Acoustic-Waveguide Sonar Finds Enormous Fish Shoals

Overfishing has devastated the oceans' stock of fish. Backscattered echoes of low-frequency signals may provide an accurate census of that stock.

In May 2001, MIT's Nicholas Makris and his then postdoctoral fellow Purnima Ratilal were searching for the ancient riverbeds buried within the continental shelf off the New Jersey coastline. Although hidden in muck when the sea level rose during the last ice age, those ancient channels had been previously mapped using high-frequency sonar that distinguished the slight density differences in the sediment. Researchers sent a signal, listened for its echo, and then deconvolved the spectral components to resolve underwater features.

Makris wondered if low-frequency sonar could tell whether those ancient features were also the source of acoustic clutter, anomalous backscattering prevalent in coastal regions.[1] But instead of the correlations some hoped to see between riverbeds and clutter, he, Ratilal, and their colleagues noticed puzzling and transient features—features that turned out to be gigantic shoals of tens of millions of fish, some assembled into an area 10 kilometers wide.

Although fish move and riverbeds don't, distinguishing the two in backscattered acoustic signals can be tricky. Shipping lanes along coastlines are noisy; the presence of turbulence, eddies, and tidal fluctuations can decorrelate acoustic modes; and the speed of sound varies with the ocean's temperature and salinity. Even small density variations between water layers form internal waves that cause sound waves to fluctuate (see reference 2 and the article by Bill Kuperman and Jim Lynch in PHYSICS TODAY, October 2004, page 55).

It took two years and a more controlled experiment for Makris's team to be sure that the dynamic changes produced by fish were not simply fixed features that, "like the glint on a spoon from a moving flashlight," as Makris puts it, were transient because of his ship's motion. The recently published account of the experiment details the structure and dynamics of perhaps the largest massing of animals imaged in nature.[3]

Highs and lows

During conventional acoustic surveys, researchers transmit high-frequency sound pulses vertically downward from a ship that moves slowly along narrow transects. Such surveys provide a record of the backscattered echoes from fish in a highly localized slice of ocean perhaps tens of meters wide. That approach has long provided local estimates of fish populations but is time-consuming and misses vast areas that fish may inhabit.

In shallow coastal shelves, where Makris's team worked, the ocean behaves like a waveguide that traps sound between the air and sea floor; the huge difference in density and sound speed at those interfaces causes sound to scatter and reflect with little attenuation. The entire water column acts like a plucked guitar string. Normal modes of the waveguide propagate and spread cylindrically, with intensities that fall off inversely with distance—far more slowly than the spherical spreading in conventional sonar geometries. Moreover, audio-frequency signals, at a few hundred hertz, suffer far less attenuation from absorption and scattering than the high-frequency signals of 20 to 100 kHz used in conventional sonar.

The waveguide properties of a coastline make it possible to send low-frequency signals and receive their scattered echoes over a huge range—thousands of square kilometers. Figure 1 illustrates Makris's technique: One ship, moored at sea, uses a vertical array of speakers to radially transmit a 1-second broadband chirp. A long array of hydrophones towed behind another ship, typically less than a few kilometers away, picks up the backscattered signals from all directions.

The challenge is to reconstruct what's in the sea. Essentially an underwater antenna, the receiver array is long compared to the wavelength and distinguishes which waves come from which directions by monitoring the delay in their arrival times at different points along the array. To make sense of all the convoluted returns, the researchers deconvolve the various ocean contributions to the original pulse. In effect, this "match filtering" selects echoes that closely resemble the original waveform template to maximize the signal-to-noise ratio. The recipe—basically multiplying the complex conjugate of the Fourier transform of the transmitted pulse with the transform of the received pulse—has the effect of taking all the signals over the bandwidth and compressing them. The pulse compression dramatically increases the temporal resolution.

The bare bones of Makris's imaging technique has been in the literature for decades. V. H. Lichte described the first rudimentary ocean acoustic waveguide in 1919, and the US Navy used long-range echo sounding to search for submarines even before World War II. David Weston first demonstrated the use of long-range active sonar along the Bristol Channel to detect fish shoals in the early

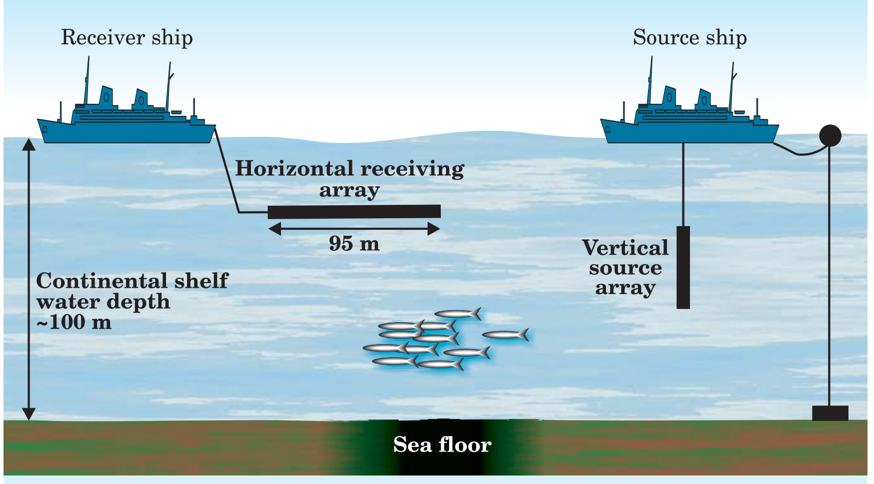

Figure 1. Acoustic waveguide imaging. A broadband signal, centered around 400 Hz and transmitted uniformly in azimuth from a vertical array of speakers, sets up normal modes in the water column. A horizontal array of hydrophones, towed on a separate ship a few kilometers away, picks up the backscattered signal, convoluted from its interaction with the ocean's surface and sea floor, fluctuating temperatures, internal waves, tidal fronts, and marine life. (Courtesy of Nicholas Makris.)

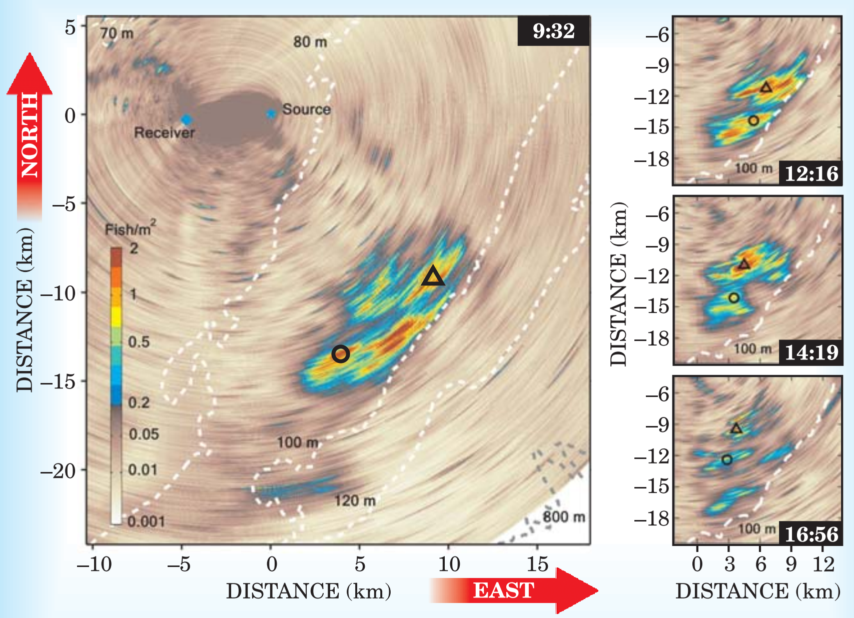

Figure 2. Areal population density of fish, estimated from scattered sound intensity, plotted as a function of position some 200 km south of Long Island, New York. Successive pictures are separate snapshots in time. The roughly 20–30 dB contrast between colored blobs and ocean background reveals the presence of fish shoals, and the two centroids (○, △) mark the presence of local clusters or schools whose movements were monitored. Dashes outline the ocean's depth. Shoal populations can fluctuate dramatically, particularly in mid to late afternoon when the shoal quickly fragments. Classic herring behavior, for instance, is to disperse toward the surface at sunset as light levels drop. Daytime hours find them hovering a few meters from the sea floor. (Adapted from ref. 3.)

1960s and was aware of the principal reason that fish scatter low frequencies so well—their swim bladders resonate at audio frequencies. J. S. M. Rusby later confirmed the fish backscattering in 1971 using a towed-array system to explore a Scottish inshore herring fishery.[4]

Acoustical processing has matured since then. Advances in modeling the way sound propagates and scatters in a fluctuating, range-dependent waveguide and better signal processing methods are largely what separate Makris's relatively high-resolution images of fish population density from the pioneering efforts of Weston and Rusby. Moreover, today's computers are fast enough to sort through the vast data within minutes and reconstruct snapshots of the ocean—even movies of how shoals change dynamically. It takes much longer for fish to swim across one of the roughly 30-m cells that form a pixel than for the acoustic waves, traveling at around 1500 m/s, to interact with everything in a typical wide-area image.

Consider the sequence of images in figure 2. Each picture registers measured echo intensities—corrected for propagation, intensity fluctuations, and varying sonar-resolution footprints—at a particular time as a function of position from the source and receiver arrays. To properly interpret those scattering intensities in terms of fish populations in areal views, Naval Research Laboratory biologist Redwood "Woody" Nero made conventional, line-transect measurements through the shoals in a separate vessel. Specifically, he measured the scattering strength of individual fish locally with high-frequency acoustics. That allowed the team to translate their audible-frequency intensity readings into population estimates.

At the moment, researchers must tolerate some uncertainty in that translation: It's difficult to reliably distinguish species, and scattering strength varies among species. Moreover, the resonance frequency of a swim bladder can vary with depth. Using nets to trawl for local samples can help, although that information comes with its own bias: Some species are far easier to catch than others. The likely suspects off the New Jersey coast include Atlantic herring, scup, hake, and black sea bass.

Still, Makris says that the team's population estimates are accurate to within 1 dB, and the dynamic range in the images spans more than three orders of magnitude.

School rules

Evolution has hardwired fish to congregate into schools, and those schools into larger shoals. The behavior maximizes eating opportunities and minimizes the risk of being eaten; herring, for instance, typically open their gill rakers wide and filter-feed on plankton for longer times and with less risk while swimming in groups. A large school also presents a confusing target to predators, as individual fish blur into the crowd. To combat a threat—a shark following closely behind the school, say—fish resort to defensive tactics. A compact school may suddenly explode like a hand grenade, whereby the fish dart off in all directions thanks to special nerve cells. Alternatively, individuals may gradually peel off from the school, just outside of visual range, only to reassemble somewhere behind the predator.[5]

Makris's team noticed the rapid fluctuations in shoal populations, whether in response to predation or some other prompt, that bear out such behavior dynamics. The numbers could vary by as much as 20% over the course of a few minutes as a few million fish were observed to migrate between schools within the shoal or through narrow bridges that briefly connect one region to another.

The behavior is tied to the evolutionary preference of fish to quickly assemble and reassemble into schools, explains Tony Pitcher of the University of British Columbia's Fishery Centre. Indeed, schooling fish are biologically adapted to copy the movements of their neighbors. Special sensory hairs in a fish's lateral line system, located within shallow canals just below its skin and scales, pick up transient pressure waves from close neighbors.

Uwe Kils, while working at the Institute for Marine Research in Kiel, Germany, realized in the late 1980s that the evolutionary behavior goes beyond simply maintaining a school's organizational coherence. It can serve to pass a signal through the school, an effect Kils termed synchrokinesis. As a few fish quickly turn to avoid a predator, say, nearby ones follow suit as the pressure wave travels through the crowd. Such fish density waves can exceed the typical speed at which fish swim by an order of magnitude, Makris says. Monitoring the large-scale internal motion and migration patterns in shoals should address the degree of coordination and interaction between different species that may coexist in shoals in the wild.

Apparently, what happens at small scales also happens at large scales. Makris's observation of synchrokinesis, structure, and rapid reassembly dynamics at large scales bears out what biologists have observed in far smaller schools—on a scale of tens of meters.

The preference to rapidly form large shoals from smaller subunits makes fish populations especially vulnerable to overfishing, cautions Pitcher. Even though overfishing has diluted the stock of fish in the world's oceans to roughly 1% of estimated abundances 100 years ago, fishermen remain able to reach their catch quotas. The trick lies in finding the shoals, whose individual densities may be little changed. The true depletion in fish stock may then appear invisible even to the fishermen, as populations shrink under their feet. Pitcher remains sanguine, arguing that what fishery regulators really want—an accurate record of the biomass in the oceans—is within reach.

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Gravitational Microlensing Reveals the Lightest Exoplanet Yet Found

Earth-like planets halfway across the galaxy can disclose themselves by bending light from background stars.

Since 1995, almost 200 extrasolar planets have made themselves known by spectral Doppler oscillation as they tug their host stars to and fro. In the last two years, a very different technique—gravitational microlensing—has revealed only three planets. But the most recent microlensing discovery makes clear the special advantages of that technique for finding Earth-like planets. In January, a worldwide collaboration of three microlensing groups—PLANET, OGLE, and MOA—reported[1] the discovery of a planet of roughly 5.5 Earth masses ($M_\oplus$) circling a red-dwarf star with an orbital radius of about 2.6 astronomical units (1 AU is Earth's orbital radius). It's the lightest extrasolar planet ever discovered.

The great majority of the planets found by the Doppler method have been Jupiter-like gas giants, two or three orders of magnitude heavier than Earth. That's because the amplitude of the telltale Doppler oscillation of the host star's spectrum increases as the mass of the planet that's making it wobble. The technique also favors planets much closer to their hosts than 1 AU; the Doppler oscillation amplitude increases with proximity, and close-in planets, with orbital periods of days or weeks rather than years, can be discerned in comparably brief observations.

Even before the recent announcement of the 5.5-$M_\oplus$ planet, simulations had suggested that microlensing could reveal planets substantially lighter than Earth.[2] Furthermore, for typical microlensing events within our galaxy, the technique is most sensitive for planets orbiting a few AU from their stars. Hence the fond hope that microlensing would soon discover Earth-like planets. It's not just a matter of loneliness or geochauvinism. Discovering the relative abundance of gas giants and Earth-like rocky planets around different kinds of stars is important for testing theories of planet formation.

Gravitational microlensing

The deflection of light by gravitation is a central feature of general relativity. The historic 1919 solar-eclipse observation of the deflection of starlight by the Sun made Albert Einstein and his theory famous. In 1936 he pointed out that the image of a stellar source perfectly aligned behind a foreground