Remote sensing of fish

With the worldwide decline of fish in the oceans, it is important to be able to remotely image and monitor fish populations, as well as accurately estimate their abundances. A better understanding of the behavior and dynamics of fish populations, including their response to environmental and anthropogenic pressures, is essential for effective management of marine fisheries. Recently, an acoustic imaging technique was developed, called ocean acoustic wave-guide remote sensing (OAWRS), for instantaneously imaging and rapidly locating fish and other biomass in the ocean over wide areas spanning the continental shelf. This new technology will influence the way in which fish and other biological organisms in the ocean are surveyed and studied. It will provide a more global approach for studying fish and marine ecosystems, analogous to an optical or radar satellite system for sensing the Earth's surface.

In the ocean, sound can travel much greater distances with far less absorption than light and any other form of radiation. Under water, limited visibility makes sound the primary means for remote sensing and imaging. Marine mammals, dolphins, and whales naturally use sound to echolocate food, to navigate their surroundings, and to communicate. Devices and instruments that use sound to probe the ocean environment are called sonars. Since the 1930s, sonars have been used to detect and study the abundances and behavior of fish and other biological organisms in the ocean.

All fish-finding sonars consist of one or more projectors that generate a short burst of sound. The sound travels through the water column until it is reflected and scattered off fish (fish echo) and then received by one or more underwater microphones called hydrophones. A projector that can also receive echo signals is called a transducer. Based on the travel time of the received echoes, the distance of the fish from the sonar system can be determined. A sonar system's range of detection depends on the frequency of sound it transmits. Lower sound frequencies undergo less absorption and can travel longer ranges and detect more distant objects than higher sound frequencies. Most fish have air-filled swim bladders, which are responsible for reflecting over 90% of the acoustic energy incident on them. Some fish, such as the Atlantic mackerel, have no swim bladder but still scatter sound with their bone and flesh, producing weaker echoes.

Conventional fish-finding sonars

Until recently, the standard technique for surveying fish used a combination of capture-trawl methods, along with acoustic surveys with a high-frequency echo sounder. An echo sounder is a device with a narrow acoustic beam, like a searchlight, that is directed vertically downward. It is towed by a ship along line transects typically several to tens of kilometers apart in a back-and-forth pattern to produce images of the ocean in depth and range along the ship's track (Fig.1). Echo sounders have been used commercially for finding fish since the 1950s, and they operate at high frequencies, above 20 kHz and up to 600 kHz. The survey rates of echo sounders are small, typically 0.2 km^2/h (0.08 mi^2/h). This rate is determined by the resolution footprint, or insonified area, of the echo sounder at any instant, which is highly localized to within several tens of meters of the tow ship and by the tow speed of roughly 5 m/s (16 ft/s). As a result, echo sounders tend to undersample the environment in both time and space, leaving highly aliased and ambiguous records of fish activity and abundances. Since the 1970s, side-scan sonars have been used to image fish. The side-scan sonar uses two echo sounders to project the sound beam sideways from the ship, providing a horizontal aerial coverage that is roughly 10 times larger than a conventional echo sounder along the ship track. In the late 1980s, multibeam sonars were developed with multiple sound beams pointing in many different directions to provide wider angular coverage of the water column surrounding the sonar. This enabled the system to image both pelagic and demersal fish, which are found close to the sea surface or sea bottom, respectively. The multibeam sonar extends the two-dimensional imaging of the echo sounder to allow limited three-dimensional imaging of the morphology of a fish school. The conventional fish-finding sonars (CFFS), described so far, rely on direct water-borne propagation paths from the sonar to an object. As a result, the maximum detection ranges for these systems are limited to within roughly a kilometer of the survey vessel. For surveying large areas of the ocean, the biggest challenge in using CFFS, due to their limited aerial coverage, is to figure out exactly where the fish are located. Since conventional sonar systems are not capable of distinguishing fish species from their echoes, capture-trawl sampling methods are necessary for classifying the fish groups.

Ocean acoustic waveguide remote sensing

In recent years, ocean acoustic waveguide remote sensing (OAWRS) has been developed and applied to study fish populations on the New Jersey continental shelf (Fig.2). For the first time, it revealed the instantaneous horizontal structural characteristics of a very large fish shoal (school) spanning several tens to a hundred square kilometers in area, and the evolution of the shoal over time. The technique uses the ocean as a waveguide to channel sound over very long ranges, imaging the ocean at about a million times greater rate than conventional fish-finding methods. OAWRS uses a vertical source array to transmit a short broadband pulse at low frequencies (several hundred hertz up to several kilohertz) that spreads out omnidirectionally in a horizontal azimuth. The sound waves reflect from the sea surface and bottom to form standing waves in depth that are called waveguide modes, analogous to the modes of a vibrating guitar string. These modes propagate outward in range, suffering only cylindrical spreading loss rather than the spherical loss of the CFFS. Return echoes from fish and other environmental features are continuously received on a horizontal array of hydrophones that can be either towed from a ship (Fig.2) or deployed as a fixed structure off the sea floor. The echoes are charted in horizontal range from the receiving array using match filtering over the two-way travel time of the signal and in bearing, or horizontal azimuth, by plane-wave beamforming. Match filtering is a pulse compression technique that matches the return echoes with the original transmitted pulse over the signal bandwidth, which greatly improves the range resolution of the system. Beamforming is a method that utilizes delay in the arrival time of a signal, measured by the hydrophones on an array, to determine the bearing of the signal. The resulting image is an instantaneous snapshot of the ocean environment over the two-way travel time of the echoes. The instantaneous aerial coverage of OAWRS is roughly circular with typical diameters of 60 and 120 km (37 and 74 mi), corresponding to the maximum two-way travel times of 40 and 80 s, respectively, for a sound speed of 1500 m/s (4900 ft/s) [Fig.2]. In the OAWRS system, sound is propagated to ranges about ten to a thousand times the waveguide depth, to image fish. It readily provides fish localizations horizontally, but it can be challenging to determine the depth location of fish in the water column with this system.

OAWRS was used during an experiment on May 14, 2003. As a result, a typical snapshot of the continental shelf environment on the east coast of the United States is shown in Fig.3. The image reveals the instantaneous horizontal morphology of a very large fish shoal, representing probably the largest mass of animals ever imaged instantaneously. Several population centers interconnected by fish bridges through which the fish migrate can be seen in the image. OAWRS measurements of fish distribution were found to be in good correspondence with measurements made concurrently along line-transect surveys of the shoal with a conventional echo sounder. The OAWRS imagery also revealed that fish in large shoals and smaller fish groups are structurally similar, with spatial distributions that follow a fractal or power-law spectral process. This enables accurate statistical predictions to be made of the instantaneous spatial distribution of fish populations over wide areas. Movies were made of the ocean environment by concatenating OAWRS imagery at a 50-s update rate, which provided information of the temporal evolution, behavior, and dynamics of such a massive shoal, again for the first time. Clustering, fragmentation, and dispersal of fish groups were found to occur over time scales of 5-10 min. This showed that OAWRS can provide an image of a fish population that is unaliased in both time and space, and that the temporal and spatial variations of large fish groups and shoals are too rapid to be tracked using CFFS methods. Fish density waves were observed in the movies, with speeds of up to 10 m/s (33 ft/s) due to a sequence of localized compaction and expansion events within the dense population centers. These density waves were found to propagate over the coherence width of the population centers of roughly 1-3 km (0.6-2 mi) before bouncing off the boundaries of this region. The waves may be used by fish to sense the spatial extent and maintain the coherence of the locally dense subgroup. They may also be used for communication, for instance, in response to predation. In Fig.3, the fish species imaged by the OAWRS system are likely to be Atlantic herring, scup, hake, and black sea bass, based on annual trawl surveys in the area, along with visual observations made during the experiment.

Fish classification and abundance estimation

One of the challenges in fish research is to remotely identify fish species, characterize their sizes, and make estimates of their abundances in a given region. In CFFS systems, the echo returned from an individual fish is highly dependent upon the aspect of the fish imaged, relative to the sonar beam. This is because at high operating frequencies most fish have bodies and swim bladders that are large compared to the acoustic wavelength, making them highly directional scatterers. There is also shadowing of the acoustic waves from one fish to the next and multiple scattering in dense fish groups that must be accounted for with these systems. This, combined with the fact that the survey rates for CFFS are small, makes estimation of fish abundances challenging, since abundances need to be extrapolated to the vast areas where data are not available from these systems.

One advantage of the OAWRS system is that it uses low acoustic frequencies for imaging, and fish are compact and small compared to the acoustic wavelength. As a result, the scattering from fish becomes omnidirectional for both the swim bladder and body, independent of the fish aspect. Shadowing of the incident acoustic waves is also negligible at low frequencies. These advantages and the fact that entire fish shoals can be instantaneously imaged over very wide areas with OAWRS without temporal aliasing allow estimates of fish abundances to be made more readily.

All current sonar technologies, both CFFS and OAWRS, require the fish imaged to be identified and statistically characterized in order to make reliable estimates of abundances from the acoustic imagery. Apart from capture-trawl sampling of fish, fish groups may be identified using remote acoustic sensing methods. Most swim-bladder-bearing fish have acoustic resonance frequencies for scattering at less than 5 kHz for fish several tens of centimeters long. To characterize the fish, multifrequency systems can be used to measure the resonance frequency of the fish group. Many factors, such as bathymetric migration and feeding, may affect the resonance within the fish group, which must be taken into account. Other methods use the spatial distribution, intensity, oceanographic and environmental correlation, along with dynamics of the fish group echo for species identification and classification.

Future fish surveys

Fish-finding sonars have evolved over the last 70 years from the initial simple high-frequency echo sounders that survey the water column locally in depth, to the recently developed and more sophisticated low-frequency OAWRS system that can instantaneously image environments covering thousands of square miles. It is now possible to explore the ocean with various technologies of different capabilities to remotely map and study fish and marine ecosystems.

We envisage that in the near future the low-frequency OAWRS system will be deployed in various regions of the ocean as a wide-area system to remotely locate and monitor fish and other biomasses from long ranges. Higher-resolution local investigation of the depth distribution and classification of these dense biomass regions may be provided by high-frequency echo sounders and multibeam acoustic systems, along with underwater video cameras. These devices may be dynamically deployed from mobile platforms, ships, and submersibles or mounted off the sea bottom. The unaliased spatial and temporal mapping of the ocean with OAWRS, combined and integrated with data from high-frequency sonars and video imagery, can provide the knowledge base needed for more accurate and reliable studies of fish behavior, dynamics, and abundances.

See also: Continental margin; Echo sounder; Hydrophone; Marine biological sampling; Marine ecology; Marine fisheries; Matched-field processing; Population ecology; Remote sensing; Sonar; Underwater sound; Waveguide

Purnima Ratilal

Deanelle T. Symonds

How to cite this article

Suggested citation for this article:

Purnima Ratilal, Deanelle T. Symonds, "Remote sensing of fish", in AccessScience@McGraw-Hill, http://www.accessscience.com, DOI 10.1036/1097-8542.YB071610, last modified: April 12, 2007.

For Further Study

Topic Page: Earth Science: Oceanography