Acoustic Tomography of the Ocean

At a special session of the American Geophysical Union's spring meeting in early June,* oceanographers reported the first successful use of the oceanic equivalent of medicine's CAT scan to snap three-dimensional pictures of the temperature patterns of the sea. Both ocean acoustic tomography and a CAT (computerized axial tomography) scanner provide two-dimensional maps of slices taken through the object being studied, but most of the similarity ends there. The ocean version of tomography tested last year southwest of Bermuda consisted of stationary acoustic sources and receivers moored 2000 meters beneath the sea surface. The experimenters, who call themselves the Ocean Tomography Group,† moored four sources and five receivers around a 300-kilometer square, thus crisscrossing the study area with 20 different horizontal paths for acoustic signals to travel.

The stationary sources and receivers of the ocean tomography system can also slice the ocean into a vertical stack of layers because of a convenient coincidence. The interplay of decreasing temperature and increasing pressure with depth in the ocean creates a sound velocity minimum called the sound channel centered at a depth of about 1000 meters. The higher velocities outside the channel tend to refract sound back into it. This trapping effect forces part of a source's signal to follow a path that loops up through near-surface water, plunges several kilometers toward the bottom, and turns back to repeat the cycle. Other paths followed by the same signal form a spectrum of less extreme loops closer to the center of the sound channel. The result is a crisscross of vertical paths that sample different depths. When an appropriately coded signal arrives at a receiver along different paths, the path of each arrival can be identified.

Ocean tomography ultimately depends on differences in travel time over these multiple paths. Sound travel time in the ocean in turn depends primarily on the temperature along the path. Researchers can transform the travel times of signals across a tomography network into a map of temperature, using linear inverse theory. Seismologists developed much of this theory in order to unscramble seismic waves and deduce the structure of the earth.

Last year's experiment proved that the acoustic tomography concept is a practical one, at least under certain circumstances. Conventional observations from ship-lowered instruments and moored current meters mapped the same 100-kilometer-wide eddy of cold water that tomographic observations revealed. A major difference, says Peter Worcester of Scripps Institution of Oceanography, was that the group could construct a reliable map from each day's tomography data during the 4-month experiment but a single conventional survey with ship-lowered instruments required 18 days. The experimental results show that a number of such eddies could be mapped in a 1000-kilometer square, he says. A large tomographic array in some parts of the Atlantic could be used to track continuously the movement of eddies that carry heat and salt across the basin. Another possible application is monitoring the behavior of the Gulf Stream, he says.

Despite this initial success, mapping the ocean by acoustic tomography has definite limitations. Some areas, especially poleward of 55°N, have no sound channel at all. Some ocean features are marked less by temperature differences than by salinity differences, which do not greatly affect the speed of sound and are thus not detected.

Some ocean features may perturb acoustic signals too much to allow their straightforward mapping by tomography. In a paper delivered at the session, James Mercer and John Booker of the University of Washington, who are not group members, cautioned that the nonlinear effects of strong temperature contrasts could frustrate attempts to identify individual paths at the receiver. Although the eddy observed in the experiment, which was only 1.5°C colder than the surroundings, could not produce such effects, stronger eddies and Gulf Stream rings could, they said. Rings are pools of warm or cold water that spin off the Gulf Stream into the western Atlantic and have temperature contrasts of up to 9°C. Mercer and Booker also warned that, contrary to previous assumptions, temperature contrasts within an eddy can create new paths outside of it that significantly change travel times.

All in all, the method is not necessarily impractical over larger areas, they note, but it will be much more difficult than originally envisioned. The greatest problem, they and the tomography group agree, may be finding an economical balance between tomographic mapping and the periodic conventional surveys needed to identify paths initially and to keep track of them over long periods. Eventually, says Walter Munk of Scripps (the originator of the concept with Carl Wunsch of MIT), the best system for whole-ocean monitoring may be a combination of acoustic tomography, satellites, and sophisticated computer modeling.

After much discussion, the tomography group recently decided that instead of another mapping project, which had been contemplated for the Gulf Stream, the most exciting undertaking would be the application of their technique to the measurement of the average properties of a large section of the ocean. "There is just no other way to integrate over large areas," notes Worcester, "but there are other ways to monitor the Gulf Stream."

The group proposes to measure the temperature, layer by layer, of almost 2 million square kilometers of the northeast Pacific with a precision of 0.3 millidegree Celsius. Average currents along 1000-kilometer segments might be measured with a precision of 1.5 millimeters per second by the use of reciprocal transmissions between stations, according to Munk. It might be possible to determine seasonal and year-to-year changes in heat content, heat flux, upwelling, and vorticity, the latter being a crucial measure of the rotation of the gyres that dominate the large-scale circulation of ocean basins. An encouraging achievement during last year's experiment was the detection of the summer warming of surface water by a receiver located 1000 kilometers west of the main experiment site. Many physical oceanographers agree that the determination of such average properties, rather than mapping, could be the most rewarding application of ocean acoustic tomography.—RICHARD A. KERR

*Abstracts appeared in *Eos (Trans. Am. Geophys. Union)* **63**, 361 (1982).
†The Ocean Tomography Group consists of researchers from Scripps Institution of Oceanography, Woods Hole Oceanographic Institution, Massachusetts Institute of Technology (MIT), University of Michigan, and the Atlantic Oceanographic and Meteorological Laboratories, Miami.

0036-8075/82/0702-0038$01.00/0