BEYOND DISCOVERY™

THE PATH FROM RESEARCH TO HUMAN BENEFIT

Sounding Out the Ocean's Secrets

The oceans of Earth cover more than 70 percent of the planet's surface, yet, until quite recently, we knew less about their depths than we did about the surface of the Moon. Distant as it is, the Moon has been far more accessible to study because astronomers long have been able to look at its surface, first with the naked eye and then with the telescope—both instruments that focus light. And, with telescopes tuned to different wavelengths of light, modern astronomers can not only analyze Earth's atmosphere, but also determine the temperature and composition of the Sun or other stars many hundreds of light-years away. Until the twentieth century, however, no analogous instruments were available for the study of Earth's oceans: Light, which can travel trillions of miles through the vast vacuum of space, cannot penetrate very far in seawater.

It turns out that, for penetrating water, the phenomenon of choice is sound.

Had the world known how to harness the extraordinary ability of sound to travel through water in 1912, the Titanic *might have had some warning of the iceberg that sent the luxury liner to the bottom of the North Atlantic and took the lives of 1,522 passengers and crew. The tragic event spurred the development of tools for echolocation, or echo ranging—the technique of detecting distant objects by sending out pulses of sound and listening for the return echo. Using these tools, scientists and engineers went on to devise even more sophisticated instruments for finding submarines during both World Wars.*

Today, researchers apply their knowledge of how sound travels underwater to carry out myriad tasks, such as detecting nuclear explosions, earthquakes, and underwater volcanic eruptions. And just as astronomers use light to probe the secrets of the atmosphere, scientists in a field called acoustical oceanography use sound to study the temperature and structure of Earth's oceans—measurements crucial to our ability to understand global climate change. Researchers in biological acoustics also use sound to study the behavior of marine mammals and their responses to human-generated underwater noise, helping to guide policies for protecting ocean wildlife.

All of these modern uses of underwater acoustics are founded on investigative work, dating back centuries, into how sound behaves in the different media of air and water. These early investigations at first had no practical application; rather, they were pursued by curious researchers interested in a basic understanding of nature. As later investigators began to build on these foundations, however, they laid the groundwork for the development of tools and techniques that have widespread applications today.

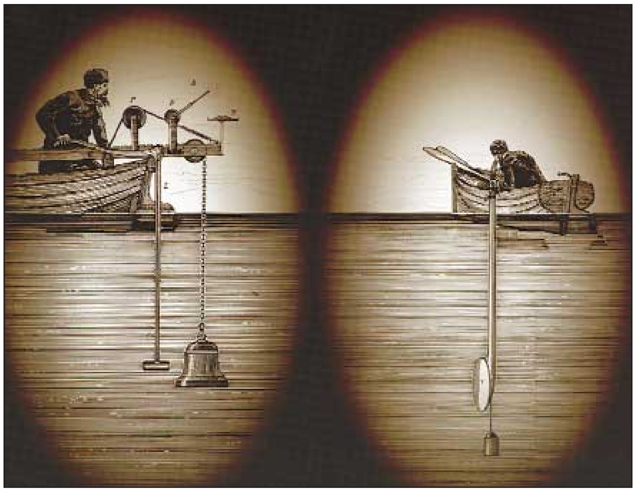
Water is an excellent medium for sound transmission. Sound travels almost five times faster in water than in air. © Digital Vision

Good Vibrations

Curious investigators long have been fascinated by sound and the way it travels in water. As early as 1490, Leonardo da Vinci observed: "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." In 1687, the first mathematical theory of sound propagation was published by Sir Isaac Newton in his *Philosophiae Naturalis Principia Mathematica.* Investigators were measuring the speed of sound in air beginning in the mid-seventeenth century, but it was not until 1826 that Daniel Colladon, a Swiss physicist, and Charles Sturm, a French mathematician, accurately measured its speed in water. Using a long tube to listen underwater (as da Vinci had suggested), they recorded how fast the sound of a submerged bell traveled across Lake Geneva. Their result—1,435 meters (1,569 yards) per second in water of 1.8 degrees Celsius (35 degrees Fahrenheit)—was only 3 meters per second off from the speed accepted today. What these investigators demonstrated was that water—whether fresh or salt—is an excellent medium for sound, transmitting it almost five times faster than its speed in air!

But how does sound travel? Sound is a physical phenomenon, produced when an object vibrates and generates a series of pressure waves that alternately compress and decompress the molecules of the air, water, or solid through which the waves travel. These cycles of compression and rarefaction, as the decompression is called, can be described in terms of their frequency, the number of wave *cycles per second*, expressed in Hertz. The human voice, for example, can generate frequencies between 100 and 10,000 Hertz and the human ear can detect frequencies of 20 to 20,000 Hertz. Dogs and bats are examples of many creatures that can hear sounds at much higher frequencies—up to 160,000 Hertz. Whales and elephants, at the other end of the spectrum, generate sounds at frequencies in the range of 15 to 35 Hertz, mostly below human hearing and thus called subsonic, or infrasonic. Sound waves, like light waves, also can be described in terms of their wavelength—the distance between the peaks of two waves; the lower the frequency, the longer the wavelength.

In 1877 and 1878, the British scientist John William Strutt, third Baron Rayleigh, published his two-volume seminal work, *The Theory of Sound*, often regarded as marking the beginning of the modern study of acoustics. The recipient of the Nobel Prize for Physics in 1904 for his successful isolation of the element argon, Lord Rayleigh made key discoveries in the fields of acoustics and optics that are critical to the theory of wave propagation in fluids. Among other things, Lord Rayleigh was the first to describe a sound wave as a mathematical equation (the basis of all theoretical work on acoustics) and the first to describe how small particles in the atmosphere scatter certain wavelengths of sunlight, a principle that also applies to the behavior of sound waves in water.



In 1826, Charles Sturm (left) and Daniel Colladon (right) made the first accurate measurement of the speed of sound in water. Sturm rang a submerged bell and Colladon used a stopwatch to note the length of time it took the sound to travel across Lake Geneva. Their measurement of 1,435 meters per second was only 3 meters per second off from the speed accepted today (reprinted with permission from the Acoustical Society of America).

Navigation by Sound

Through the ages, fishermen and seafarers had taken advantage of the way sound travels through water and used rudimentary techniques of echolocation. In the days of the ancient Phoenicians, for example, fishermen gauged the distance to a headland concealed by fog by making a loud noise, such as ringing bells, and listening for the echoes. By 1902, ships passing along the American coast were warned of hidden shoals by underwater bells placed on stationary lightships. Ten years later, the *Titanic* tragedy motivated the Submarine Signal Company of Boston (now part of Raytheon Company) and others to develop more active devices that would warn of icebergs and other navigational hazards. Within a week of the tragedy, L. R. Richardson filed a patent with the

British patent office for echo ranging with airborne sound, following a month later with a patent application for the underwater equivalent. The first functioning echo ranger, however, was patented in the United States in 1914 by Reginald A. Fessenden, who worked for the Submarine Signal Company. Fessenden's device was an electric oscillator that emitted a low-frequency noise, then switched to a receiver to listen for echoes; it was able to detect an iceberg underwater from 2 miles away, although it could not precisely determine its direction.

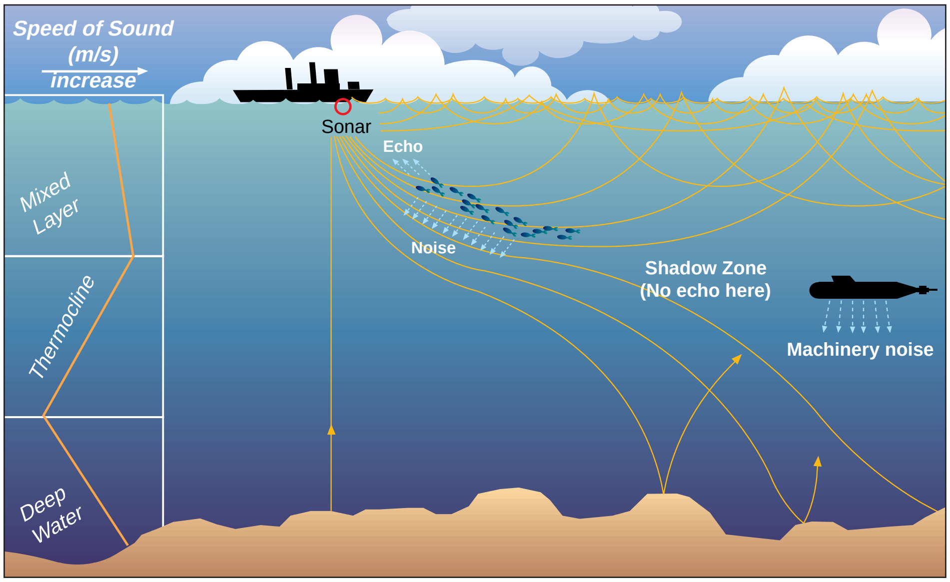
More sophisticated echo sounders were developed during World War I by the allies, but they were no match for the German U-boat menace because they could not locate and track a moving object. Shortly after the war, however, H. Lichte, a German scientist looking into using acoustics to clear German harbors of mines, offered a theory on the bending, or refracting, of sound waves in seawater that would provide clues to solving the difficulty. Building on work by Lord Rayleigh and an earlier Dutch astronomer named Willebrord Snell, Lichte theorized in 1919 that, just as light is refracted when it passes from one medium to another, sound waves would be refracted when they encountered slight changes in temperature, salinity, and pressure. He also suggested that ocean currents and changes in seasons would affect sound propagation. Unfortunately, Lichte was so far ahead of his time that his insights went unrecognized for almost six decades.

In the United States, efforts to develop more sophisticated echolocating devices continued between the wars under the guidance of Harvey C. Hayes of the Naval Engineering Experimental Station at Annapolis, Maryland. Hayes encouraged the U.S. Navy to play a role in civilian oceanography during peacetime, a collaboration that continues today. Thus, by the years just prior to the outbreak of World War II, U.S. naval ships were equipped with sonic depth finders as well as improved echo rangers called sonar (for sound navigation and ranging) that could pick up the noise of a submarine's propeller or an echo off a sub's hull from several thousand yards away. However, the devices were mysteriously unreliable. In the summer of 1937, officers aboard the *U.S.S. Semmes* were at a loss to explain or correct the ship's sonar problems during exercises in the waters off Guantánamo Bay, Cuba. For some reason, the performance of the devices consistently deteriorated in the afternoon; they sometimes failed to return echoes at all. The captain of the *Semmes* sought help from the Woods Hole Oceanographic Institution (WHOI) in Woods Hole, Massachusetts. Columbus Iselin, then associate director of WHOI, joined the *Semmes* with his laboratory's research ship, *Atlantis*, to investigate this puzzling "afternoon effect."

A Sound-Free Shadow Zone

The scientists had at their disposal a new device called a bathythermograph, or BT, invented in 1937 by Athelstan Spilhaus of WHOI and the Massachusetts Institute of Technology (MIT). The BT was a small torpedo-shaped device that held a temperature sensor and an element to detect changes in water pressure. Lowered overboard from a ship, the BT recorded pressure and temperature changes as it dropped through the water. Because the pressure in decibars is approximately equal to the depth in meters, technicians could correlate depth with temperature. Spilhaus thought his BT would have wide applications in learning many fundamentals about the ocean—the effect of temperature and depth on marine life, for instance, and the structure of ocean currents, especially the eddies along the

In the warm upper layer of the ocean, sound is refracted toward the surface. As sound waves travel deeper into colder water, they slow and are refracted downward, creating a shadow zone in which a submarine can hide (adapted from "Underwater Sound" by R. A. Frosch in International Science and Technology).



sides of grand currents such as the Gulf Stream. But Iselin and the U.S. Navy used the BT to make a different, and more immediately useful, discovery.

The BT readings demonstrated that by early afternoon, the sun had warmed a layer of surface water 5 to 9 meters (16 to 30 feet) thick until it was about 1 to 2 degrees Celsius (2 to 4 degrees Fahrenheit) warmer than the water beneath it. Below the surface layer, the water rapidly grew colder with depth. Knowing that the speed of sound increases with temperature, the scientists realized that signals from the ship's sonar would travel quickly through the warm layer and then slow dramatically when they hit the cooler layer below. They discovered that sound waves passing between layers with different properties underwent refraction, bending away from the region where sound travels faster and toward the region where its speed slows. This bending creates an acoustic "shadow zone," allowing any submarine positioned just beneath the dividing line between the warmer and cooler layers of water to become invisible to sonar signals (see diagram on page 3).

Columbus Iselin immediately recognized the significance of the acoustic shadow zone and the BT to submarine warfare. A submarine equipped with a BT could use it to determine where the shadow zone lay in relation to the pursuing ship, thus becoming nearly invisible to an enemy sonar. A sub chaser, for its part, could use a BT to opposite effect, adjusting the direction of its sonar to take into account the expected refraction.

During World War II, the BT became standard equipment on all U.S. Navy subs and vessels involved in antisubmarine warfare. Naval officers went to WHOI to learn how to use the BT, and oceanographers traveled to naval bases around the country to train battle-bound sailors. Submariners were directed to send all of their BT records to WHOI or to the University of California Division of War Research at Point Loma, where sonar charts were prepared and issued to the fleet.

Propagation of Sound in the Ocean

Once the war was over, the BT database provided a foundation for the kinds of basic ocean research Athelstan Spilhaus originally had in mind. In 1946, the U.S. Navy created the Office of Naval Research, which went on to become the premier funder of research in ocean acoustics. Scientists then resumed their investigations of the conditions that affect the propagation of an underwater sound signal.

A number of factors influence how far sound travels underwater and how long it lasts. For one, particles in seawater can reflect, scatter, and absorb certain frequencies of sound—just as certain wavelengths of light may be reflected, scattered, and absorbed by spe-

Advances in Underwater Acoustics

This timeline shows the chain of basic research that has led to a greater understanding of Earth's oceans through research in acoustical oceanography.

1490
Leonardo da Vinci notes how the sound of ships travels great distances underwater.

1687
Sir Isaac Newton publishes the first mathematical theory of sound propagation in *Philosophiae Naturalis Principia Mathematica*.

1826
Swiss physicist Daniel Colladon and French mathematician Charles Sturm measure the speed of sound in Lake Geneva at 1,435 meters per second—nearly five times faster than the speed of sound in air.

1877
Lord Rayleigh publishes *Theory of Sound*, laying the theoretical groundwork for modern acoustics.

1912
L. F. Richardson files a patent in Britain for echo ranging in water.

1914
Reginald A. Fessenden patents in the United States a new kind of transducer for echo ranging.

1919
German scientist H. Lichte theorizes that sound waves in water will refract upward or downward on encountering slight differences in temperature, salinity, and pressure.

1937
Athelstan Spilhaus builds the bathythermograph (BT).

cific types of particles in the atmosphere. Seawater absorbs 30 times the amount of sound absorbed by distilled water, with specific chemicals (such as magnesium sulfate and boric acid) damping out certain frequencies of sound. Researchers also learned that low-frequency sounds, whose long wavelengths generally pass over tiny particles, tend to travel farther without loss through absorption or scattering.

Further work on the effects of salinity, temperature, and pressure on the speed of sound underwater has yielded fascinating insights into the structure of the ocean. Speaking generally, the ocean is divided into horizontal layers in which sound speed is influenced more greatly by temperature in the upper regions and by pressure in the lower depths. At the surface is a sun-warmed upper layer, the actual temperature and thickness of which varies with the season. At midlatitudes, this layer tends to be isothermal, that is, the temperature tends to be uniform throughout the layer because the water is well mixed by the action of waves, winds, and convection currents; a sound signal moving down through this layer tends to travel at an almost constant speed. Next comes a transitional layer called the thermocline, in which temperature drops steadily with depth; as temperature falls, so does the speed of sound. However, at a point roughly 600 meters to 1 kilometer (0.4 to 0.5 miles) below the surface, further changes in temperature are slight (the water the rest of the way to the bottom is effectively isothermal). At that point, the dominant factor influencing the speed of sound is the increasing pressure, which causes sound to speed up.

A Sound Pipeline

In 1943, Maurice Ewing and J. L. Worzel at Columbia University conducted an experiment to test a theory Ewing had proposed a few years earlier. Ewing theorized that low-frequency waves, which are less vulnerable than higher frequencies to scattering and absorption, should be able to travel great distances, if the sound source is placed correctly. The researchers set off an underwater explosion of 1 pound of TNT in the Bahamas—and learned that it was detected easily by receivers 3,200 kilometers (2,000 miles) away on the coast of West Africa. In analyzing the results of this test, they discovered a kind of sound pipeline, which they called the sound fixing and ranging, or SOFAR, channel. Also known as the "deep sound channel," this pipeline was discovered independently by Russian acoustician Leonid Brekhovskikh of the Lebedev Physics Institute, who analyzed the signals received from underwater explosions in the Sea of Japan.

The scientists had found that, because of the laws of refraction, sound waves can be trapped effectively in a narrow channel that straddled a region of minimum speed where the bottom of the thermocline met the

1943
Maurice Ewing and J. L. Worzel of Columbia University discover the deep sound channel. Russian scientist Leonid Brekhovskikh, working independently in the Sea of Japan, discovers the same phenomenon.

1954-1955
The U.S. Navy activates the first-generation ocean-bottom listening devices in an array that eventually is called the Sound Surveillance System (SOSUS).

1978
Walter Munk of the Scripps Institution of Oceanography and Carl Wunsch of the Massachusetts Institute of Technology suggest mapping ocean temperatures three-dimensionally with sound.

1983-1989
John Spiesberger, now at Pennsylvania State University, and Kurt Metzger of the University of Michigan provide experimental verification that slight changes in acoustic travel time across an ocean basin indicate changes in average water temperature.

1991
In the Heard Island Feasibility Test, scientists from nine nations send sound 18,000 kilometers (11,000 miles) underwater through all of the oceans but the Arctic.

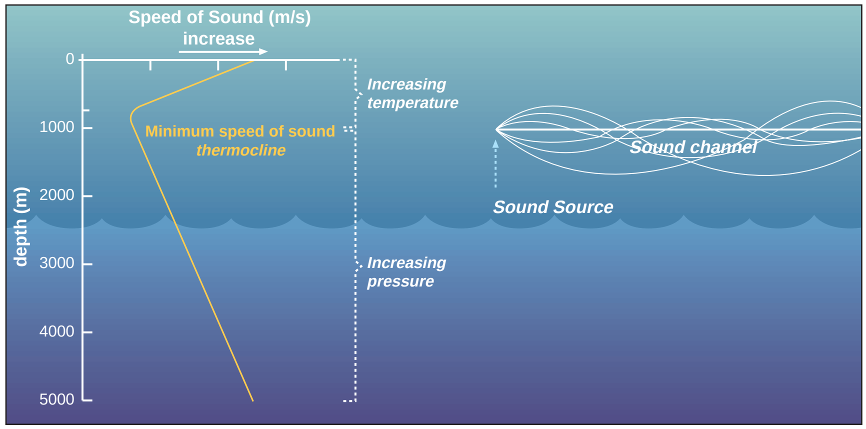
1992
Scientists begin to track whales in real time with the SOSUS.

1993
Using SOSUS, scientists make the first remote detection of an underwater volcanic eruption.

1996
The Acoustic Thermometry of Ocean Climate (ATOC) experiment begins to transmit sound in the northern Pacific Ocean.

1998
The Arctic Climate Observations using Underwater Sound (ACOUS) program begins regular sound transmissions in the Arctic Ocean.

top of the deep isothermic layer. As shown in the illustration, a sound wave traveling obliquely through the thermocline will bend downward as the speed of sound decreases, and then bend upward when increasing pressure causes sound to speed up—only to bend downward again toward the depth of minimum speed as warming temperatures cause sound velocity to increase. Sound introduced into this sound channel thus could travel thousands of miles horizontally with minimal loss of signal. The deep sound channel occurs at a depth that varies with ocean temperature; in the polar regions, for example, where the colder surface temperature brings the thermocline nearer to the surface, the deep sound channel approaches the surface as well.



The velocity of sound slows as the water temperature decreases approaching the thermocline. Beneath the thermocline the temperature is constant, but increasing pressure causes the speed of sound to increase (left). Because sound waves bend, or refract, toward the region of minimum velocity, changes in temperature or pressure cause the sound waves to bounce back and forth within a region called the deep sound channel (also known as the Sound Fixing and Ranging Channel). In this channel, sound travels long distances with minimal loss of signal.

The U.S. Navy was quick to appreciate the usefulness of low-frequency sound and the deep sound channel in extending the range at which it could detect submarines. In great secrecy during the 1950s, the U.S. Navy launched a project that went by the code name Jezebel; it would later come to be known as the Sound Surveillance System (SOSUS). The system involved arrays of underwater microphones, called hydrophones, that were placed on the ocean bottom and connected by cables to onshore processing centers. With SOSUS deployed in both deep and shallow waters along both coasts of North America and the British West Indies, the U.S. Navy not only could detect submarines in much of the northern hemisphere, it also could distinguish how many propellers a submarine had, whether it was conventional or nuclear, and sometimes even the class of sub.

Listening to the Ocean

With the end of the Cold War, the U.S. Navy permitted civilian scientists to use SOSUS for basic research, giving them access to information they could not get otherwise. Scientists now could apply underwater acoustics to learning more about the geology and biology of the ocean's murky depths. In 1990, Christopher Fox and his colleagues from the Pacific Marine Environmental Laboratory were part of the military's initial evaluation of this dual civilian-military use for SOSUS. Since 1991, Fox's team, working on VENTS, the Study of Hydrothermal Venting Systems, has been using SOSUS to pinpoint the location of underwater volcanic eruptions. This has given scientists a better picture of the events that occur along mid-ocean ridges—the mountain-like elevations where the ocean floor actually is being created from molten rock pushing up from below Earth's crust. (For more information on seafloor spreading, see the *Beyond Discovery* article "Restless Planet: Seafloor Spreading and Plate Tectonics".)

When Fox and his colleagues listened to the recordings of the underwater eruptions they also heard other underwater noises—including the vocalizations of baleen whales. The realization that SOSUS could be used to listen to whales also was made by Christopher Clark, a biological acoustician at Cornell University, when he first visited a SOSUS station in 1992. When Clark looked at the graphic representations of sound, scrolling 24 hours day, every day, he saw the voice patterns of blue, finback, minke, and humpback whales. He also could hear the sounds. Using a SOSUS receiver in the West Indies, he could hear whales that were 1,770 kilometers (1,100 miles) away.

Whales are the biggest of Earth's creatures. The blue whale, for example, can be 100 feet long and weigh as many tons. Yet these animals also are remarkably elusive. Scientists wishing to observe blue whales firsthand must wait in their ships for the whales to surface. A few whales have been tracked briefly in the wild this way but not for very great distances, and much about them remains unknown. Using the SOSUS stations, scientists can track the whales in real time and position them on a map. Moreover, they can track not just one whale at a time, but many creatures simultaneously throughout the North Atlantic and the eastern North Pacific. They also can learn to distinguish whale calls. For example, Fox and colleagues have detected changes in the calls of finback whales during different seasons and have found that blue whales in different regions of the Pacific ocean have different calls.

One of the most intriguing mysteries about whales is how they find their way across such vast distances. Christopher Clark is interested in whether whales, like dolphins and bats, echolocate. Rather than bounce sound off objects a few yards away, however, whales send their sound pinging off geologic structures hundreds of miles away. The theory that whales use their own sound to get their bearings has been around for some time; now the data from SOSUS tracking give Clark some compelling circumstantial evidence to support it. When he superimposed the SOSUS-made track of a whale on a map of the ocean floor, it looked as though the whale was slaloming from one underwater mountain to another, with these seamounts being hundreds of miles apart. He did a similar matchup with other whales and got the same results. Clark hypothesizes that whales use sound not just to communicate, but to navigate, that is, they map the ocean acoustically to find their way around in it.

Probing the Ocean Interior with Sound

SOSUS, with its vast reach, also has proved instrumental in obtaining information crucial to our understanding of Earth's weather and climate. Specifically, the system has enabled researchers to begin making ocean temperature measurements on a global scale—measurements that are key to puzzling out the workings of heat transfer between the ocean and the atmosphere. The ocean plays an enormous role in determining air temperature—the heat capacity in only the upper few meters of ocean is thought to be equal to all of the heat in the entire atmosphere.

Given increasing evidence of global warming, scientists around the world are struggling to determine how much of the observed warming trend is simply part of the natural climate cycle and how much has been caused by the burning of fossil fuels and other human activity. Current numerical models that simulate the global climate and predict climate change are hampered by insufficient temperature measurements in many areas of the globe, and especially below the ocean surface.

In 1978, Walter Munk of the Scripps Institution of Oceanography and Carl Wunsch of MIT suggested using the methodology of computer-aided tomography—the CAT scan—to study and monitor the ocean over distances of about 1,000 kilometers (600 miles). A medical CAT scan constructs a three-dimensional image by combining information from many different x-rays taken at different angles. The oceanic equivalent of a CAT scan—ocean acoustic tomography—would combine information from low-frequency sound instead of x-rays.

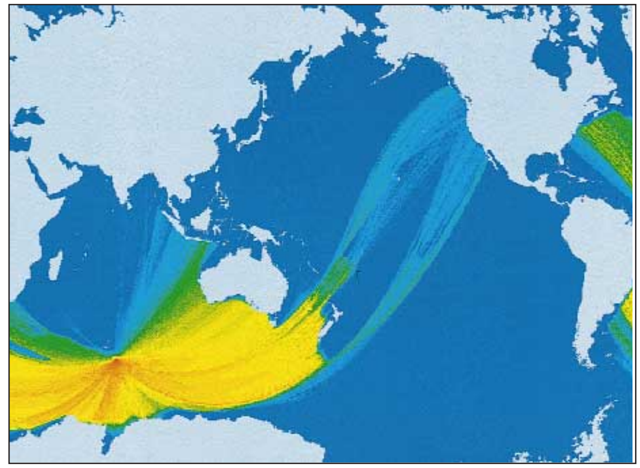
For sound waves traveling horizontally in the ocean, speed is largely a function of temperature. Thus, the travel time of a wave of sound between two points is a sensitive indicator of the average temperature along its path. Transmitting sound in numerous directions through the deep sound channel can give scientists measurements spanning vast areas of the globe. Thousands of sound paths in the ocean could be pieced together into a map of global ocean temperatures and, by repeating measurements along the same paths over time, scientists could track changes in temperature over months or years.

In 1983, John Spiesberger, now at Pennsylvania State University, and Kurt Metzger at the University of Michigan supplied the first experimental verification that tomography was possible across an entire ocean basin—much farther than Munk and Wunsch had proposed. Spiesberger and Metzger sent sound pulses 4,000 kilometers (2,300 miles) from a source on the seafloor off Oahu, Hawaii, to nine of the U.S. Navy's SOSUS listening arrays in the northeast Pacific. By repeating the experiment in 1987 and 1989, Spiesberger and Metzger demonstrated for the first time that extremely slight changes in acoustic travel time across an ocean basin reflect changes in water temperature along the sound path. A decrease of two-tenths of a second in travel time in this experiment was about equal to an average temperature rise of one-tenth of a degree Celsius.

In 1989, Munk and Andrew Forbes of the Commonwealth Scientific and Industrial Organization in Australia suggested transmitting sound globally on a regular basis for a decade to try to monitor climate change. To determine whether the signal would be stable enough to obtain measurements across half the globe, they placed a sound transmitter near Heard Island, an uninhabited Australian island in the southern Indian Ocean, with receivers in all oceans but the Arctic. For five days in January 1991, scientists from nine nations, led by the United States, transmitted sound from a ship off Heard Island. Sixteen listening sites picked up the signals in the deep sound channel from as far away as 18,000 kilometers (11,000 miles). Measuring temperature change was not an objective of this experiment, but the signals were tracked with enough fidelity to demonstrate that global tomography is possible.

The Heard Island experiment launched the Acoustic Thermometry of Ocean Climate (ATOC) project, led by Walter Munk at Scripps and involving scientists from 13 countries in 1992. A key objective is to establish baseline ocean temperatures in the Pacific against which changes can be measured. Because of concern about the effects that the sounds might have on marine mammals, the ATOC transmissions were delayed until 1996. However, in April 1994, a team of U.S. and Russian scientists led by Peter Mikhalevsky at Science Applications International Corporation transmitted sound across the Arctic Ocean and made a startling discovery. This Transarctic Acoustic Propagation (TAP) experiment not only proved the feasibility of long-range acoustic thermometry in the ice-covered Arctic, but the travel-time measurements revealed an average warming of approximately 0.4 degree Celsius [0.72 degrees Fahrenheit], when compared to historical temperature measurements, at the mid-depths of the Arctic Ocean along the propagation path. Extensive measurements by submarines and ice-breakers have subsequently documented this pervasive temperature change in the Arctic Ocean, which is now the focus of intensive new research. The TAP experiment launched the joint U.S. and Russian Arctic Climate Observations using Underwater Sound (ACOUS from the Greek, akouz, meaning "listen!") program in 1995. Although the pioneering ATOC program will end in 1999, ACOUS and other acoustic monitoring programs are continuing.

Researchers also are using other acoustic techniques to monitor climate. Oceanographer Jeff Nystuen at the University of Washington, for example, has explored the use of sound to measure rainfall over the ocean. Monitoring changing global rainfall patterns undoubtedly will contribute to understanding major climate change as well as the weather phenomenom known as El Niño. Since 1985, Nystuen has used hydrophones to listen to rain over the ocean, acoustically measuring not only the rainfall rate but also the rainfall type, from drizzle to thunderstorms. By using the sound of rain underwater as a "natural" rain gauge, the measurement of rainfall over the oceans will become available to climatologists.



In the Heard Island Feasibility Test, conducted in 1991, low pitched sounds originating offshore of Heard Island, in the Southern Indian Ocean, were detected more than 18,000 kilometers away (reprinted with permission from the Acousticial Society of America).

In the centuries since Leonardo da Vinci's inspired suggestion for listening to ships underwater, many researchers have contributed to the development of techniques that take advantage of the way sound travels through water. From military uses such as submarine warfare and detecting underwater explosions to scientific endeavors such as monitoring climate change and studying ocean wildlife, we have seen how modern society benefits from the investigations of those who pursued the answers to basic questions of the workings of nature.

This article was written by science writer Victoria Kaharl, with the assistance of Drs. David Bradley, Kenneth Brink, Christopher Clark, Christopher Fox, Peter Mikhalevsky, Walter Munk, Jeffrey Nystuen, and Gary Weir for **Beyond Discovery™: The Path from Research to Human Benefit,** *a project of the National Academy of Sciences.*

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