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

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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, (2) continuously monitor the areal densities and behavior of these fish populations over time, and (3) remote species classification, 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. The OAWRS ability to assess biological and behavioral characteristics at entire-population scales with high spatio-temporal resolution is an important technological step forward, and represents a new approach in the study of marine ecology and ecosystem-based fisheries management.

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.

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- 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.
- Developing range-dependent waveguide scattering model calibrated for bottom reverberation in continental shelf environment.
- Improving the existing analytical model for waveguide propagation by considering forward scattering through random inhomogeneities.
- Investigating the capability of OAWRS to be used in a variety of ecosystems around the world to remotely assess populations and study the behavior of fish and other marine organisms.

APPROACH

Recently, a method that surveys fish populations at an areal rate tens of thousands to millions of times greater than that of conventional methods has been developed and demonstrated [Makris et al, Science 311, 660-663 (Feb. 3, 2006)]. This technique, known as Ocean Acoustic Waveguide Remote Sensing (OAWRS), can be used in continuously monitoring 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, it was possible 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 observed follows a fractal or power law process, so that structural similarity exists 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 2D than was previously believed based on 1D 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.

OAWRS can also be used to remotely classify species by sensing the physiological characteristics of fish. We obtain measurements of the scattering response of fish at and around their resonance frequencies and compare them to modeled scattering responses. If the scattering responses vary significantly across species, through dependent parameters such as fish length, depth and swimbladder volume, it may be possible to classify species. Fish swimbladder volume depends on neutral buoyancy depth, or the depth at which the weight of the fish is balanced by its buoyancy force. At any given depth, this usually requires the swimbladder to occupy roughly 5% of the total fish volume. By constraining fish length and depth distributions from in-situ measurements, fish scattering response can be modeled as a function of a single parameter, the neutral buoyancy depth, which is closely linked to physiological behavior. Variations in neutral buoyancy depth lead to dramatic changes in scattering response at and below resonance. With measured scattering responses at these frequencies we can determine neutral buoyancy depth, which in turn reveals physiological characteristics that may provide supporting evidence for species classification.

To include the effect of bottom reverberation, an analytic model is developed in range-dependent ocean environment and bistatic source-receiver geometries. The model is derived from first principles using the acoustic wave equation for inhomogeneous media and by application of Green's theorem. The model takes into account the full three-dimensional (3D) scattering interaction of the acoustic wavefield with volume or surface inhomogeneities. For efficiency, the model is implemented in terms of scattering from the spatially varying resolution footprint of the sonar, typically determined by beamforming and temporal matched filtering. The model is calibrated for ocean bottom reverberation with data acquired by instantaneous ocean acoustic waveguide remote sensing (OAWRS) during the 2003 Main Acoustic Experiment and geophysical surveys of the ONR Geoclutter Program.

WORK COMPLETED/RESULTS

The OAWRS system was deployed in the Gulf of Maine, near Georges Bank to image Atlantic herring and other fish populations from Sep-Oct 2006. OAWRS provides spatially unaliased imaging of herring over wide areas, spanning over 100 km diameter. Migration and spawning behavior of Atlantic herring was observed using OAWRS over several diurnal periods, including massive movements on and off the bank to spawn. Measurements made simultaneously with a conventional fish-finding echosounder (CFFS) and a multibeam sonar provide the depth distribution and local 3D morphology respectively of the herring schools in the water column. Concurrent trawl surveys provide identification of the fish species. Measurements made by OAWRS and CFFS systems are highly correlated. Calibration of the OAWRS system using CFFS estimates of fish population densities along with a full-field scattering model that takes into account both coherent and incoherent scattering from a fish group has been investigated. The fish swimbladder is modeled as a spheroidal bubble. Resonance scattering behavior of herring is observed in the OAWRS system with significant changes in scattering amplitude over the 300 Hz to 1.5 kHz frequency range of the OAWRS system.

The experimental data from the 2006 experiment was used in estimating the mean low frequency target strength (TS) of spawning Atlantic herring populations in the Gulf of Maine in the frequency range from 300 Hz to 1.2 kHz. The OAWRS system's scattering strength measurements are calibrated with areal fish population density estimates obtained from concurrent localized imaging with several conventional fish finding sonars. The CFFS systems also provide the local depth dependence of the fish populations. The imaged species were identified through net trawl sampling at selected locations. High spatial-temporal correlation is found between fish distributions imaged with OAWRS and along line-transect measurements of the CFFS. The mean TS estimates of herring individuals exhibits significant variation over OAWRS operating frequency range, in accordance with a physics-based resonant scattering model for swimbladder-bearing fish. The neutral buoyancy depth of herring and the species composition in the population is inferred by comparing the mean TS estimates with those derived from the model. Our analysis indicates the spawning herring populations have a neutral buoyancy depth of between 80 to 100 m and are therefore negatively buoyant between 120 and 180 m water depth at which they are commonly found. The population of herring instantaneously imaged with OAWRS often exceeds 200 million, of which over 150 million individuals can be organized into a large shoal.

Recent developments in OAWRS have also enabled the group behavioral dynamics of entire ecosystems of shoaling fish to be studied by instantaneous imaging and continuous monitoring over tens of thousands of square kilometers. Here we used a combination of OAWRS, CFFS and trawl survey methods to describe the process by which hundreds of millions of Atlantic herring rally to form vast queues on the northern flank of Georges Bank before migrating to the bank to spawn. We observed a regular diurnal pattern where formation of these extensive social groups is not gradual, but rather rapidly cascades over tens of kilometers in tens of minutes, much greater than the swimming speed of an individual herring in a group. This extremely abrupt behavior, characterized by the synchronous actions and chain reactions of tens to hundreds of millions of fish, provides ecosystem-scale evidence for the high degree of conformity expected in schooling fish populations from both laboratory and theoretical investigations. We also observed massive evening migrations of these vast shoals toward spawning grounds on Georges Bank, which occur at a much more ponderous rate, consistent with the swimming speed of individual herring in a group.

As mentioned earlier, OAWRS can be used in species classification. OAWRS was used to help reveal physiology, behavior and aid in classifying the species of shoaling fish observed during the 2003 main acoustic experiment [Makris et al, Science 311, 660-663 (Feb. 3, 2006)]. The average scattering response of a shoaling fish determined by OAWRS with local CFFS constraints were compared with the corresponding target strength for three frequencies 415 HZ, 925 Hz, and 1325 Hz. The best fit of OAWRS target strength estimates to modeled scattering responses is given by a fish species that has a neutral buoyancy depth of 78 m with a resonance peak occurring at roughly 700 Hz. Concurrent CFFS measurements imaged the fish at 70-90 m depth in a layer near the 100 m isobath, consistent with the best fit estimate of neutral buoyancy depth obtained by OAWRS.

The estimated neutral buoyancy depth suggests that Atlantic herring were the major constituent of the large shoals imaged by OAWRS in 2003, and also the dominant cause of scattering measured by both OAWRS and CFFS. Atlantic herring populations comprised the majority of all species sampled in the region, and none of the other candidate species are known to form such large, extended shoals as those imaged. For herring to be the dominant population in the imaged shoals, they would have to be neutrally buoyant at 78 m. This suggests that they have a mechanism for building up gas in their swimbladder, e.g. gas-producing bacteria in their digestive tract. Herring have previously been found to be neutrally buoyant at depths significantly greater than the surface.

We believe it is unlikely that another, less abundant species could have dominated the scattering measured by OAWRS and CFFS, since this would require “contaminants” with unrealistically large target strengths. Such contamination is inconsistent with trawl data, as well as the observed preference of fish to shoal among similar-sized individuals. Additionally, stationarity of CFFS and OAWRS scattering measurements suggests that the fish imaged were characterized by similar length and target strength, respectively.

We have also shown that OAWRS may be used to image a variety of ecologically significant fish species around the world as well as other species such as Antarctic Krill. For all fish species examined, typical shoaling densities are at least two orders of magnitude greater than the minimum densities detectable by OAWRS, making them excellent candidates for future surveys. For Antarctic krill of at least 2 cm length, OAWRS should be capable of imaging typical swarming densities with a dynamic range at least two orders of magnitude greater than the minimum detectable densities. With appropriate system designs, it may be possible to image smaller krill with OAWRS.

To include the effect of seabed reverberation, an analytic model for 3D, bistatic scattering from medium inhomogeneities is developed from first principles by application of Green's theorem. Statistical moments of the scattered field are expressed in terms of statistical moments of medium compressibility and density fluctuations. The model is applied to seabed reverberation and optimally calibrated with both OAWRS and geological data on the New Jersey continental shelf. Analysis with the model indicates that (1) seabed reverberation is incoherent, and (2) scattering strength varies with frequency depending on wavenumber k, medium coherence volume V_c and seabed depth penetration factor F_p following a $10\log_{10}(F_p V_c k^4)$ dependence. An efficient numerical approach is also developed for rapidly computing seabed reverberation over wide areas for bistatic sonar systems in range-dependent ocean waveguides. It exploits the correlation between monopole and dipole scattering terms and the limited penetration of acoustic fields in the seabed. The model handles the scattering of evanescent waves in the seabed. Finally, an approach for distinguishing the statistically stationary background reverberation from the scattered fields of moving targets in sonar data by tracking the temporal and spatial evolution of the returns is developed.

To improve the analytical model for the acoustic propagation and scattering, we have also considered multiple forward scattering through random three-dimensional inhomogeneities in an ocean waveguide. An analytical expression is derived for the temporal coherence of an acoustic field after multiple forward scattering through random three-dimensional (3D) inhomogeneities in an ocean waveguide. This expression makes it possible to predict the coherence time scale of field fluctuations in ocean-acoustic measurements from knowledge of the oceanography. It is used to explain the time scale of acoustic field fluctuations observed at megameter ranges in various deep ocean-acoustic transmission experiments. It is shown that this time scale is nonlinearly related to the much longer coherence time scale of deep ocean internal waves through a multiple forward scattering process. It is also shown that 3D scattering effects become pronounced when the acoustic Fresnel width exceeds the cross-range coherence length of the deep ocean internal waves, which lead to frequency and range-dependent power losses in the forward field that may help to explain historic long range measurements.

IMPACT/APPLICATIONS

- 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 (OAWRS) 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.
- This technology opens the way in studying the physiological characteristics of fish that can result in species classification.
- OAWRS is proved to be capable of being used in a variety of ecosystems around the world to remotely assess populations and study the behavior of fish and other marine organisms.

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.

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