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, and (2) continuously monitor the areal densities and behavior of these fish populations over time using a novel low to mid frequency acoustic system (300-5000Hz) referred to as Ocean Acoustic Waveguide Remote Sensing (OAWRS). This new method will be 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 will become an invaluable 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:

- 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 [R7].

- To test this new OAWRS technology with simultaneous line-transect methods using both conventional fish finding sonar (CFFS) [R3,R4] and directed capture sampling with nets.

- 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.

APPROACH

In its first demonstration, OAWRS was used in May 2003 on the New Jersey Continental Shelf just south of the Hudson Canyon by the same PI, co-PI's and collaborators of this program. We were able to successfully image thousands of square kilometers, remotely, with minute to minute updates. We found high spatial-temporal correlation between the Eulerian OAWRS system and the Lagrangian CFFS system for both isolated fish schools as well as large continuous shoals. From OAWRS imagery, we were able to continuously estimate fish population densities over wide-areas [P1,P2,P3-P6,P17].

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 [P7-P13,P16,P18,P19] rather than the spherical loss suffered in conventional fish finding sonar technologies. OAWRS uses sound typically three orders of magnitude less intense than CFFS [P2,P6]. Waveguide modes [R1,R2] 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 [R2, P7-P13]. 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 [P4,P5,R7-R10].

WORK COMPLETED/RESULTS

The planned technical approach for the September-October 2006 OAWRS exploration of fish populations in the Gulf of Maine and Georges Bank is similar to that successfully implemented by the same team on the New Jersey Continental Shelf in May 2003. The OAWRS source will again be primarily deployed on a shelf, this time the northern flank of Georges Bank, at similar depths as in 2003, with the receiver ship again running hour-glass or star shaped tracks within a few kilometers of the source as shown for at typical imaging scenario in Fig 1. Here the circle indicates the area imaged instantaneously in a single OAWRS transmission, for a typical 80-second reception window. The plan is to use OAWRS to continuously detect, image, monitor and enumerate fish populations, determine their areal densities, and to quantitatively describe their temporal and spatial behavior. Calibrated targets will be deployed in the water column to serve as navigational beacons for OAWRS charting and scattering calibration as in previous OAWRS applications [P2,P12,P13,R14].

The primary fish populations to be detected and imaged are expected to be the Atlantic herring that have consistently inhabited the regions along the northern flank of Georges Bank, based on annual National Marine Fishery surveys of the region [R9]. The September-October time period selected for the OAWRS experiment was chosen to coincide with migration of herring onto shallower waters on the northern flank of Georges Bank for spawning [R7,R15]The expectation is that OAWRS imagery should be able to robustly detect, monitor and quantify this movement of herring populations. The most recently available herring surveys in the vicinity were conducted by one of the co-investigators on this project and are shown in Fig 1 where the relatively typical value of Sa=16384 [m^2/nmi^2] corresponds to an areal fish population density of roughly 30 herring/m^2, from which the other values of Sa can be converted to areal herring density. This is based on typical measured target strength values of -38 dB re 1 m for Atlantic herring in these deep shoals at 38 kHz [R10]. CFFS transects show dense and extended shoals of herring stretching for many kilometers in the vicinity of the roughly 50-200 m depth contours in Fig. 1 (a)-(b). Based on measured swim bladder resonance of Atlantic herring in shoals at such depths by co-PI's of this proposal [R10] and their observed areal densities, these shoals are expected to have similar scattering cross-sections per unit horizontal area in the 400 Hz range as those observed by OAWRS on the NJ shelf [P1-P6]. The herring shoals should then stand as prominently in OAWRS imagery as the shoals do in the OAWRS images on the New Jersey Continental Shelf.

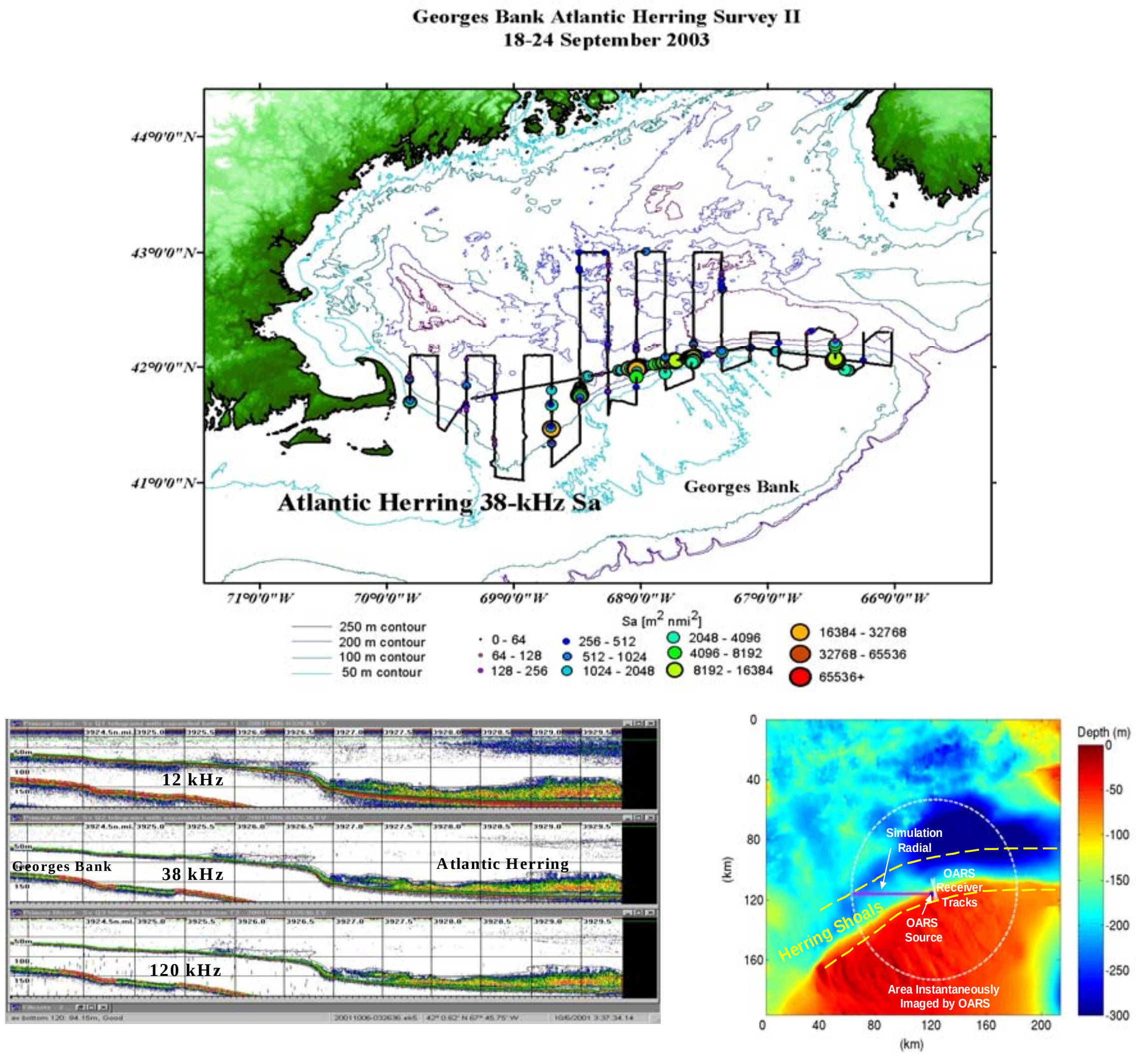

Figure 1: (a) Spatial distribution of Atlantic herring on Georges Bank and corresponding CFFS line transect images of local fish concentrations (b). (c) Potential setup of OAWRS system for instantaneously imaging Atlantic herring and other fish species on the northern flank of Georges Bank.

Simulations of the broadside beam scattered levels expected by OAWRS as a function of range from Atlantic herring for typical high, moderate and low areal shoaling densities are shown in Fig. 2 along with levels modeled for seafloor scattering. The radial used is shown in Fig. 1C and is over a similar ocean waveguide environment to that explored by OAWRS in the New Jersey Continental Shelf. Range-dependent waveguide propagation and scattering was modeled with the parabolic equation. Fish target strengths from swimbladder scattering at 400Hz were modeled for fish column concentrations within roughly 10-m of the local seafloor. Seafloor scattering returns were modeled with Rayleigh-Born theory [P14,P15] and calibrated with scattering measurements from similar experiments in similar seafloor environments [P2, P12,P13]. The modeling results show that even low-density shoals should consistently stand at least an order of magnitude above seafloor returns. OAWRS should then be able to robustly estimate the areal density of Atlantic herring on the northern flank of Georges Bank over a dynamic range spanning more than three orders of magnitude. This is similar to results obtained from the OAWRS field experiment on the New Jersey Continental Shelf in 2003 in a similar environment [P1].

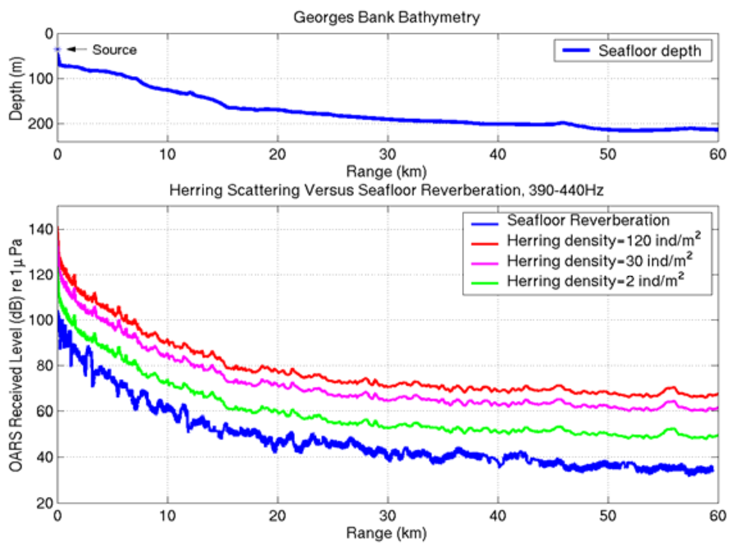

Figure 2: Simulation with full waveguide scattering models show that scattering from Atlantic herring is expected to be many orders of magnitude greater than reverberation from the sea floor in OAWRS imagery of the Georges Bank region. The bathymetric radial used is shown in Fig 4 (c). Range increases westerly.

Concurrent line transects will be made with two independent CFFS vessels, one including captures with net and trawl. The latter will run fixed tracks surveying the overall region as part of the annual surveys shown in Fig. 1 [R9]. The other vessel will be directed to survey areas of high fish concentration as they are detected during continuous OAWRS monitoring. This approach proved to be highly successful during the 2003 New Jersey Continental Shelf application of OAWRS where direction from OAWRS enabled the CFFS vessel to focus survey transects on areas of high fish density with extremely high efficiency [P1,P2]. Both CFFS systems will be calibrated and used to determine information about the dominant fish layers such as depth, density and high frequency target strength. The CFFS vessel following OAWRS detections will also employ a broadband system in the 1.5-5 kHz range to determine resonance characteristics of fish for target strength calibration. This system was used by the co-PIs in previous analysis of the swim bladder resonance characteristics of Atlantic herring in the Gulf of Maine [R10]. This information will enable calibrations of the average scattering cross section of individual fish to be determined as a function of depth from which wide-area estimates can be made of areal fish population density by concurrent OAWRS imagery.

In an attempt to remotely identify fish species by the spectral dependencies of their target strengths, the OAWRS system will also produce wide area images using transmissions at differing center frequencies [P2] spanning the range from roughly 390 Hz, below typical swim bladder resonances, to well above them at over 5 kHz. Various other species of fish are expected to be imaged by the OAWRS system on and near Georges Bank. The target strengths expected for an individual of some of these species are given in Fig. 3 [R10], and their place among the most abundant species in Georges Bank is shown in Table 1. At night, regardless of the depth of the site, herring are expected to migrate vertically toward the sea surface where their target strengths increase significantly [R16,R17]. An attempt will be made to make a limited number of OAWRS images at night to investigate this phenomenon, which may aid in species identification as well as elucidate behavior. The fish species believed to populate the predominant shoals in the NJ 2003 OAWRS experiments are scup [P1] with target strength curves similar to those of haddock in Fig 3. While their individual target strengths are much higher than Atlantic herring, the herring typically form schools and shoals of much greater areal density, by orders of magnitude.

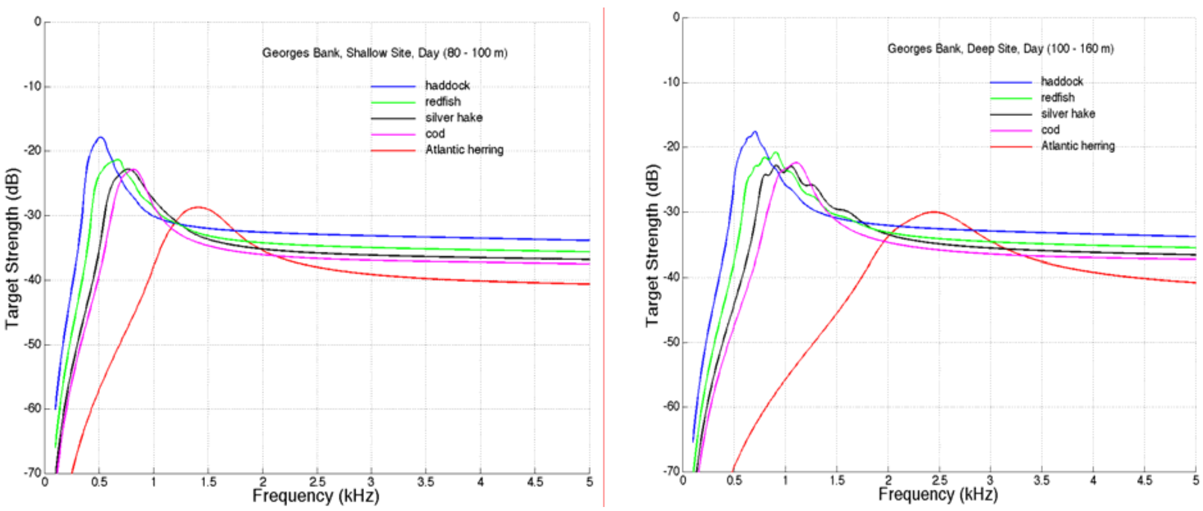

Figure 3: Other less densely populated species than herring have stronger individual target strengths and will likely also be detected by the OAWRS system.

		Year	Catch(MT)	Factor	Stock(MT)	Fish L (cm)	W (gm)	N millions
Atlantic herring	NEFSC News release	2005			170000	30	270	630
Acadian redfish	NEFSC News release - prediction	2006			170000	35	428.75	397
Haddock	NEFSC News release	2003			120000	45	911.25	132
Silver hake	Nero - guestimate	2004	0		50000	40	640	78
White hake	NEFSC pdf file	2000	4000	4	16000	40	640	25
Atlantic cod	Mayo&O'Brien 2000	1998			14000	40	640	22
Pollock	NEFSC pdf file	2000			5000	40	640	8
Red hake	NEFSC Status Document	1999	600	4	2400	40	640	4

Table 1: Population of fish species in Georges Bank region.

IMPACT/APPLICATIONS

- 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. Remarkably, these observations have all been made remotely from distances typically greater than 10 km from the shoal boundaries with sound at least three orders of magnitude less intense than conventional fish finding sonar.

- 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.

- The waveguide remote sensing technology has revealed the detailed horizontal structural characteristics and volatile short-term behavior of very large fish shoals, containing tens of millions of fish and extending for tens of kilometers. During MAE 03, we find that fish shoaling populations exhibit structural similarity at all spatial scales. This suggests that the instantaneous distribution of fish over wide areas follows a consistent fractal or power law process. Quantitative knowledge of this power law now enables more accurate statistical predictions of the spatial distribution of fish populations to be made.

- Even though shoals may be structurally similar to schools, we show that they do not exhibit the synchronized motion characteristics of a school over short time scales.

- We find that the autocorrelation time scale of major population and areal change in a very large fish shoal is extremely short, only between 5 to 10 minutes. This is most dramatically exhibited in our finding that large shoals can disperse with extreme rapidity, in less than one hour at rates of up to 0.5 million fish/minute. Temporal and spatial sampling limitations in conventional fish finding sonar made it previously impossible to quantify dispersal rates and time scales of major population change.

- We have discovered what appear to be large-scale fish density waves occurring regularly, every few minutes, within the shoal. The waves cause relative displacements of population mass centers that are bounded by the 1-3 km internal coherence area within the shoal. These fish density waves can provide a rapid means of communication within smaller schools, for example, in response to predation or other pressures.

TRANSITIONS

The OARS 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. From a Navy sonar perspective, understanding fish behavior and morphology are critical distinguishing nature from man-made targets. Quantitative knowledge of spatial and temporal power laws of clutter by fish school enables more accurate statistical predictions of the distribution of fish populations to be made.

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, NRL, NMFS, WTE, WHOI, ARL-PSU, MAI, SNWSC, and NFESC.

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PATENTS

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