Seeing Underwater with Background Noise

With a technique called acoustic-daylight imaging, sounds in the sea can “illuminate” submerged objects, thereby creating moving color pictures without sonar

by Michael J. Buckingham, John R. Potter and Chad L. Epifanio

Ping...ggg.” The sound of a sonar transmission is familiar from classic films on submarine warfare, such as *Das Boot* and more recently *The Hunt for Red October.* An echo provides the submariner with the clue to a target’s presence and position. Alternatively, one can passively listen for the sound generated by the target itself. In both techniques, however, the acoustic noise that permeates the oceans compromises the integrity of the signals. Breaking waves, passing ships, falling rain and even sea creatures such as snapping shrimp all contribute to this cacophony. It is only to be expected that sonar operators have traditionally regarded background noise as a nuisance and, accordingly, have directed great efforts to suppress the effects of ambient noise.

Yet that approach is gradually changing, as researchers have begun to recognize that the noise itself can be useful. Noise surrounds any object immersed in the ocean; the object, in turn, modifies this noise field in ways that depend on the object’s shape, composition and position. Ambient noise has a familiar optical analogue: daylight in the atmosphere. We can see and photograph outdoor objects because they scatter, reflect and otherwise modify the light in the air. Likewise, noise that permeates the ocean acts as a kind of “acoustic daylight.” Recent experiments have shown that we can indeed create images of underwater objects by using ambient noise as a source of illumination. Our results are sufficiently encouraging that we believe acoustic-daylight imaging should prove useful for a variety of purposes, from harbor security to underwater mine detection.

To be sure, at present the resulting pictures lack a certain aesthetic appeal. The image resolution is no match for that achieved with optical light. The acuity of human vision stems from the fact that the dilated pupil is 10,000 times the size of the wavelength of visible light, enabling the eye to “collect” a great number of light waves. Achieving a similar resolution with sound would demand an impractically large receiver 600 meters wide. But because seawater strongly absorbs light and all other forms of electromagnetic radiation, sound has become the favored—and in many cases, the only—means of acquiring information about the ocean depths.

Humanity’s interest in sound in the ocean dates back to antiquity. Aristotle and Pliny the Younger wondered if fish could hear. Fishermen in ancient China located shoals of fish by using a bamboo stick as an underwater listening device, placing one end in the water. Leonardo da Vinci further developed the idea, noting in his studies of the properties of water that “if you cause your ship to stop, and place the head of a long tube in the water and place the outer extremity to your ear, you will hear ships at a great distance from you.”

It was not until early in the 20th century, however, that inventors fashioned the first underwater sonic location systems, in order to counter the submarine threat during World War I. As rudimentary as those early devices were, they formed the basis of all subsequent sonar, the development of which accelerated rapidly during World War II. Current sonar systems, which have found widespread military, commercial and scientific application, have evolved to a high degree of sophistication. Still, they operate on much the same principles as their predecessors: they either actively transmit sounds or passively receive sounds produced by a target.

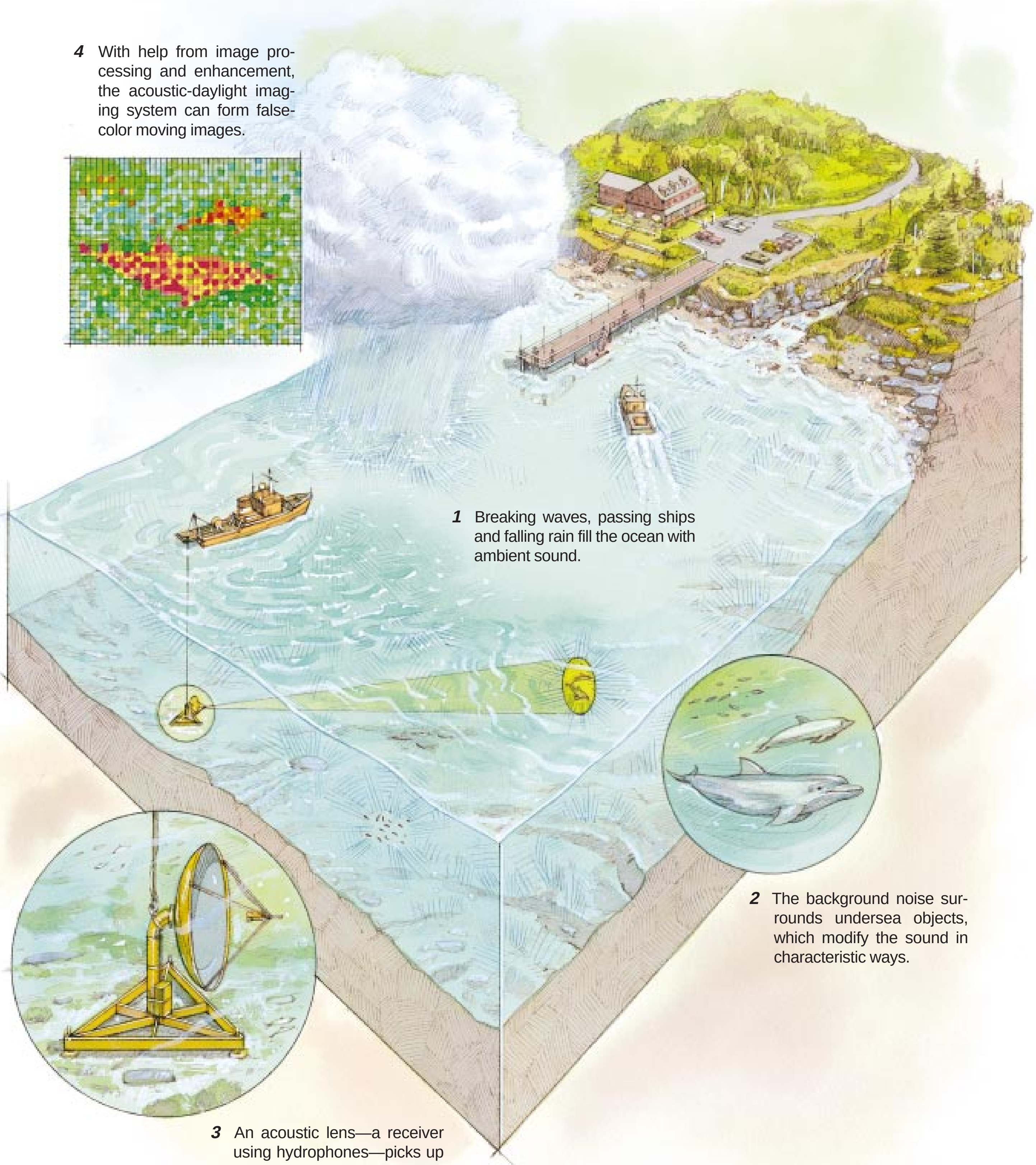
In view of the historical emphasis on active and passive techniques, it is not surprising that the notion that noise might provide an entirely new way of “seeing” in the ocean evolved only recently. In the mid-1980s one of us (Buckingham) recognized that visual imaging as performed by the eye is neither active nor passive. That is to say, the eye functions in a manner that differs fundamentally from the conventional ways of using acoustics in the ocean. Once this idea had registered, it became natural to speculate on the possibility of creating an underwater acoustic analogue of visual imaging. On a practical level, acoustic-daylight imaging would avoid the main drawbacks of conventional undersea detection techniques: echolocation unavoidably reveals the presence of the operator, and passive detection, though entirely covert, fails with quiet or silent targets.

The First Experiment

In mid-1991 we conducted the first acoustic-daylight experiments in the Pacific Ocean off Scripps Pier at Scripps Institution of Oceanography in La Jolla, Calif. Working for his master of science degree at Scripps was a young navy lieutenant, Brodie Berkhout, who constructed and deployed the equipment. The main device was an acoustic receiver in the form of a simple parabolic reflector, 1.2 meters in diameter, with a single hydrophone (underwater microphone) at the focus. In effect, the reflector played the role of an acoustic lens.

The purpose of the experiment was to answer a simple question: Does the perceived noise level at the receiver change when an object is placed in its “beam,” that is, its listening field? A rectangular plywood board, 0.9 by 0.77 meter and faced with neoprene rubber—a good reflector and scatterer of sound—served as the target. We found that for frequencies between five and 50 kilohertz (within the range produced by breaking waves, which are often the main source of ambient noise in the ocean),

Acoustic Daylight in Action



BARRY ROSS

MICHAEL J. BUCKINGHAM

KILLER WHALE at Sea World park in San Diego served as a moving target for ADONIS, the first acoustic-daylight imaging system.

the noise intensity nominally doubled when the target was placed in the listening field of the reflector. This result persisted when we moved the target from seven to 12 meters from the receiver. Moreover, the target strongly reflected some frequencies and absorbed others, a phenomenon that can be interpreted as acoustic "color." This development suggested that we could translate the reflected acoustic signature into optical hues to create acoustic-daylight images in false color.

Spurred on by this success, we began thinking about the next stage of development. The parabolic reflector with a hydrophone at its focus "looks" only in a single direction, corresponding to just one pixel of an image. To create a more complete picture, more pixels are necessary, which means more receiver "beams" are needed (rather like the compound eye of a fly). The noise in each receiver beam could then be converted to a certain level of brilliance in a pixel on a video monitor, with the intensity of the noise governing the degree of the brightness. As in a newspaper photograph, the contrast between pixels would enable the eye to interpret the result as a more or less granular pictorial image.

With the success of the initial test, we became convinced of the feasibility of achieving genuine acoustic-daylight images that would contain 100 or more pixels. In mid-1992 we began designing a new acoustic lens, which came to be known as ADONIS, for acoustic-daylight, ambient-noise imaging system. Working in conjunction with EDO Acoustics in Salt Lake City, which produced an elliptical array of 128 hydrophones for ADONIS, we constructed a spherical reflector three meters in diameter and placed the hydrophones at the focus of the dish. This system formed a total field of view of approximately six degrees (horizontal) by five degrees (vertical), which is about one tenth the angular view afforded by a typical camera.

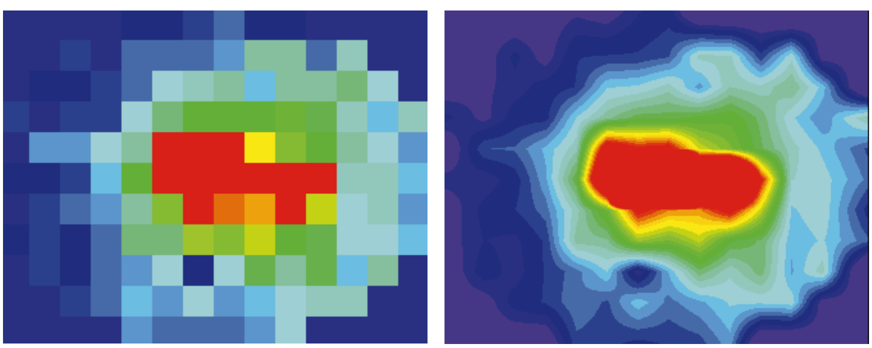
We lowered ADONIS, looking rather like a satellite dish, onto the seabed for the first time in August 1994. ADONIS was deployed from one of Scripps's research platforms, *R/P ORB,* moored off Point Loma in southern California. Square panels (one meter per side) of aluminum sheeting faced with neoprene rubber formed the targets to be imaged. The panels were mounted in various configurations on a square tic-tac-toe-type frame set on the seabed. Roiled-up sediment in the busy harbor made visibility through the water extremely poor during most of the experiment. On one occasion the turbidity was so bad that Hélène Vervoort, one of our divers, collided with the target frame.

An electronics package housed in a sealed pressure canister rested alongside the mast supporting the spherical dish. Among other processing tasks, the electronic equipment, designed by our colleague Grant B. Deane, would convert the ambient noise data acquired by ADONIS into digital form. The data would then be transmitted to the surface and rendered into real-time, false-color images on the screen of a Macintosh desktop computer. An immense amount of time and effort hung in the balance as ADONIS was lowered into the sea for its first deployment.

To See or Not To See?

The air of hushed expectancy that hung over our group as ADONIS disappeared below the ocean surface was soon dispelled—not, however, because of an initial, resounding success. Almost immediately, the gauges monitoring several onboard power supplies surged—a strong indication that seawater was flooding into the electronics canister. Sure enough, when ADONIS was hauled up and the canister opened, saltwater gushed out. As a reflex reaction, we removed the delicate circuit boards and soaked them in deionized water, although nobody really believed they could be salvaged. But with help from a number of quarters, we flushed the boards with alcohol, tested all the electronic components of the complex 128-channel system, replaced them where necessary and sealed the leak in the canister. Twenty-four hours later ADONIS was again lowered into the water.

This time the tension on *ORB* was tangible as the divers made last-minute checks on the equipment. When the data started to flow, the laboratory became quiet. We had set three panels in the frame to form a simple horizontal target, one meter high by three meters wide, at a distance of 18 meters from



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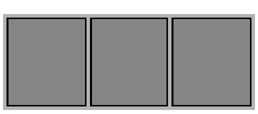


BAR TARGET (*left*) was imaged by ADONIS as a vaguely elongated form and artificially colored red (*upper left*). Each "pixel" represents the signals from a hydrophone. Computer processing enhanced the image (*upper right*).

ADONIS. As we gathered around the screen, we realized that a faint rectangular shape was visible, almost filling the elliptical image space. We were watching the first acoustic-daylight picture.

Within minutes our confidence in the imaging system had soared. Divers had placed a sound source in the center of the target to help us align ADONIS with the target frame. But the source proved unnecessary: we could see where the targets were just from the ambient noise. We then extended the space between ADONIS and the target from 18 to 38 meters, as far as we could go without interfering with shipping traffic. At the greater range we expected perhaps a slight degradation in performance, but astonishingly the target became far clearer. Of course, the image was also smaller than it had been previously, but as a result, the surrounding ocean formed a nice, contrasting background that made the rectangular target stand out dramatically. As these raw images continued to appear on the screen, refreshed 30 times a second, we knew that acoustic-daylight imaging worked.

There was still much to be done during this deployment, however. We wanted to know if ADONIS could detect moving objects. A hydraulic motor mounted within the mast supporting the dish could slowly rotate the spherical receiver in azimuth, taking 12 minutes or so to complete a full 360-degree sweep. As the dish panned around, we watched the target appear on one side of the screen, creep to the center and finally drop off the far side. There was no doubt that we could create moving images.

One more test, the most demanding of all, remained. Divers replaced the bar-shaped target with four panels in the frame, forming a cross with vertical and horizontal arms and a one-meter-square hole in the center. Resolving the hole was the challenge: at a range of 38 meters, the size of the hole would be close to the resolution limit of ADONIS.

The first raw images of the cruciform target were indistinct. We could see the shape of the cross, but the appearance of the central hole fluctuated from instant to instant. Since then, we have reexamined the data and applied some computer processing. It turns out that the power spectrum of the noise—the intensity of the sound at different frequencies—serves a discriminatory function. It is essentially the acoustic version of color. By using the power spectrum, the four empty corners and the hole in the cruciform target could easily be identified and the edges of the panels located. The panels in the target frame showed a distinctly different "color" from the empty regions, including the central hole. It was as if the frame looked "red," and the hole appeared "blue." Currently we are exploring this technique as a means of enhancing acoustic-daylight images.

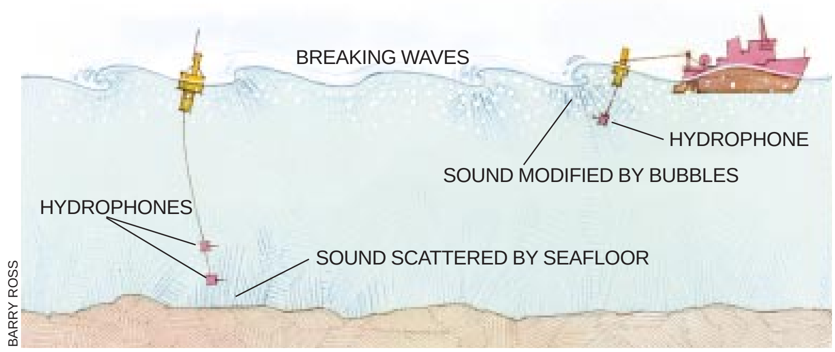
Sounding Out New Uses for Noise

Acoustic-daylight imaging is just one form of remote-sensing technology that relies on the background noise in the seas. Oceanographers have recently demonstrated other examples of similar techniques. One is to use ambient noise to determine the acoustic properties of the seabed and hence to determine its composition to some extent. In the shallow waters over the continental shelves, where the depth is less than about 200 meters, the noise reflects off the seafloor. The manner in which the sound bounces off indicates the speed with which vibrations move in the floor. That, in turn, reveals the composition of the bottom: sound travels at different speeds through bedrock than it does through sand, for instance.

To carry out such measurements, one can deploy a fleet of hydrophone-dangling buoys to map the seabed using ambient noise. The hope is that this technique will offer a cost-effective alternative to conventional methods, such as the often slow and laborious practice of bouncing sonar signals off the sea bottom.

Background sounds may also prove beneficial in the study of processes occurring at the sea surface. In particular, they can reveal the amount of atmospheric gas the oceans are absorbing. Crucial for models of global warming and the greenhouse effect, the extent of gas exchange has been difficult to quantify. Ambient noise may help, because the phenomenon mostly responsible for the sound also happens to govern the transfer of gas from the air to water—namely, wave breaking. In driving air into the water, the process creates a layer of bubbles immediately below the surface. These bubbles modify the sound of the breaking waves in a characteristic way, leaving an acoustic signature for hydrophones below the bubbles to detect.

From such a simple acoustic measurement, it may be possible to infer the amount of air in the bubble layer and the depth to which the bubbles extend. Both quantities are related to the amount of gas entering the ocean. Some preliminary testing suggests the idea is feasible; major experiments are currently under way. —*M.J.B.*

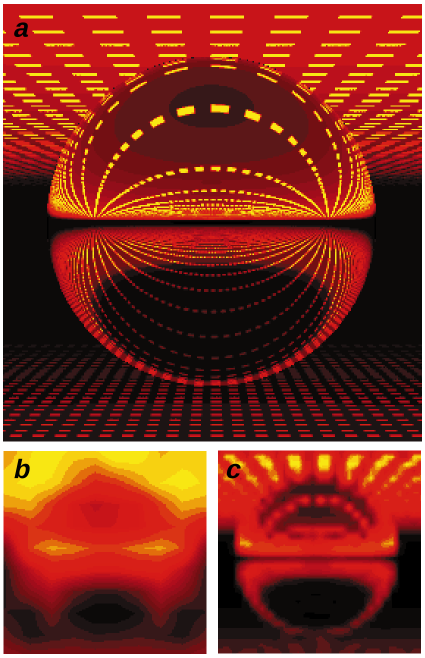


AMBIENT NOISE could also measure the acoustic properties of the ocean bottom (*left*) and the amount of gas absorbed by the sea (*right*).

Imaging at Sea World

Static targets served us well in demonstrating that acoustic-daylight imaging is a workable technique. Inspired by our results, we were anxious to try a more difficult target: killer whales (*Orcinus orca*). Through the good offices of Ann Bowles, a research biologist at Hubbs Sea World Research Institute in San Diego, we were invited to deploy ADONIS in the outdoor killer-whale tank at Sea World. We could try to image highly mobile marine mammals while Bowles conducted behavioral studies on the response of the animals to a strange object in "their" tank; the whales, it seems, feel that anything placed in the tank, by definition, belongs to them.

In February 1995, working between the killer whales' public performances,



JOHN R. POTTER

SIMULATED IMAGES of a steel sphere hint at the promise of acoustic daylight. The ambient noise comes from breaking waves, represented by yellow dashes. A system with 90,000 pixels would yield the highest resolution (*a*) but is probably not practical. Technology now uses about 100 pixels (*b*), and systems using 900 pixels are planned (*c*).

we set up ADONIS in one corner of the tank in rather unpleasant weather conditions. Rain lashed down most of the time; to protect our computers and recording equipment, we rigged up makeshift tarpaulins, but even so water seeped everywhere.

Meanwhile, as we set up the system, the killer whales swam freely in the tank, taking as much interest in us as we did in them. Cautious at first, they quickly grew accustomed to the large reflecting dish. The whales became curious on finding that because of the focusing effect of the dish, sound reflected intensely back to them when they "pinged" in front of it. A young male, Splash, grew more adventurous, taking one of the oil-filled electronics cables (crunchy on the outside and chewy on the inside) into his mouth to try some exploratory mastication. Another animal swam fast toward the dish and breached over the top—at this point we felt that something had to be done. The trainers moved the whales to another tank, where they could play with their own toys until we were ready for them.

After one false start (all the electronics boards in the underwater housing had shaken free of their connectors during transportation), we switched on the equipment again, and data started flowing. We were not sure what to expect. Pumps and other machinery bring the noise in the Sea World tanks to quite high levels, comparable to those in the ocean. Despite some minor damage that the electronics boards had sustained when they were flooded by seawater, signals from all but two of the 128 channels were received and displayed as real-time moving images.

As we watched the raw data (that is, with no image enhancement) on the screen, a shadowy form suddenly appeared and remained in sight for several seconds. At the same time, we could see (with our own eyes) one of the whales move into the field of view of ADONIS, where it stayed as it swam directly away from the dish. Hydrophone monitors and the trainers confirmed that the whales themselves were not transmitting sound, indicating that the images we saw were a direct result of acoustic daylight. We still have to examine the images of the killer whales carefully and correlate them with the video recordings that were made simultaneously to confirm whether we actually imaged the whales. But the preliminary observations and the *ORB* experiment off Point Loma support the analogy between conventional photography with daylight and underwater imaging with ambient sound.

The results immediately suggest several potential applications. One is the detection of underwater mines, some of which can be rigged to detonate on receiving a sonar signal. An acoustic-daylight system might be able to locate these devices without triggering them. Imaging with ambient noise could provide vision for autonomous underwater vehicles, enabling them to steer around obstacles without help from a human operator on a surface ship and to monitor the structural integrity of oil rigs and other large maritime platforms. The inherently covert nature of acoustic-daylight imaging also makes it suitable for monitoring harbors—just as video cameras keep vigilance in shopping malls—and for counting marine mammals, because there would be no sonic interference with the animals themselves. (That, in turn, raises the question of whether marine mammals themselves use acoustic daylight to acquire information.)

Conceivably, we can take acoustic-daylight imaging further, for it is still a nascent concept. In recent tests, ADONIS successfully imaged plastic floats, titanium spheres and polyvinyl chloride oil drums containing wet sand and foam. Preliminary analysis indicates that the barrels can be seen even when they are on the seafloor. We have reached a stage rather like the earliest days of television: what is important is not the quality of the images but the fact that there are images at all. In the months ahead, we plan to replace the spherical reflector with a phased array containing as many as 1,000 hydrophones. At the same time, we shall be developing dedicated algorithms to provide image enhancement and automatic image recognition. These efforts will, we hope, improve the quality of acoustic-daylight images significantly and perhaps make the successors to ADONIS the underwater video cameras of the future.

The Authors

MICHAEL J. BUCKINGHAM, JOHN R. POTTER and CHAD L. EPIFANIO developed acoustic-daylight imaging at the Scripps Institution of Oceanography in La Jolla, Calif. Buckingham is professor of ocean acoustics there and holds a visiting professorship at the University of Southampton in England. He received his Ph.D. in physics from the University of Reading and has written and edited numerous articles and books on acoustics. An itinerant yachtsman, Potter sailed across the Pacific Ocean last fall to direct the Acoustic Research Laboratory of the National University of Singapore. After spending four summers on the Antarctic peninsula, he received his Ph.D. from the Council for National Academic Awards and the University of Cambridge. Epifanio is close to completing his Ph.D. on acoustic-daylight research at Scripps. He received his B.S. in electrical engineering from Bucknell University in 1991. The authors are grateful to Sea World in San Diego, to Hubbs Sea World Research Institute and to the U.S. Office of Naval Research for their research support.

Further Reading

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