

Acoustic reflections on marine populations

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Armed with a simple diffraction-based model, an acoustic oceanographer can bounce sound off marine animals to learn important information about their size and orientation.

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Monitoring populations of marine animals has never been easy. Yet nowadays, as global natural resources become ever more depleted, tracking our precious marine animal populations is vitally important as part of a program of ecosystem management. The Gulf of Mexico oil spill and its resultant effects, to cite one instance, highlight how accurate information about marine populations is paramount to the management of oil drilling and the promotion of healthy ecosystem recovery.

Marine conservationists who oversee ecosystems—commercially viable fish stocks, for example, but especially federal- and state-protected areas—are in need of tools that will help them acquire better information about their status. Physicists can provide essential assistance in helping them to understand and implement the necessary measures to restore ecosystems. Modeling the dynamics of those systems, measuring the rates of individual biophysical properties, and helping to invent new technologies are only a few examples of the contributions we can make.

A curious feature

The need to detect objects in the marine environment was highlighted one foggy night when the *Titanic* collided with an iceberg and sank. The ensuing development of sonar (sound navigation and ranging) enabled measurement of the ocean depth and, during World War II, assisted the allied detection of deadly Nazi U-boats. Early on, a curious feature of the sound reflected from a downward-looking echo sounder was attributed to animals suspended in the water column. The practice of studying marine populations by bouncing sound off them was born shortly thereafter.

A key advantage of acoustic over other remote-sensing techniques such as those that use light is that sound can sense much farther in the marine environment—up to hundreds of meters for a variety of marine organisms, including fish and plankton. Presently, various people use commercial and scientific sonars to detect biological targets; examples include recreational and commercial fishers as well as surveyors whose goal is to obtain quantitative estimates of marine populations for management decisions.

For quantitative purposes, one usually calibrates the sonar so that the energy density of sound incident on the animals is known. The reflectivity of the targets—on the sea floor or suspended in the water column—can be measured as the fraction of energy reflected, a quantity that over a useful range is independent of the actual level of incident sound. The job of the bioacoustic oceanographer is to infer valuable information about the population of animals from those reflections.

So, how well can we do? In brief, not bad, but we could do better. Abundance (that is, number density) estimates for herring, pollock, and whiting, for example, are likely within 25% of the natural densities. However, marine surveys often suffer from interpretational ambiguities, since the acoustic reflectors can be animals, air bubbles, or even suspended particles. Furthermore, as we discuss below, animal orientation can affect the strength of the reflected energy; for long skinny things like fish, the intensity of backscattered sound typically varies by several orders of magnitude as orientation changes. In the mixed assemblages encountered in many important situations, it may be difficult to tell what kind of creature is observed. Moreover, abundance estimates are complicated by the fact that lots of small animals that are extremely close together can appear as a single, big one.

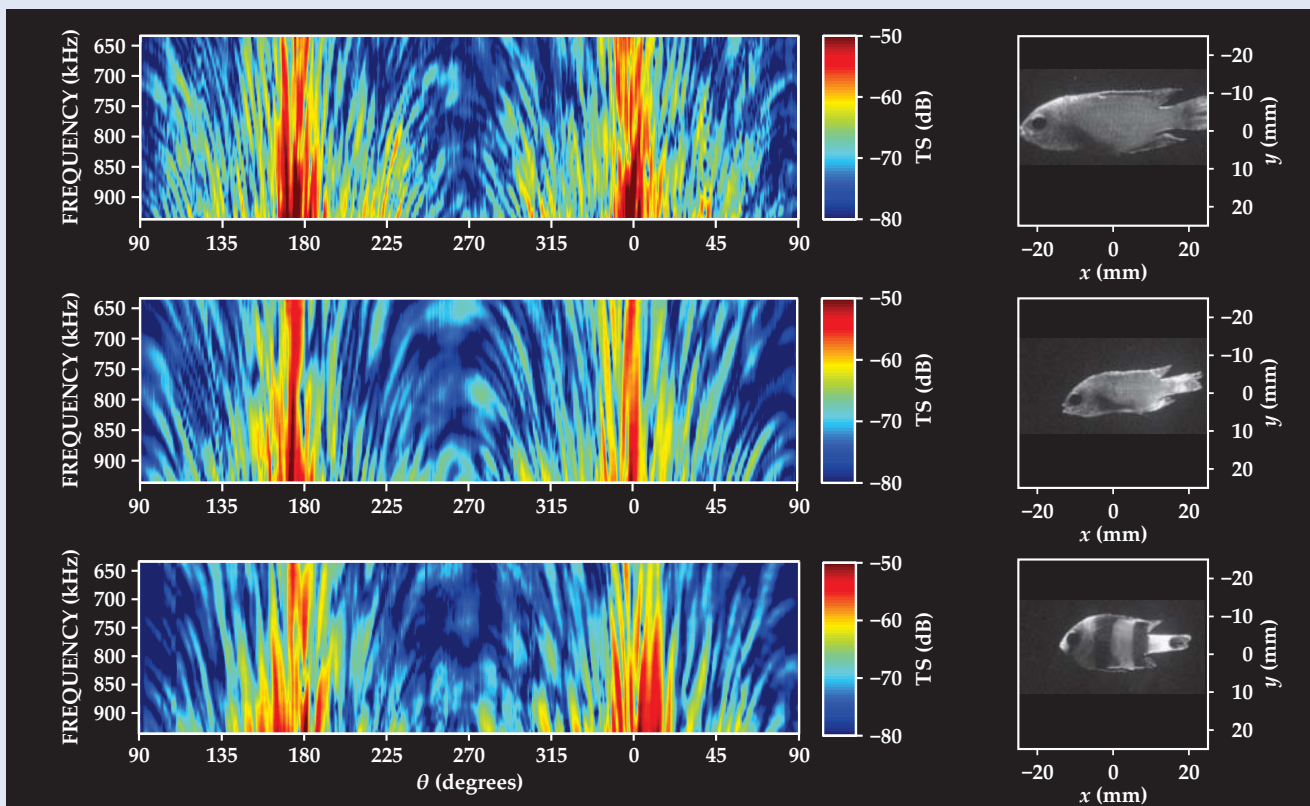
How we might do better

As a first step in better surveying marine populations it is natural to look for accessible degrees of freedom not currently exploited in the typical measuring process. For example, if one were to measure the fractional reflectivity of an animal at many frequencies and from many directions, could the resulting angular backscatter spectrum improve the capability to discern size, or even species? Although a field-deployable system may not be able to measure a full-angle wideband spectrum, a knowledge of the potential benefits could guide the development of future instruments. To explore the possibilities we fabricated a lab system that allowed us to measure the complete angular backscatter spectra of live animals. The figure shows the results of those measurements for three fish.

One can think of the pictures as acoustic signatures, or fingerprints. The top two correspond to fish of the same species but of different size, whereas the bottom two correspond to animals that are about the same size but of different species. Supposing that bioacoustic oceanographers were able to obtain such fingerprints in real-world settings, what would people do with the data? The answer to that question lies in the future. For the present, the two of us are working to construct simple models that can help us infer more information about animal size and type.

Bars and spokes

A set of data collected by Kenneth Foote in the 1980s established the foundation for our work. Foote's experiment consisted of tilting a fish, looking from above, and measuring the intensity of the reflected energy as a function of tilt angle at four frequencies. The acoustic scatter arises from differences in the acoustic impedance (the product of the sound speed and



Acoustic fingerprints of fish. The three colorful spectra show a quantity called target strength (TS). Measured in decibels (dB), target strength is a logarithmic measure of the fraction of backscattered sound. Here it is presented as a function of frequency and animal orientation to yield what are called angular backscatter spectra. The top two spectra were obtained for two blue damselfish of different size, the bottom spectrum from a four-stripe damselfish; see the photos to the right. Note that the target strength is a maximum at values of 0° and 180° , when the head–tail axis of the animal is broadside to the acoustic beam. The reflectivity is minimal when the animal is either head-on (90°) or tail-on (270°).

density) between the fish's body, its internal features, and the surrounding water. As an optical analogy, think of changes in refractive index leading to reflection and refraction.

In a great many cases, the acoustic reflection from a fish's swim bladder, an air-filled sac that is used to adjust buoyancy, dominates the reflected energy. That's simply because the sound speed and density of the swim bladder are very different from those of the surroundings. Assuming that the swim bladder was the major reflector, one of us (Jaffe) hypothesized that it could be approximated as a bar and compared the scatter patterns predicted via simple diffraction theory with those obtained by Foote. A best match occurred when the lengths of the bar and the animal's swim bladder were within 10%.

The synthetic data generated by the bar model share many features with the live-fish data shown in the figure. For example, both model and measured data predict maximal reflection at 0° or 180° (broadside) and a series of spokes that curve away from the broadside reflection.

Inspired by the similarity of those patterns, we devised and tested an algorithm designed to infer animal orientation from a small set of angular observations in the recorded backscatter spectrum. The basic idea follows from the observation that to a large extent for the model, and to some extent for the data as well, the spokes are perpendicular to animal orientation. So, for example, at broadside, when the animal is horizontal, the spokes point vertically. Since the gradient operator computes the direction of steepest descent—here, the direction perpendicular to the spoke—we tested whether applying that operator to the two-dimensional angular

backscatter spectrum would be a good way to estimate the direction in which the animal points. The details of the implementation are a bit too lengthy to be described here, but the bottom line is that we were able to determine orientation to within an error of about 9° .

Will diffraction theory come to be used to infer important properties of marine animals in their natural environment? As we have discussed, concepts from the theory can already be applied to a simple bar model that embodies important features of the frequency- and angle-dependent acoustic reflections from fish. It is, of course, impossible to predict exactly what elements will be incorporated in a future system to characterize marine animals, but based on the results we've obtained we would venture to say that the answer to the question is yes.

Additional resources

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