Continuous Monitoring of Fish Population and Behavior by Instantaneous Continental-Shelf-Scale Imaging with Ocean-Waveguide Acoustics

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Award Number: N00014

LONG-TERM GOALS

The long-term goals of this program are to (1) instantaneously detect, image and spatially chart fish populations over continental-shelf scales, and (2) continuously monitor the areal densities and behavior of these fish populations over time using a novel audible frequency acoustic system (300-5000Hz) referred to as Ocean Acoustic Waveguide Remote Sensing (OAWRS). This new method is being applied to explore the abundance, temporal and spatial distributions and behavior of fish populations in the Gulf of Maine on and near Georges Bank, a marine ecosystem being studied in the Census of Marine Life program. OAWRS is a valuable conservation tool for rapid imaging and enumeration of large scale fish populations over thousands of square kilometers to effectively monitor and manage the national fish stock.

OBJECTIVES

The primary objectives of this proposal are:

- Conduct a major multi-institutional offshore oceanographic experiment to explore the population distributions and behavior of living marine fish in the Gulf of Maine on and near Georges Bank with the new OAWRS technology.
- To specifically monitor the temporal and spatial population densities of herring, a fish of major ecological and commercial importance, on the northern flank of the George’s Bank, where they are known to congregate in large quantities.
- To test this new OAWRS technology with simultaneous line-transect methods using both conventional fish finding sonar (CFFS) and directed capture sampling with nets.
- To use the OAWRS technology in conjunction with an official US National Marine Fisheries Service Survey, in particular the Annual Herring Survey in Georges Bank and the Gulf of Maine, to enable quantitative comparison.
- To investigate the limits of taxonomic resolution inherent to the OAWRS system, and to use OAWRS imagery to assess the taxonomic limits of more conventional systems that rely upon sparse line-transect surveys that significantly under-sample fish populations in time and space.
- To use the spatial distributions and behavior detected by OAWRS to more quantitatively calibrate abundance estimates made by under-sampled line transect methods employing CFFS and capture by net and trawl and to determine optimal temporal and spatial scales of sampling.

- To study the diurnal behavior of fish over wide areas in the Georges Bank and Gulf of Maine region with data unaliased in space or time.

APPROACH

We have developed an underwater remote sensing technology for instantaneously detecting, locating and imaging fish populations over thousands of square kilometers in continental-shelf environments [Makris et al, Science 311, 660-663 (Feb. 3, 2006)]. Our new approach surveys at an areal rate roughly orders of magnitude greater than that of conventional fish finding methods. It does so by utilizing the ocean as an acoustic waveguide for efficient long-range propagation. With the technique, which we call Ocean Acoustic Waveguide Remote Sensing (OAWRS), we can continuously monitor fish population dynamics, behavior and abundance with minute to minute updates, producing records *unaliased* in space and time (essentially wide-area movies) that are valuable in the study of ocean ecology, conservation of ocean life, and preservation of marine fisheries.

With the "first look" of OAWRS in an experiment of the ONR Geoclutter Program in 2003, we were able to make a number of fundamental scientific discoveries about the (i) instantaneous horizontal structural characteristics, (ii) temporal evolution and (iii) propagation of information in very large fish shoals. These include the findings that: the instantaneous spatial distribution of fish over wide areas follows a fractal or power law process, so that structural similarity exits at all scales from meters to tens of kilometers (previously evidence for structural similarity existed only for small scales, tens of meters or less); large shoals are far more horizontally contiguous in 2-D than was previously believed based on 1-D line transect methods which inaccurately portray them as disjoint clusters; the temporal autocorrelation scale of population change within a very large shoal is extremely short, on the order of minutes, which is why fish shoals can suddenly disappear from conventional survey vessels; temporal fluctuations in shoal population also follow a power-law process, making them far more predictable; and fish density waves regularly propagate information over kilometer scales, orders of magnitude larger than previously observed, at speeds an order of magnitude faster than fish can swim, which apparently help large shoals remain cohesive. These observations were made from distances typically greater than 10 km from the shoals with sound at least three orders of magnitude less intense than conventional fish finding sonar.

This is possible because underwater-acoustic remote sensing in the ocean relies on the capacity of the continental-shelf environment to behave as an acoustic waveguide where sound propagates over long ranges via trapped modes that suffer only cylindrical spreading loss rather than the spherical loss suffered in conventional fish finding sonar technologies. OAWRS uses sound typically three orders of magnitude less intense than CFFS. Waveguide modes are excited by a moored vertical source array. Scattered returns are received by a horizontally towed line array and charted to form images in range by temporal matched filtering and in azimuth by plane-wave beamforming. OAWRS range resolution is $r=c/(2B)$ where c is the mean ocean sound speed during an experiment, and B is the bandwidth of transmitted signals. OAWRS azimuthal resolution in radians is roughly the acoustic wavelength λ divided by the projected array length $L\cos\theta$, where the azimuth θ is zero at broadside or normal to the array axis and L is the receiver array length. At endfire or parallel to the array axis the resolution becomes roughly sqrt($2/L$) radians. The array has left-right ambiguity about its axis which is resolved both by changing the receiver array position and orientation.

WORK COMPLETED/RESULTS

We applied our OAWRS technology in Sept-Oct 2006 in the Gulf of Maine in a multinational, multi-institutional oceanographic experiment sponsored by ONR, NOPP and the Sloan Foundation and done in conjunction with the National Marine Fisheries (NMF) Annual Herring Survey. With a single OAWRS transmission covering a 150-km diameter area, we were able to image a region in 75 seconds that would take the conventional NMF survey roughly one week to sparsely survey with several line transects. We found the NMF surveys could not accurately determine shoal morphologies or populations from their sparse line transects. We observed a startling new patterns of diurnal behavior, dramatic new evidence of information transfer by very large scale biological waves, and many other discoveries about the migrations of spawning herring, their population, and the frequency dependence of scattering. We obtained direct trawl samples confirming fish species.

The technical approach for the September-October 2006 OAWRS exploration of fish populations in the Gulf of Maine and Georges Bank was similar to that implemented by the same team on the New Jersey Continental Shelf in May 2003. The OAWRS source, however, was this time primarily deployed off the shelf in or on the other side of the Franklin Basin from the northern flank of Georges Bank. Water depths and variations in water depth were significantly greater than in 2003, but the receiver ship again running hour-glass or star shaped tracks within a several kilometers of the source as shown for at typical imaging scenario.

Massive shoals and isolated schools were successfully imaged over wide areas by the OAWRS system. Pronounced diurnal behavioral patterns emerged, as well as apparent migrations of populations. The primary fish populations detected and imaged were Atlantic herring, as verified by capture trawl samples during the 2006 OAWRS experiment at regions of high fish density identified by OAWRS. Herring consistently inhabit the regions along the northern flank of Georges Bank in the September-October time period. This period was selected for the OAWRS experiment, which coincides with migration of herring onto shallower waters on the northern flank of Georges Bank for spawning.

Concurrent line transects were made with two independent CFFS vessels, one including captures with net and trawl. The latter ran fixed tracks surveying the overall region as part of the annual surveys of the National Marine Fisheries Service, but also had time to be directed by OAWRS vessels to regions where high fish concentrations were detected remotely to make both CFFS surveys and obtain ground truth samples with trawls. The former was free at all times to be directed by the OAWRS systems to areas of high fish concentration and was equipped with both multifrequency calibrated fish echo-sounders as well as a multibeam system donated by RESON Corp to provide 3-D information about local fish schools.

It is noteworthy that the Institute of Marine Research of Bergen Norway supplied both essential people and equipment to help conduct the CFFS research on this vessel at short notice when the original NRL Fisheries Scientist could not make the trip due to the aftermath of Hurricane Katrina. University of New Hampshire donated a person to operate the RESON multibeam.

To potentially identify fish species by the spectral dependencies of their target strengths, the OAWRS system produced wide area images using transmissions at differing center frequencies spanning the range from roughly 390 Hz, below expected swim bladder resonances, to roughly 1.5 kHz, near some expected resonances. While significant differences in OAWRS imagery were often observed at low versus high frequencies, high concentrations of fish were observed remotely in both frequency regimes.

IMPACT/APPLICATIONS

- Early in this fiscal year, we successfully completed a major oceanographic experiment showing that OAWRS can be used as a valuable tool for studying the population and behavior of Atlantic Herring in Georges Bank and the Gulf of Maine. The experiment was conducted jointly with the US National Marine Fisheries Service Annual Herring Survey of Georges Bank and the Gulf of Maine.
- We show that fish populations can now be instantaneously detected, located and imaged over thousands of square kilometers in continental-shelf environments with a remote sensing technology surveys at an areal rate roughly one million times greater than that of conventional fish finding methods.
- The waveguide technology makes it possible to continuously monitor fish population dynamics, behavior and abundance with minute to minute updates, over thousands of square kilometers producing records unaliased in space and time.

TRANSITIONS

The OAWRS technology for instantaneously detecting, imaging and continuously monitoring fish populations over continental-shelf-scale areas is extremely valuable to the study of ocean ecology, the conservation of ocean life and the management of marine fisheries. After publication in the journal Science, numerous applications to fisheries around the world have emerged.

RELATED PROJECTS

This program is part of the Census of Marine Life in the Gulf of Maine. Other organizations participating in this program are NEU, IMR Bergen Norway, NRL, NMFS, WTE, WHOI, ARL-PSU, MAI, UNH, RESON, SNWSC, and NFESC.

RECENT RELEVANT PUBLICATIONS

P. Ratilal et al and N.C. Makris, “Long range remote imaging of the continental shelf environment: The Acoustic Clutter Reconnaissance Experiment 2001 Experiment,” J. Acoust. Soc. Am. 117, 1977-1998 (2005).

T.R. Chen, P. Ratilal and N.C. Makris, “Mean and variance of the forward field propagated through three-dimensional random internal waves in a continental-shelf waveguide,” J. Acoust. Soc. Am. 118, 3532-3559 (2005).

P. Ratilal and N.C. Makris, “Mean and covariance of the forward field propagated through a stratified ocean waveguide with three-dimensional inhomogeneities,” J. Acoust. Soc. Am. 118, 3560-3574 (2005).

S. Lee and N.C. Makris, “The array invariant,” J. Acoust. Soc. Am. 119, 336-351 (2006).

J. D. Wilson and N.C. Makris, “Ocean Acoustic Hurricane Classification,” J. Acoust. Soc. Am. 119, 168-181 (2006).

N.C. Makris, P. Ratilal, D. Symonds, S. Jagannathan, S. Lee, R. Nero, "Fish population and behavior revealed by instantaneous continental-shelf-scale imaging," Science 311, 660-663 (Feb. 3, 2006). See extensive online supporting material and movies at Science website via free link on acoustics.mit.edu/faculty/makris/makris.html.