast majority of data used for ice analysis at the Navy/NOAA Joint Ice Center (JIC) in Suitland, Maryland, is from satellite-image products. The largest source of satellite data is the Advanced Very High Resolution Radiometer (AVHRR) aboard the NOAA TIROS-N satellite. JIC is presently the only facility in the western world that provides global sea-ice analyses and forecasts including determinations of ice edges, ice concentrations, and ice leads, and estimations of the age of the ice.

Global Ocean Circulation. Advances in global ocean observing systems, data management, and modeling during the 1990s will help predict ocean conditions during the 21st century. The Tropical Ocean Global Atmosphere (TOGA) program in the Tropical Pacific demonstrates the feasibility of identifying patterns with far-reaching consequences in interannual variability related to the El Niño cycle. Several NOAA programs will be components of any in situ global ocean observing system, including the Voluntary Observing Ship Program (V-O-S), drifting buoys, and moored buoy arrays. Of some 1,600 volunteer ships collecting

This enlargement of a thermal infrared image was downloaded from the NOAA polar orbiting satellite on October 30, 1990. North Carolina's Outer Banks, Maryland's Eastern Shore, New Jersey, and Delaware are outlined along the left side of the image; the warm Gulf Stream appears as a dark band, east of the Outer Banks. Three warm eddies circulating clockwise north of the Gulf Stream appear as dark (warm) circles surrounded by lighter gray (cool) water.



meteorological data in the V-O-S program worldwide, approximately 120 operating in the Atlantic and Pacific oceans are equipped with the NOS automated Shipboard Environmental Data Acquisition System (SEAS) system that provides shipboard marine atmospheric and oceanographic data in real time. SEAS can include barometric pressure, winds, waves/swell, ice, surface air temperature, ocean temperature profiles, and ocean currents. The data are entered into a computer and then are automatically telemetered through GOES satellites to the National Meteorological Center (NMC), Camp Springs, Maryland, and the Navy's Fleet Numerical Oceanography Center, in Monterey, California, for use in atmospheric and ocean forecast models. SEAS data are widely distributed from NMC to US National Weather Service forecasters and to others around the world. Using SEAS helps to eliminate many of the errors and time delays associated with conventional radio transmission.

As part of a program to examine the Southern Ocean, NOS deploys small buoys that drift with the currents in the oceans of the Southern Hemisphere while measuring sea level pressure, sea surface temperature, and surface air temperature in data-sparse regions important to weather forecasts and climate research. The buoys are deployed from ships of opportunity and occasionally from aircraft in areas devoid of shipping. The buoys last about one year, and annual "reseeding" is required to keep the array at full strength. Data is telemetered from each buoy through the ARGOS satellite system to stations ashore and to NOAA's National Data Buoy Office in Bay St. Louis, Mississippi, and is then transferred to users worldwide. NOS presently manages approximately 40 drifting buoys, and another 40 buoys are maintained by representatives of other countries.

Assessing and Mitigating the Human Impact

The NOS Office of Oceanography and Marine Assessment is responsible for assessing and mitigating the impact of human activities on the marine environment. Its programs include the pollution-monitoring National Status and Trends (NS&T) Program, Oil Spill Response, Natural Resource Damage Assessment and Restoration, and Environmental Information for Decision Making. Advances in computer technology, data acquisition, and management enable NOS to respond to increasing public demand for timely, accurate information for managing the coastal and estuarine environment.

A NOAA spill-response team was at work on the scene within 24 hours of the **Exxon Valdez** *grounding.*

Pollution Monitoring. NOS routinely monitors US coastal and estuarine environmental quality, and measures the concentrations of a large number of contaminants in selected biota and sediments. New efforts are directed toward identifying better bioindicators of toxic contamination for ecological monitoring programs.

Oil Spill Response. NOS is responsible for responding to oil spills and assessing damage to natural resources. Experience with the March 1989 *Exxon Valdez* spill in Alaskan coastal waters has brought improved decision making capabilities to the oil-spill cleanup process. A NOAA spill-response team was at work on the scene within 24 hours of the *Exxon Valdez* grounding. Throughout the spring and summer of 1989 and the following winter, these environmental assessment specialists advised the US Coast Guard (USCG) on the physical processes affecting the movement and spread of the spill, conducted assessments of the environmental resources at risk, planned and analyzed cleanup operations, and monitored the impact of the spill on the overall environment. From these activities we learned much about improving the response to oil spills and how the spills affect the environment.

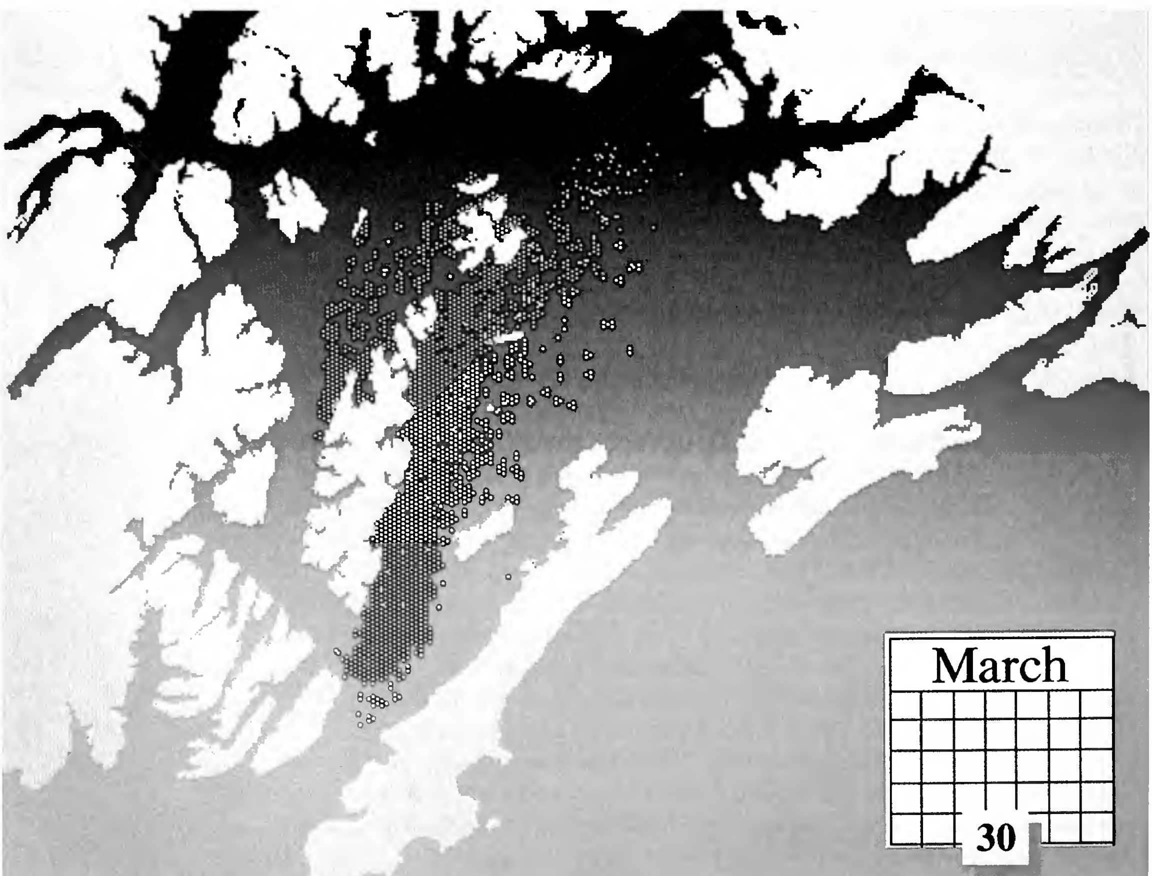
For example, during this period the Computer-Aided Management of Emergency Operations (CAMEO) system, developed by NOAA to assist emergency teams in dealing with hazardous chemical spills, was adapted to manage the vast amounts of oil-spill related information coming into Valdez, Alaska. CAMEO processed information and data from overflights, ground-based shoreline assessment teams, and USCG oversight teams to predict oil spill trajectories, and help the federal coordinator manage and report the status of the oil spill response program.

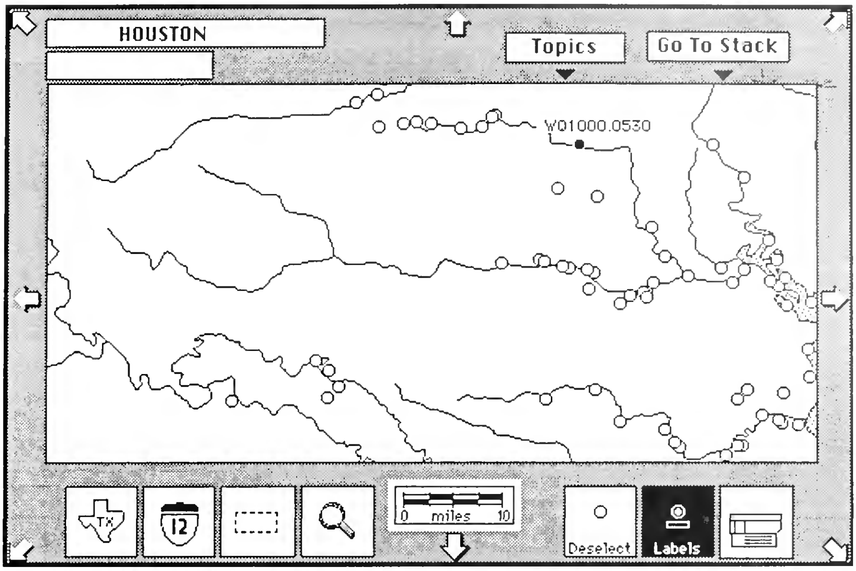
However, newer and more comprehensive decision support systems are needed to merge data on the state of a spill, evaluate the risk to environmental resources, and estimate weather and sea conditions. A significant effort is also needed to codify the collective knowledge of scientists throughout the world on spill-response issues. For example, there is no agreement on the effectiveness and ecological impact of using dispersants on oil spills. Thus, it is essential that research on chemical countermeasures be undertaken if dispersants are to become a viable alternative to mechanical containment and recovery of oil.

Natural Resource Damage Assessment and Restoration. Under the Superfund Act of 1980 and the Oil Pollution Act of 1990, the Administrator of NOAA acts on behalf of the Secretary of Commerce as a federal trustee for natural resources in coastal areas. In 1984, NOAA's Hazardous Materials Response Program initiated evaluation of nearly 500 coastal hazardous waste sites and concluded that about half of these could affect NOAA's trust resources. Since then, we have worked closely with EPA at over 250 sites to ensure that ecological issues related to marine and estuarine resources are an integral component of Superfund cleanups. Important technical problems remain: It is difficult to define the "original condition" of ecosystems long exposed to societal stress, and there are persistent problems in understanding the natural variability, ecosystem recovery processes, and how to conduct economic analysis of restoration alternatives. Clearly, much work needs to be done to control costs and improve the long-term restoration process.

Environmental Information For Decision Making. Advancements in information science and technology provide encouraging new opportunities to improve the application and delivery of information. We are applying these rapidly evolving analysis, synthesis, and dissemination technologies to resource and environmental data through a prototype, desktop Coastal Ocean Management Planning and Assessment System (COMPAS). Previously, Geographic Information System (GIS) software

The Exxon Valdez *oil spill trajectories in Prince William Sound, Alaska, are predicted by the CAMEO computer program for the March 24 to April 20, 1989 period.*





This GIS-generated map depicts locations of water quality monitoring stations and major rivers in the Houston, Texas, area. From this screen a computer user can link directly to information for any monitoring station, including the data itself.

was only available on large mainframes, but now it can be placed on the enhanced desktop computers of scientists and resource managers. The figure above illustrates the kinds of GIS information available to resource managers through COMPAS.

Outlook for the Future

Applying creative, new techniques to oceanography, meeting requirements for quality scientific coastal and ocean data in digital form, and integrating data and information generated from a wide variety of sources are the immediate challenges of the 90s. In this time of limited resources we must fully explore the application of new technologies from other disciplines. For example, our ability to measure global sea level on an absolute scale is only possible now because we applied a new technology, VLBI, used by astonomers to observe quasars. The NOAA Marine Modernization Initiative, begun in 1990 and known as The Marine Resources and Oceanic Services 2000 Program, includes modernization of the NOAA fleet, satellite oceanographic capabilities, fisheries assessments, and ocean services. Through this initiative, NOAA will be forging a strong partnership between government and the academic and private sectors to modernize the marine capability of the US in order to meet the challenges of the 21st century.

Acknowledgements: The authors would like to acknowledge the many scientists and engineers who have worked hard to improve the technical capabilities of the National Ocean Service. A special thanks goes to Austin Yeager, Dana Kester, and Bud Ehler and to all who contributed to this article.

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John H. Cawley is the Director of the NOS Engineering Staff. Prior to his present assignment, he was Chief, Physical Oceanography Division.

Artificial Reefs: Emerging Science and Technology

Japan is the world leader in innovative reef design, engineering, and deployment.

Iver W. Duedall and Michael A. Champ

The history of man-made or artificial reefs probably predates recorded time, when early man recognized that both natural material and artificial structures (submerged or floating) attracted fish. Richard B. Stone, author of the 1985 Federal National Artificial Reef Plan, reported the first published account pertaining to artificial reefs in the US: In 1860 it was reported that inlets in South Carolina containing naturally fallen trees became devoid of fish when the surrounding land was cleared of trees and brush for agricultural purposes. The tree and leaf litter falling into the inlets apparently created and maintained "artificial" reefs, and removing the natural debris caused the reefs, and consequently the fish population, to dwindle away. This idea was supported when it was soon discovered that encrusting organisms and fish returned once timbers, brush, and stones were intentionally placed in the water.

Government Interest in Artificial Reefs

Most US coastal states have very active marine artificial reef programs, collectively spending millions of dollars to develop reefs for use by sport and commercial fishermen and recreational divers. Florida alone has over 200 artificial reefs, more than any other state. Through their own environmental and fishery agencies, states administer research and reef demonstration projects. California, Florida, North Carolina, and Washington have very active programs. Funding for state development of artificial reefs should benefit from the 1984 Wallop-Breaux amendments to the Dingell-Johnson Act of 1950, a federal law.

Reefs are constructed in some states by county governments and private or public fishing clubs. Private companies have also experimented with different materials and shapes, hoping to develop (and sell) a new reef. The Artificial Reef Development Center, an arm of the Sport Fishing Institute in Washington, DC,* is a public-interest clearinghouse of information for those interested in learning more about artificial reefs. Many universities here and abroad actively support scientific research in artificial reefs, and national and international symposia and workshops periodically convene to discuss and evaluate scientific findings. The 4th International Conference on Artificial Habitats for Fisheries was held in Miami, Florida, in 1987 and attracted more than 350 people from 26 countries. The 5th International Conference convenes in November 1991 in Long Beach, California. To complement the increasing level of interest, the number of published papers relating to artificial reefs has increased from one or two articles in 1955 to 30 or 40 per year preceding major artificial reef symposia or meetings.

At the federal level, interest in artificial reefs is steadily increasing as well. The government provides direction through the National Artificial Reef Plan developed by the National Marine Fisheries Service of the Department of Commerce. It is funded through the Dingell-Johnson Act and its amendments. The plan provides: 1) guidance on technical design planning, siting, construction, and reef management; 2) help to federal and state agencies involved in permitting reefs; and 3) information on site-specific state, regional, and local reef plans. At the international level, Japan, the world leader in innovative reef design, engineering, and deployment, has spent billions of dollars developing and testing new designs. Other centers of activity include the northern Mediterranean Basin, Southeast Asia, Taiwan, Australia, and areas in the Caribbean.

Reef-Building Materials

The table on the following page shows the variety of materials used for artificial reefs. It includes rubble, discarded wastes, junked automobiles, aircraft, boxcars, quarry rock, and marine-grade concrete cast in large, specially designed reef units. In the US, costs for materials and transportation are often limiting factors; thus, materials of opportunity are primarily used. In US waters, artificial reefs are likely to be submerged Liberty

Juvenile Weke are attracted to this pyramid-shaped artificial reef. It is made from 38 scrap tires, and resides in about 40 feet of water near the Kewalo Basin, Hawaii.

Photo by Fred Casciano/Ocean Innovators

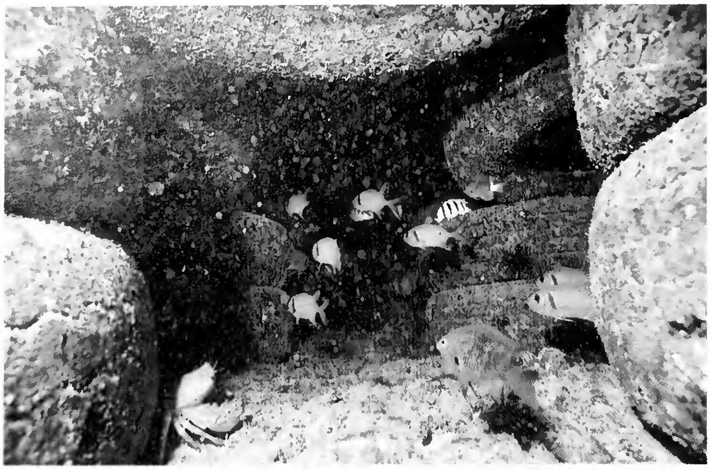


Photo by Fred Casciano/Ocean Innovators

This closeup of the artificial reef also shown on page 95 depicts samples of the variety of organisms (in addition to fish) that may choose to colonize reef sites.

Ships, automobiles, trolley cars, or concrete rubble. Robin Lewis of the California Department of Fish and Game notes that quarry rock is the prime artificial reef material for west- coast organisms. On a per-unit density basis, properly designed quarry rock reefs typically support more fish than natural reefs, according to Lewis.

In the US, nearly everything (including the kitchen sink!) has been tested or used to build artificial reefs. Using materials from the city dump (engines, old refrigerators, tires, etc.) for reef construction is currently discouraged, however, as the practice conjures up images of dumping activity rather than reef building. Besides, these types of discarded materials often contain pollutants that can be released to the water, potentially harming biota, divers, and fishermen.

Ideally, artificial reefs should be made of economical materials that are placed on the seabed or prefabricated on land in a design that will serve the specific purpose of attracting fish. Considering the size and surface area of the reef, void-space geometry and dimensions (habitat geometry), longevity of materials, ease of sampling (to verify fish catch), and costs, and merging those considerations with oceanographic and biological characteristics (water depth, currents, thermocline depth, primary and benthic production) will lead to the successful design and function of a reef.

Artificial reefs are designed not only to support general or specific fisheries, leading to the creation of new fishing grounds or fisheries, but also to increase the production and diversity of colonizing organisms. Primary productivity can also be enhanced through the use of high-relief

Materials Used Worldwide for Artificial Reef Construction

- Aircraft
- Automobiles, buses, and trolleys
- Bamboo and bamboo combined with tires
- Baled garbage
- Bridges
- Concrete blocks
- Construction rubble (concrete debris such as culverts, pile cutoffs)
- Engines, including internal-combustion engines
- Fiberglass and reinforced plastic
- Freight trains (boxcars) and wheels
- Metal (mainly steel, iron)
- Quarry rock (granite, sandstone, limestone)
- Offshore oil and gas platforms
- Polypropylene rope and cable
- Polyvinyl chloride piping
- Refrigerators, stoves, water heaters, and washing machines
- Ships and boats
- Stabilized ash (coal ash, oil ash, incineration ash) in a concrete matrix
- Sinks and toilets
- Tires
- Weapons of war
- Wood, trees, and brush

Some Functions of Artificial Reefs

Provide increased fish abundances for:
- Sport and commercial fishing
- Recreational diving and photography
- Mitigating damaged or lost habitats
- Rejuvenating over-exploited fisheries
- Mariculture

Provide increased port, marina, and anchorage protection from:
- Sedimentation and siltation
- Erosion
- Ice
- Strong waves and storms

Photo by C. H. Turner

In Emerald Bay, near Catalina Island, three old cars rest in 60 feet of water to create an artificial reef. The kelp bass appear interested in the idea. (Courtesy of Robin Lewis)

reef structures that induce bottom turbulence, making nutrient-rich water more available at the surface. Reefs can rebuild fishery stocks, or mitigate some of the impacts or losses related to coastal development projects. In California, work on artificial reefs has been supported by the Southern California Edison Company with the direction of the California Department of Fish and Game. The power company constructed Pendleton Reef of quarry rock to explore the potential use of artificial reefs to mitigate the effects of power plants on coastal areas. Also in California, the Long Beach Harbor Authority is interested in using reefs as a mitigating measure for harbor development projects.

Biological Enhancement

Fish abundances at and near an artificial reef are always greater than abundances in nearby sandy areas. Quantitative information on the number of fish taken from a reef or a reef unit varies greatly, and depends on the reef system or unit, geographical area, light penetration and depth of water, and sampling methodology. Generally, larger and more complex structures attract more and greater numbers of different fishes, and overall species diversity is greater compared to original site conditions. University of West Florida scientists compared eight artificial reefs in Florida and found that a steel barge reef (encompassing 1,300 square meters) had the highest species diversity (15 families) while a 1,200 square-meter concrete-culvert-and-rubble reef area had the lowest diversity (seven species in four families) when compared to a control area. The largest standing crop (biomass) of fishes was observed at an oil platform that covered an area of 324 square meters. In an analysis of four types of reefs (concrete cube, "Japanese type" aggregated tires, surplus pipes, dispersed tires) in Hawaii, the concrete cube-type reef had the largest number of species, the greatest mean weight per reef, and the highest standing crop. In American Samoa, the fish catch-per-unit-of-effort (pounds per vessel hour) was 8.4 to 17.4 for a control area, 40.4 to 49.8 at an artificial reef fish aggregating device, and 52.8 to 90.9 for an

Considerations in Selecting an Artificial Reef Site

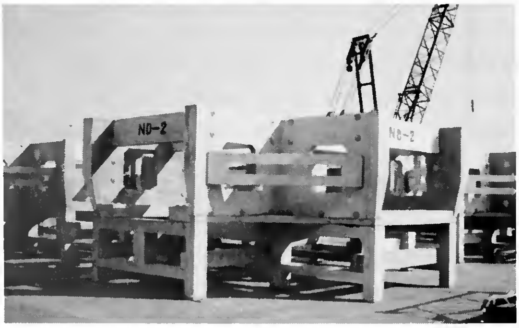
- Accessibility to and distance from shore
- Availability of reef-building materials
- Biological characteristics of the site and nearby areas
- Depth of photic zone
- Detriments, such as shipping and boating lanes
- Ease of reef deployment
- Liability, insurance, and permit requirements
- Oceanographic characteristics, currents, and wave conditions
- Projected uses and benefits of the site, both economic and recreational
- Sedimentation rate
- Target species (pelagic and/or bottom fishes)
- Turbidity
- Weather and storms

offshore bank.

Sampling methods used at artificial reefs include fish nets, fish line (hook and line), fish tagging, diver observations, electronic fish counting, videotaping, and sport fishermen reports. It is very difficult to compare fish abundances for different reefs when there is no standardized unit used for reporting. In addition, an accurate comparison of fish production among reef types requires analysis of replicate reefs of various materials, all placed under similar environmental conditions plus a careful, long-term study of fish abundances in adjacent control areas (away from the artificial reefs). This sampling period could require 10 to 15 years to allow for a complete observation of the development of different successional stages, since reefs develop complete food webs. Costs of sampling rapidly become prohibitive; therefore, few replicate reefs have been constructed and analyzed. Hence we have little information on the variability of fish production for a particular type of reef at a particular site.

There is probably no single or precise answer to the question, "Why are fish so attracted to an artificial reef?" Clearly, a reef provides the basic needs of food and protective shelter, as well as unique community structural functions. A reef also possibly provides a spot for resting and can act as some sort of navigational aid for fishes en route. Thus, one would expect more fish at or near an artificial reef than in areas without a reef. Little is known of the effect of a reef on overall community structure, diversity, and species interactions within and outside the reef site. A major research question deals with whether reefs lead to increased overall fish production or merely provide for redistribution (via attraction) of the existing population. Virtually all scientific studies have documented large increases in fish abundance at reef sites that were otherwise barren. But sampling limitations make it difficult to accurately determine the origin of the fish found at the reef, and the

The four Japanese reef structures below are a small representation of the many styles being manufactured and tested. All four are made of high-volume fly-ash concrete, which has a low specific gravity that helps prevent the reefs from sinking into the often-soft seafloor. (Courtesy of Tatsuo Suzuki and Hazama Corporation.)



area's overall capacity to support fish production. It has been suggested that attraction and production are really two extremes on a continuum.

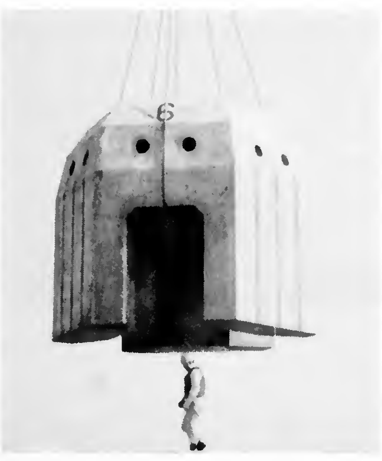
Japanese Artificial Reefs: A Case Study in Advanced Reefs

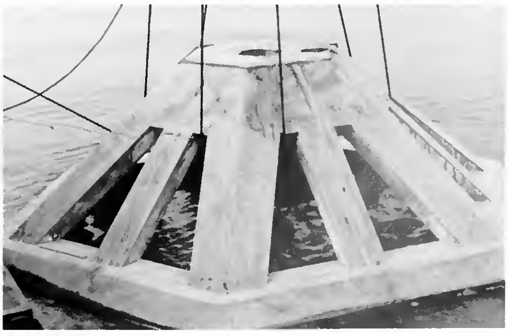
An island country, Japan has for centuries depended heavily on the marine environment for food and commerce. Food from the sea instead of from the land is a priority because of the large population and the high cost of land. Japan exhibits high productivity in virtually all elements of modern technology; therefore, it should come as no great surprise that Japan leads the world in artificial reef design, technology, and utilization. Japan is so advanced in this field that if reef building by Japan's standards were chemistry, the rest of the world would be described as practicing alchemy.

Japan gives the name **Tsuk Iso,** *or constructed shore rock, to artificial reefs—but the* **Tsuk Iso** *is far more than its name implies.*

Japan gives the name *Tsuk Iso*, or constructed shore rock, to artificial reefs—but the *Tsuk Iso* is far more than its name implies. The modern, Japanese artificial reef begins with a basic cube or module (an open cylinder or igloo shape) structure. The structure is placed in the sea either as a single unit or in multiples of the same unit. The cube is selected for ease of both construction and development of design criteria related to engineering performance. Concrete, which is usually reinforced, is the basic construction material; fly ash, which has cementlike properties, is sometimes used in the mix design (thus Japan appropriately makes use of a solid waste for productive purposes; see Box on page 101). Japanese engineers have developed many calculations and formulae to determine maximum stresses for compression, stretching, and shearing of both the materials used and the final cube structure, the stress on the cube(s) when it strikes the bottom, and the stability (potential for shifting or capsizing) of the reef under different wave and current conditions. The engineers are also attempting to predict the long-term longevity of their reefs.

The principal biological advantages (advantages leading to increased biological colonization) of the cube are the large void volumes and the potentially complex reef geometry that can result when the structures are brought together like tinker toys. Shapes, void spaces, and opening diameters are also adjusted in an attempt to attract particular species and juvenile groups, and even to enhance egg production. The Japanese reef, with its surrounding waters (upper layers and midlayers) and adjacent seafloor, is viewed as a single system





in which different fishes prefer different parts of the system.

Some reefs in Japan are designed not necessarily to attract or produce fish (vis-a-vis reef shape) but rather to induce turbulence or upwelling in order to stimulate primary productivity, and thus enhance the entire system.

Japanese artificial reefs are expensive. Only the government has the means to subsidize the millions of dollars per year required to fund reef research, construction, and deployment. The impetus for the monumental effort by Japan stems from the fact that catches by traditional Japanese fisheries have recently been negatively affected by pollution and restrictions on high seas fishing, especially in other Exclusive Economic Zones, imposed by other nations. The latter resulted in the Coastal Fishing Ground Development Act of 1974, a Japanese law that led to development of several thousand artificial reef projects by 1988.

Some reefs in Japan are designed to induce turbulence or upwelling in order to stimulate primary productivity.

While it is too early to determine the overall efficiency of Japanese artificial reefs, available reports indicate that the reefs are attracting large numbers of fish. It is hoped that a comprehensive analysis of Japanese programs and results will allow fisheries ecologists to determine whether reef fish harvests result from a net increase in fish production, redistribution of existing stocks, or some combination of the two. The answer to this question has long-term ecological consequences.

Constraints and Future Considerations

Increased development of artificial reefs in the US is constrained by the continued use of "materials of opportunity" and the absence of a strong justification of need. Because reef materials in the US are not usually designed for the ocean and don't provide a specific or unique marine habitat, structure, or function, their effectiveness is limited at best. On the issue of need, it is primarily the recreational element in US society that uses reefs—the fish are caught as sport, with consumption considered to be secondary. An American individual consumes (on average) 17.5 pounds of fish annually (likely to increase to 40 pounds within this decade), while his or her Japanese counterpart consumes 200 pounds per year. Were fish the main staple in the US, governmental and commercial sectors would likely be more aggressive and innovative in developing, managing, and harvesting marine fish.

There are some optimistic signs in the US owing to increasing interests in reefs within the scientific community. Some researchers are working with their Japanese counterparts, and others are testing new materials, such as ash concrete, utilizing not only coal fly ash but also bottom ash from the combustion of municipal solid waste. Japan is well on its way in the development of large, well-engineered reef systems that are both biologically compatible and structurally durable; many countries could and should learn from the Japanese experience. Likewise, the Japanese should strengthen their efforts to quantify their success with scientific information more interpretable by western scientists.

Future considerations should contend with ecological consequences of large-scale reefs such as those being developed by the Japanese. These "marine ranching" efforts involve altering and enhancing many components of the coastal marine ecosystem. These efforts may prove to be very productive, but their overall effect must be addressed as the concept of marine ranches is developed.

Acknowledgements: We thank Robin D. Lewis (California Department of Fish and Game), Robert Grove (Southern California Edison), William Seaman (Florida Sea Grant College Program), and Walter G. Nelson (Florida Institute of Technology) for their very helpful comments. We thank Tatsuo Suzuki (Japan) for sending us his report and for some of the illustrations used in this report, and Annette Bernard for assisting in manuscript preparation.

Iver W. Duedall is a Professor of Oceanography, Ocean Engineering, and Environmental Science at Florida Institute of Technology, Melbourne, Florida. He is Board Chairman for the Research Center for Waste Utilization, and has 15 years research experience on the utilization of stabilized ash for artificial reef construction.

Michael A. Champ is President of Environmental Systems Development Company. He is also a Senior Scientist at Texas A&M University's Geochemical and Environmental Research Group, and directs the Washington, DC office.

*Artificial Reef Development Center, Sport Fishing Institute, 1010 Massachusetts Avenue, Suite 100, Washington, DC, 20001; (202) 898-0770.

Traditional Japanese fisheries have recently been negatively affected by pollution and restrictions on high seas fishing.

A Reef Material of Opportunity: Ash Concrete

If one coal-fired thermal power plant of 1,000,000 kilowatts was constructed and operated for 30 years, approximately 12,000,000 tons of fly ash would be produced, enough to make 10,000,000 cubic meters of high-fly-ash concrete. If this plant's entire production of fly ash were to be used in the production of high-fly-ash concrete blocks of 100 tons each for construction of submarine mountain ridges (35 meters high, 10 meters wide at the top, and 80 meters wide at the bottom), the artificial reef would fill approximately 30,000,000 cubic meters of ocean space (allowing for a reef block-void ratio of about two-thirds). Consequently, in 30 years an offshore submarine mountain range of approximately 30 kilometers in length could be constructed. If the ridges were arranged in a straight line, an excellent upwelling of high-nutrient bottom waters would simultaneously occur.

Marine Electronic Instrumentation: An Industrial Perspective

Marine electronic instrumentation (MEI) is an important subset of ocean technology. It spans a wide range of products including:

•communication and navigation instruments (such as marine radios, global positioning satellite or GPS receivers, and electronic charts),

•sensors (such as hydrophones, current meters, bathythermographs, and video imaging systems), and

•data management instruments (such as "marinized" computer hardware and software).

Oceanography and environmental monitoring use MEI as indispensable tools. Sometimes they are custom-crafted in research labs to meet special requirements, but more often they are purchased in the marketplace from an exceptionally rich selection of product types and features. Ocean science and monitoring, however, represent only a tiny fraction of the total demand for MEI. Much larger end-use sectors include the military, offshore oil and gas industry, and commercial and recreational shipping and boating.

The ability to understand and effectively exploit the oceans' many resources thus depends crucially upon progress in MEI. Establishment of public policies to promote such progress, and ensure the ongoing vigor of US instrumentation producers, requires a good understanding of the industrial organization and commercial dynamics in this field. With funding from the National Oceanic and Atmospheric Administration and sponsorship of the Massachusetts Centers of Excellence Corporation, researchers at Woods Hole Oceanographic Institution's Marine Policy Center are working to provide that understanding through analyses that examine industrial structure and economic performance in MEI.

Most commercial MEI manufacturers can be categorized into three subgroups:

1) "shops" that tend to be small in size, often established initially as "garage" operations and usually serving mainly the oceanographic-environmental monitoring or the offshore-energy markets;

2) military systems contractors, frequently divisions of large corporations that focus narrowly on military or defense-related systems; and

3) marine electronics firms, often subdivisions of large consumer electronics producers, that provide navigation and communications products to commercial and recreational markets.

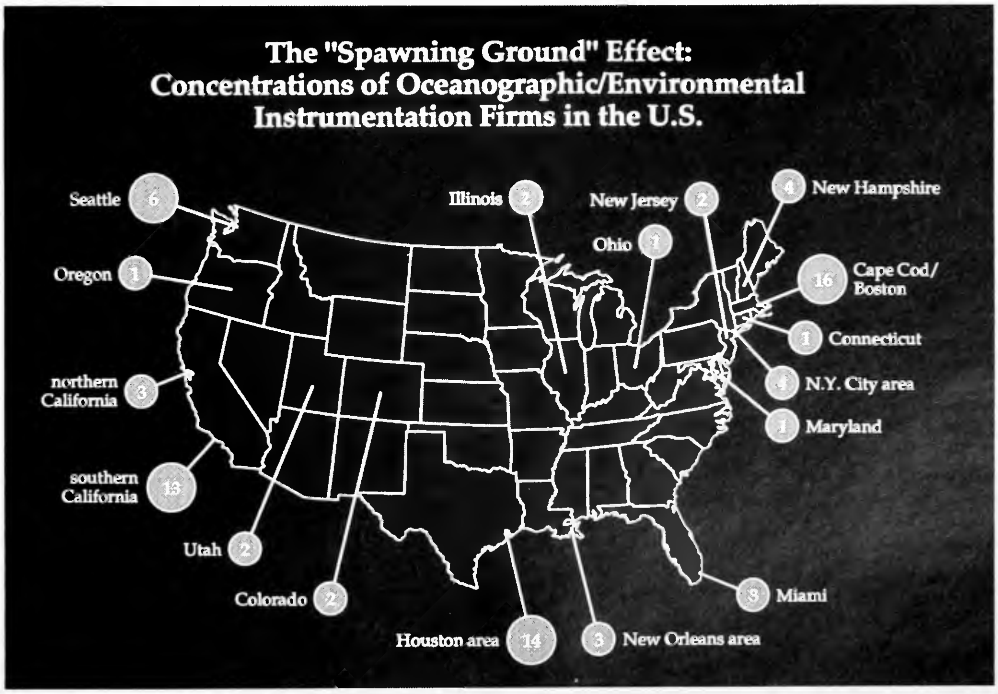
Although oceanographic research accounts for only a small share of total MEI demand, evidence suggests a much more important role in creating technological innovation and fostering technology transfer from the academic to the commercial sector. The geographic distribution of marine scientific instrumentation firms reveals a strong clustering near regional centers of marine research. We call this the "spawning ground" effect.

US firms traditionally have enjoyed a strong international competitive advantage in the marine electronic instrumentation field. The world MEI market generates estimated annual sales revenues on the order of ten billion dollars, and US sales and the share captured by US firms equal roughly 50 percent of these. However, this advantage, as in the broader, related fields of communications equipment, electronic components, and scientific instruments, now is subjected to powerful challenge from foreign competitors. While about 70 percent of all US *manufacturing products face foreign competition, virtually 100 percent of US MEI products compete with foreign rivals.*

At the WHOI Marine Policy Center, our analysis of the organization and international competitive dynamics of the MEI industry forms one part of a larger national program aimed at the development of a "National Marine Electronics Agenda." The proposed agenda itself will be devised by a 70-member panel using the results of our research projects and related projects at Hawaii's Oceanic Institute and at Florida State University. Selected on the basis of their experience with MEI, the panel members represent private firms, government agencies, national laboratories, and academic and nonprofit research institutions.

Through the results of our research and the construction of a prescriptive "national agenda," we hope to improve our understanding of international marine electronics markets, to inform constructive policy initiatives, and to demonstrate how increased interaction across sectors can contribute to national scientific progress and economic growth.

—James M. Broadus
Director, Marine Policy Center
Woods Hole Oceanographic Institution



Marine scientific instrumentation firms tend to cluster near regional centers of marine research. Each circled number refers to the number of such manufacturers located in that area.

Douglas Chester Webb

A Profile

Doug Webb poses in his workshop with the electromechanical assembly of an ALACE float.

Henry M. Stommel

Doug Webb appears to be a cautious and deliberate man, but his career shows that he is actually unusually daring. At the age of eleven, when other boys' notions of adventure might be jumping over a campfire, Doug conceived an idea for a facsimile machine—and then acting on his curiosity, tried to build one. Without benefit of machine tools or knowledge of electronics, he carefully fashioned some wooden drums, whittled a lead screw, and formed a primitive circuit using pencils as contacts. It was not a successful invention...but he dared.

Today, Doug Webb is primarily responsible for some 300 floats that have been launched to bring a new vision of ocean currents (see Philip Richardson's article on page 23). Doug's latest project is the Slocum, a small, self-powered vehicle that can move up and down and around the ocean, drawing its motive power entirely from the thermal stratification of the ocean without benefit of fuel or batteries. He is one of the most inventive of ocean engineers.

Born in 1929, Doug grew up in the little village (population 400) near Cayuga, Ontario, where his Cornish forebears settled upon immigration to Canada early in the last century. As a boy, his favorite reading was his father's back-issue set of *Popular Science* magazine. Side by side, the articles depicted such homely little inventions as novel apple corers, boots for walking on marshes, and pencils with flashlights attached for writing in the dark, next to elaborate, daring visions of future cities linked by space ships, exhibiting the infrastructure of a Buck Rogers world.

In 1944, Doug's family moved to Owen Sound on the south shore of Lake Huron's Georgian Bay, and it was here that Doug went through high school. When he was 15, his future wife, Shirley Lyons, was his chemistry lab partner. It was also at Owen Sound that Doug discovered deep water. He earned his way through Queens University at Kingston serving on wooden steamers carrying passengers, goods, and cattle to waterbound hamlets in the Manitoulin Islands and on towing barges conveying wood pulp to the *Chicago Tribune* presses. He took his B.S. degree in electrical engineering in 1952.

When Doug joined the electrical engineering firm Ferranti, he was sent to Manchester University in England for futher study. He joined an exciting new computer group assembled there under the leadership of such giants as Frederick C. Williams, the youthful inventor of the "memory tube," Tom Kilburn, who has influenced the architecture of nearly every computer, and Alan M. Turing, who built the primitive computer that decoded the messages transmitted through the Enigma machine to the German fleet during World War II.

While at Manchester, Doug "entered Bugatti competitions" and worked on his first scientific paper, describing a pioneering development to make a computer entirely with transistors using magnetic drums for memory storage. It was published in 1956, an early date in computer history. He obtained his M.S. in electrical engineering in 1954.

From 1956 to 1962, Doug worked for Olivetti, first in Pisa and later in Milan, Italy. Olivetti, then the largest manufacturer of office equipment in Europe, was exploring the application of digital computers to business needs with a team of about 100 engineers. After Shirley and Doug were married in 1957, they lived in the small town of Melegnano outside Milan. Both were very happy in Italy and might well have stayed there for the rest of their lives. Their daughter, Rebecca, was born there in 1961. They enjoyed traveling, and when they found a 28-foot gaff-rigged cutter, *MEG II*, for sale in southeastern France, they bought it. From *MEG II's* mooring at Le Grazie on the Gulf of La Spezia, sailing vacations often took them to Corsica, Sardinia, and

Doug Webb races a Bugatti Brescia at the British Silverstone racetrack in 1955.

the lesser islands. After Doug left Olivetti, the family spent a blissful five months wandering around the western Mediterranean aboard *MEG II*.

Doug, however, was seeking an outlet for his energies that would permit him to develop personal goals unfettered by the restrictions of a large company. He thought of inventing and manufacturing technologies for third-world countries, and he entertained the idea of going into shipbuilding, but he finally decided upon oceanography. In December 1961, during a computer convention in Washington, DC, he noticed a bulletin board posting for an engineering postion at the Woods Hole Oceanographic Institution (WHOI). He drove to Woods Hole and quickly made up his mind.

Upon arrival in Woods Hole, he was lucky to find himself working for Bob Walden on projects supervised by Bill Richardson, and soon, with Gordon Volkmann, he began to work on neutrally buoyant floats. Ideas for these floats had been circulating for some time. The earliest mention I remember was Allyn Vine speculating in 1946 about a device that would control ballast so a float could hover at a fixed depth. Some time about 1951, Arnold Arons and I brought an engineering graduate from the Massachusetts Institute of Technology (MIT) to WHOI to look into constructing a neutrally buoyant float. Armed with Ruark's textbook on pressure vessels, he determined that there were no materials strong and light enough to build one with, and the idea was shelved.

Then, in 1954, John Swallow, working at the British National Institute of Oceanography, built a float with scaffold tubing and a serviceable sound source that allowed acoustic tracking over several miles. Swallow embarked upon a remarkable series of deep-current measurements in various parts of the ocean. He discovered the deep southward flowing current under the Gulf Stream off Cape Romaine. In 1959, Swallow and James Crease moved to Bermuda for a year to find out if they could determine the mean abyssal currents by visiting little clusters of his floats once every week or two, using the sailing yacht *Aries* recently acquired by WHOI. They found deep currents unexpectedly energetic—the floats moved so quickly that they often traveled out of range between visits of the ship.

Doug Webb prepares a SOFAR float for the MODE I experiment during the winter of 1973.

The sound transducers available to Swallow were fairly primitive. Two hydrophones hung from bow and stern, and the observer searched for the incoming sound pulses on a two-gun oscilloscope, looking for them individually amidst the ambient noise. It required great skill and perseverence to see the signals under sea conditions on small vessels, and not many of us had the skill of John Swallow. Each set of observations enabled the observer to lay down a line of position. The ship then moved to another location to determine another line of position and a fix. Today, looking back at these early Swallow floats, we recognize them as miracles of inspired improvisation.

Doug set out to improve both the signal strength and the means of tracking. On July 5, 1963, as Doug was watching R/V *Atlantis II* depart for the Indian Ocean, a visitor showed him a new ceramic transducer. Immediately he realized that here was the promise of increasing the strength of the signal put out by floats so they could be heard more reliably and over greater distances. With

Volkmann, he developed a scheme for towing four hydrophones in a rectangular array and recording their signals on a wet-paper recorder, making signals easier to distinguish from noise. In 1965, he developed a stable time base so the distance could also be determined and a fix obtained on one pass.

Next, Doug applied his experience to production of a recoverable submerged navigational beacon, and a remarkable rotating current-meter float capable of measuring the vertical component of velocity. He and Valentine Worthington used it in the Cayman Trough. Later, with Art Voorhis, this type of instrument was used to determine the vertical velocities in the chimneys of deep convection in the western Mediterranean during the mistrals of 1969 and 1970. In 1966, Doug and M.J. (Tommy) Tucker of the International Oceanographic Society determined the optimal acoustic frequency for long-range sound transmission, and tested it successfully off Bermuda. Tucker had worked on the original Swallow float, and Doug terms him "a very important teacher for me."

Doug Webb catches forty winks atop a SOFAR float during a mid-70s cruise aboard R/V Chain, *operated by the Woods Hole Oceanographic Institution (WHOI).*

Doug then turned his mind to tracking deep floats over long distances, for long periods of time, through the abyss of the open ocean. H. Thomas Rossby had just completed his Ph.D. at MIT, and he took on the difficult job of gaining access to restricted navy tracking stations and/or devising methods for processing the signals and triangulating the positions of the floats. It was for this collaborative effort, culminating in the modern SOFAR (SOund Fixing and Ranging) float, that Webb and Rossby jointly received the Henry Bryant Bigelow Award in Oceanography in 1988.

SOFAR is based on the discovery of a sound channel in the deep ocean by W. Maurice Ewing in the 1940s. This channel confines sound rays to a range of depth so that they spread out horizontally in two dimensions rather than three, thus traveling long distances with little diminution of energy. I remember vividly a demonstration of the sound channel in those years at the US Navy Undersea Sound Laboratory in New London, Connecticut. As we eavesdropped on the marine radio communications link, we heard a modest charge exploded 4,000 miles away in the deep South Atlantic. Then, about an hour later, we heard the sound of the explosion picked up by the ketch R/V *Atlantis* off Barbados, and about 40 minutes after that by R/V *Valor* off Bermuda. This was literally a case of a shot being heard around the world!

In the words of the citation for the Bigelow Medal: "Webb and Rossby built the first two prototype SOFAR floats in 1968 with disappointing results. The first was tracked for only one week, the second for only two days. In 1969, they had their first success with a four-month drift. This third float gave them the confidence to keep going and also the credibility which led to their eventual participation in MODE (Mid-Ocean Dynamics Experiment). The first large deployment of floats and

Photo by Philip L. Richardson

Doug Webb (hardhat) and Bob Tavares of the WHOI float group prepare a bobber for launch from R/V Oceanus *(WHOI) in 1986.*

the successful acquisition of interesting scientific results from them was in 1973 as part of MODE, sponsored by the IDOE (International Decade of Ocean Exploration). Early in the experiment, however, the floats began to fail due to unbonding of the new acoustic transducers. Webb and Rossby quickly responded by [going to sea and] recalling the floats to the surface and fixing them aboard ship [*Author's note:* A remarkable feat because of the size of the floats and the need to design special tooling in an emergency situation.]. Through creative repairs and a lot of hard work, the floats were relaunched and successfully tracked for the remainder of the experiment." Some of these floats transmitted faithfully for years thereafter. The MODE floats revealed important information about ocean eddies and western boundary currents.

Always inclined toward daring, in 1982 Doug Webb resigned from WHOI to form his own company, Webb Research Corporation, to specialize in developing and manufacturing floats and sound sources. With a staff of six, including his son Dan Webb, also an engineer, he supplies scientific experimenters in France, England, and Japan, as well as in the US with these valuable instruments. Among these are the SOFAR Bobber being used in the Ventilation Experiment, which tracks the movement of surface water to the interior of the ocean, and the ALACE (Autonomous LAgrangian Circulation Explorer) used in the World Ocean Circulation Experiment.

His latest project, the Slocum, is named for Joshua Slocum, the first person to sail single-handedly around the world. As noted above, Slocums are self-propelled by ocean thermal stratification. While at the surface, the floats will transmit their data by satellite to a control center and then receive instructions on what to do and where to go next. A small number of Slocums could be deployed over the ocean to provide a world ocean observing system for monitoring long-term changes in the climate of the ocean. This might be an economical element in future efforts to record and regulate the global environment. It would be an impressive achievement for so small a shop to instrument the world ocean.

But what would please Doug most, I think, would be the fact that he had been bold enough to launch one tiny Slocum to cross the ocean without a sail or fuel tank.

Henry M. Stommel is a Senior Scientist in the Physical Oceanography Department at the Woods Hole Oceanographic Institution (WHOI). He has been associated with WHOI since 1944, and his research interest is large-scale ocean circulation.

LETTERS

To the Editor:

In the photograph caption on page 70 of the Winter 1990/1991 issue, I inadvertently identified the aircraft deploying a buoy as an Air National Guard C-130. The photograph was, in fact, taken aboard an Air Force C-130 during a peacetime Military Airlift Command Special Assignment Mission in 1988.

Michael J. Carron
Director, Scientific Technology Staff
Naval Oceanographic Office
Stennis Space Center, Mississippi

To the Editor:

Stewart B. Nelson's excellent article "Naval Oceanography: A Look Back" appears to downplay the fledgling Continental Navy's knowledge of the seas, winds, and stars, characterizing it as that of "simple American fishermen" and sailors. Not acknowledged are the considerable contributions of the merchant mariners of that era; in particular, the work of Lt. Wilke's mentor, Nathaniel Bowditch.

As a young man, Bowditch became known to the sea captains of his Salem home for finding and correcting errors in Isaac Newton's great work, *The Principia*. In 1799, Bowditch was asked by Edmund Blunt, publisher of *American Coast Pilot*, to correct and update John Hamilton Moore's standard reference for captains, *The Practical Navigator*. Bowditch tackled this task during his next voyage to the Far East and returned with corrections to 8,000 errors in Moore's calculations. Bowditch's book, *The New American Practical Navigator*, has been a principle reference for American mariners since it was first published in 1802.

In 1804, Bowditch was elected "Inspector of Journals" for the East India Marine Society, a society of experienced sea captains established in 1799 to gather oceanographic information about the East Indies and start a museum. As inspector, he organized captain's logbooks and gave each captain a bound journal to record observations; thus more than 100 voyages to the Far East were documented during the next three decades. These men were among the first to urge Washington to sponsor a naval exploring expedition to the South Pacific.

Bowditch was also a great marine educator, in keeping with your topic for the Fall 1990 issue of *Oceanus*. When he discovered a new method for determining longitude at sea by means of lunar observations, he freely shared his findings. On one voyage to the Philippines, a Scottish captain, skeptical of American navigational abilities, was surprised to discover that every member of Bowditch's ship could perform all the tasks of the navigator, including the difficult lunar-longitude determination.

Rob Moir
Curator of Natural History
Peabody Museum
Salem, Massachusetts

A Fragile Power: Scientists and the State **by Chandra Mukerji. 1990. Princeton University Press, Princeton, NJ. 253 pp. - $24.95.**

I found this a most curious and somewhat annoying book. It contains a good deal of interesting interview material with ocean scientists and information concerning their relationships to their government funders as well as to each other. The author has a thesis or two but, unfortunately, while there are repeated assertions of the theses, the interview and textual material does not seem to support them.

One principal thesis presented is that the real purpose behind government support for ocean scientists is the creation of a cadre of ocean scientists who will be available when called upon for whatever purpose the 'state' has in mind. When this assertion is made, the tone is one of sinister purpose, but what this purpose may be is never clearly discussed.

I can address this thesis from my own experience as one of the presumably sinister government officials. Government agencies support science because officials believe, generally correctly, that new scientific knowledge will help them do their statutory jobs better. (In the case of the National Science Foundation, the job is to support science.) Government agencies support science because they frequently have a specific legal requirement to do so, and they think it is useful for there to be a strong science community with which they may build strong ties and also be able to call upon for consultation and help when their missions and circumstances so require. The thesis is correct as part of the motivation, but the emphasis is wrong: The possibility of help from the scientists is only one of the well-known reasons for support of science.

In matters like the support and use of science, there is no monolithic 'state' in the US government. There are many parts of the federal government; they do not all agree or behave alike, and there is little in the way of continuous overriding policy for science, although there are numerous coordination and common bureaucratic processes. One of the virtues of the US system for supporting science has been its diversity; there are several places to go to get an idea supported.

The other principal thesis of the book is that the government support process prevents scientists from having any power or use of their voice. This thesis is repeatedly weakened by examples in the text. Given the participation of scientists in senior government positions, in testimony (sometimes acrimony) before the Congress, and in public debate, the face of the thesis is wrong. Granted, scientists are not always listened to, they do not always agree with each other, and they certainly do not have unquestioned overriding power, but it is absurd to say that they do not have an important, and frequently powerful, influence on various parts of the government. Scientists have not lost their voice, although we are not always successful in using it. But then, neither is any other group always successful in using their voice.

This book is strongest in its discussion of the situation of the ocean scientist in seeking support, and in its discussions of the politics of the profession. It is weakest in its attempts to support poorly defined political theses.

—Robert A. Frosch, Vice President,
General Motors Research Laboratories

BOOKS RECEIVED

MARINE POLICY

Crisis in the World's Fisheries: People, Problems, and Policies by James R. McGoodwin; 1990; Stanford University Press, Stanford, CA; 236 pp. - $35.00.

The Exclusive Economic Zone in International Law by David Attard; 1987 (hardcover) and 1991 (paperback); Oxford University Press, New York, NY; 416 pp. - $36.00.

Wetlands: Mitigating and Regulating Development Impacts by David Salvesen; 1990; Urban Land Institute, Washington, DC; 120 pp. - $38.00.

BIOLOGY

A Secret World: Natural Products of Marine Life by Francesco Pietra; 1990; Birkhauser, Basel, Switzerland; 280 pp. - $98.00.

Ecosystems of the World: Coral Reefs edited by Z. Dubinsky; 1991; Elsevier Science Publishers, Amsterdam, The Netherlands; 562 pp. - $220.00.

The Living Ocean: Understanding and Protecting Marine Biodiversity by Boyce Thorne-Miller and John Catena; 1990; Center for Resource Economics/Island Press, Washington, DC; 160 pp. - $10.95.

REFERENCE

Ocean Passages for the World: Fourth Edition compiled by Office of the Hydrographer of the Navy; 1990; International Marine Publishing, TAB Books, Blue Ridge Summit, PA; 318 pp. - $75.00.

Planet Earth: The View from Space by D. James Baker; 1990; Harvard University Press, Cambridge, MA; 158 pp. - $25.00.

The Water Encyclopedia: Second Edition by Fritz van der Leeden, Fred L. Troise, and David Keith Todd; 1990; Lewis Publishers, Inc., Chelsea, MI, and Water Information Center, Plainview, NY; 808 pp. - $125.00.

YOUNG PEOPLE

From Woods Hole Waters: A Coloring Book from the Marine Biological Laboratory by John J. Valois and Julia S. Child; 1990; Associates of the Marine Biological Laboratory, Woods Hole, MA; 40 pp. - $4.95.

Jack, the Seal and the Sea by Gerald Aschenbrenner; 1990; Silver Burdett Press, Englewood Cliffs, NJ; 30 pp. - $6.95.

The Whale Game; players are whales, migrating through real-life dangers in the seas; 1990; Science Books, Washington, DC; $17.95.

BOOKS RECEIVED

OCEANOGRAPHY

Handbooks of Coastal and Ocean Engineering: Volume 1, Wave Phenomena and Coastal Structures; and Volume 2, Offshore Structures, Marine Foundations, Sediment Processes, and Modeling edited by John B. Herbich; 1990; Gulf Publishing Company, Houston, TX; 1,115 pp. - $195.00 each volume.

Tectonic Evolution of the North Sea Rifts edited by D.J. Blundell and A.D. Gibbs; 1991; Oxford University Press, New York, NY; 400 pp. - $115.00.

The Deep Sea Bed: Its Physics, Chemistry and Biology edited by N. Charnock, J.M. Edmond, I.N. McCave, A.L. Rice, and T.R.S. Wilson; 1990; The Royal Society, London; 194 pp. - £42.50.

EDUCATION

Careers in Oceanography: A Special Edition With Emphasis on Opportunities for Sensory or Physically Disabled Persons compiled by the Oceanography Society for the Oceanographer of the Navy; 1990; Office of Naval Research, Washington, DC; 50 pp. - free.

Opportunities in Marine and Maritime Careers by William Ray Heitzmann; 1990; NTC Publishing Group, Chicago, IL; 142 pp. - $9.95.

ENVIRONMENT

The Rising Seas by Martin Ince; 1990; Earthscan Publications Ltd., London, England; 146 pp. - $10.95.

The Wasted Ocean: The Ominous Crisis of Marine Pollution and How to Stop It by David K. Bulloch; 1989; Lyons & Burford, Publishers, New York, NY; 116 pp. - $9.95.

Wetland Creation and Restoration: The Status of the Science by Jon A. Kusler and Mary E. Kentula; 1990; Center for Resource Economics/Island Press, Washington, DC; 594 pp. - $60.00.

RECREATION

Fly Fishing! #@%&* Cartoons by John Troy; 1985; Lyons & Burford, Publishers, New York, NY; 80 pp. - $5.95.

Treasures of the Tide: The Book for Beachcombers compiled and published by the National Wildlife Federation; 1990; Washington, DC; 176 pp. - $27.95.

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