Determining the Characteristics and Mechanisms for Biological Clutter and Environmental Reverberation and Their Impact on Long Range Sonar Performance in Range-Dependent Fluctuating Ocean Waveguides

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LONG-TERM GOALS AND OBJECTIVES

Determine the temporal and spatial characteristics, and physical mechanisms for biological clutter and environmental reverberation in long-range wide area active sonar systems. This understanding is used to develop operational and signal processing techniques to distinguish biological clutter from scattered returns due to man-man targets, and to determine the limits placed by environmental reverberation on target detection. In the second area, the statistical properties of broadband acoustic signals transmitted and scattered in range-dependent ocean waveguides is examined. This knowledge is then used to determine the extent to which environmental variabilities limit our ability to perform target localization and parameter estimation through beamforming and match-filtering broadband data from active sonars in fluctuating and dispersive ocean waveguides.

APPROACH

The research effort involves developing and enhancing physics-based theoretical models for coherent and incoherent scattering from groups of fish and other biological organisms, multi-static scattering from extended targets, and environmental reverberation in *range-dependent* ocean waveguides. The vast amounts of data collected during the ONR-sponsored acoustic experiments in the Gulf of Maine in 2006 and on the New Jersey Strataform in 2003 with long-range sonar systems are processed and analyzed.

WORK COMPLETED AND RESULTS

1. Analysis of Data from 2006 OAWRS Experiment in the Gulf of Maine

During the ONR-Sloan Foundation sponsored acoustic experiment in the Gulf of Maine from Sep 22 to Oct 5, 2006, both massive shoals and small discrete schools of fish were imaged near Georges Bank with a long-range wide-area sonar system, OAWRS (Ocean Acoustics Waveguide Remote Sensing). The OAWRS source array transmitted LFM signals simultaneously with 50 Hz bandwidths at multiple frequencies from 300 to 1500 Hz making it an extremely useful data set to examine scattering from fish as a function of OAWRS operating frequency near and below their swimbladder resonance. Concurrent measurements were made using conventional fish-finding sonars (CFFS), the Simrad EK60 (38 kHz) echosounder and the Reson 7125 (400 kHz) multibeam sonar. Trawl surveys conducted during the experiment identified Atlantic herring as the dominant species of fish (over 99%) imaged along with a small fraction of redfish and haddock.

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14. ABSTRACT

Determine the temporal and spatial characteristics, and physical mechanisms for biological clutter and environmental reverberation in long-range wide area active sonar systems. This understanding is used to develop operational and signal processing techniques to distinguish biological clutter from scattered returns due to man-man targets, and to determine the limits placed by environmental reverberation on target detection. In the second area, the statistical properties of broadband acoustic signals transmitted and scattered in range-dependent ocean waveguides is examined. This knowledge is then used to determine the extent to which environmental variabilities limit our ability to perform target localization and parameter estimation through beamforming and match-filtering broadband data from active sonars in fluctuating and dispersive ocean waveguides.

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- *Estimating fish frequency-dependent target strength*

The OAWRS and CFFS data have been processed and extensively analyzed for four days of observation, Sep 22, and Oct 1-3. High spatial-temporal correlation was found between fish aggregations imaged with OAWRS and along line-transect measurements of CFFS. The OAWRS raw scattered intensity data were corrected for source level, two-way transmission losses and the range- and azimuth dependent resolution footprint of the receiving array to provide estimates of scattering strength (SS) in the OAWRS imagery. The inversion procedure takes into account variations in the expected incident intensity as a function of target depth caused by a refracting, non-uniform water-column sound speed profile. We calibrate for the mean target strength (TS) of individual herring at OAWRS operating frequencies by correlating the expected OAWRS SS levels from several hundred OAWRS images with the areal fish population density estimates from CFFS along the line-transect. A novel approach for accurately estimating the frequency dependence in scattering from fish groups by differencing OAWRS images acquired simultaneously at multiple frequency bandwidths has also been developed. The experimentally determined herring TS increases significantly, as much as 20 dB, as the probing frequency increases from 415 Hz to 1200 Hz. The background reverberation increases only slightly, by about 4 dB making fish clutter from herring much more significant above 1 kHz. From Navy perspective, the minimum aerial density of herring needed to cause biological clutter has also been determined. The experimentally estimated herring TS are in excellent agreement to those obtained from modeling the fish swimbladder as a resonant spheroidal bubble (this swimbladder model was developed by Richard Love formerly of NRL) [2].

The calibrated target strength is then used to provide abundance estimates of the herring imaged with OAWRS during the Gulf of Maine experiment. Analytic and theoretical models that take into account potential effects of multiple scattering from a fish group are applied in the analysis of OAWRS data. We find that in the Gulf of Maine, the population of herring within the large shoals often exceed a hundred million individuals [2]. The population of herring within smaller, discrete, and dense schools are on the order of a few million individuals.

- *Classifying fish species and distinguishing fish returns from man-made objects.*

For swimbladder-bearing fish, the dominant source of scattering comes from their air-filled swimbladders that can resonate at certain frequencies to yield relatively high target strength for an individual. Their swimbladders undergo compression and expansion as they migrate vertically in the water column according to Boyle's Law. The essential mechanisms that various species employ to regulate their swimbladder volumes at depths have been extensively investigated in the last few decades. The previous modeling analysis work show that the scattering responses may vary significantly across species, through dependent parameters such as fish length, depth, and swimbladder volume. Here, we incorporate information from concurrent trawl surveys of the fish population during GOME'06, on their size and weight distributions, depth dependence, and swimbladder volume fractions. These characteristics are used as inputs along with the experimentally determined low frequency TS to an adaptive algorithm that enables optimal species classification by statistically predicting the possible species composition of the imaged fish groups [2,6].

The TS dependence of fish differs from that of underwater vehicles. In the resonance frequency range of most fish species, roughly several hundred Hz to a few kHz, fish scattering varies significantly by more than 20 dB at resonance and off resonance frequencies. In contrast, scattering from underwater vehicles remains fairly consistent, varying monotonically by a few dB across the same band. *This experiment shows that a multi-frequency sonar system can be very effective at distinguishing fish returns from man-made targets.* The results of these analysis on fish target strength and abundance estimation and species classification has been written up and submitted for journal publication.[2]

- *Future Work*

In the next year, our goal will be to use the tools already developed and apply them to complete the analysis of TS and abundance estimation for the remaining days of the experiment. These results will then be applied to study the migration and spawning behavior of herring shoals over the entire Georges Bank over several diurnal periods. An understanding of the temporal-spatial behaviour of these fish groups will then be used to derive operational cues to distinguish biological clutter from returns due to man-made targets.

2. Development of theoretical models for scattered field moments from a random distribution of discrete scatterers and output after beamforming and matched filtering, including the effects of multiple scattering

Here we developed two types of models for the mean and variance of the field scattered from a random distribution of discrete scatterers. The model mimics the output of an actual sonar system by including beamforming and matched-filtering.

- *Monte-Carlo simulation model with multiple scattering*

First a Monte-Carlo simulation model was developed that models the field multiply scattered from a random distribution of discrete targets. The spatial positions, orientations, and the scatter functions of the targets are treated as random variables. The model is applicable to large scatterers with directional dependence in their scatter function. The total scattered field from each realization is then matched filtered with the source waveform before the field moments are calculated. The sample mean square and variance of these matched filtered returns over all simulations gives us the statistically coherent and incoherent intensities respectively. An advantage of applying the matched filter is that the higher orders of scattering arrive later in time with increasing order, allowing a separation of the various orders of scattering under some scenarios.

The model has been applied to simulate a conventional fish finding sonar (CFFS) imaging dense schools of Atlantic Herring in the Gulf of Maine, as shown in Fig. 1. The CFFS system projects a narrow broadband beam downwards, and the scattered returns are matched filtered to the source waveform resulting in a volumetric scattering strength profile in depth. With knowledge of the estimated target strength, the population density can be determined as shown in Fig. 1(b) if we assume that (1) multiple scattering effects are negligible, and (2) the statistically incoherent intensity is dominant over the coherent intensity. The numerical model can be used to describe the conditions under which these assumptions are valid. While the model has been implemented for a simple monostatic echosounder system, it may be extended to remote sensing in fluctuating environments, waveguides, and can include bistatic imaging systems.

The model simulates the fish school by randomizing both the scatter functions and locations of the fish according to specified statistical distributions. For this example, the spatial locations in depth were specified to match the distributions of the echosounder data, Fig. 1(b). The primary scattering mechanism for individual herring is their air-filled swim bladder. We model this as a spheroidal bubble taking into account directional dependence of the scatter function. The model is implement for two cases, one that includes multiple scattering and another that only accounts for single scattering and are plotted in Fig. 1(e) and (d) respectively. Here, we can see that the incoherent intensity dominates over the coherent. Comparing the singly and multiply scattered incoherent intensity levels shows us that the multiple scattering contribution is negligible, and therefore the single-scattering approximation is sufficient for determining population densities. The numerical model shows that multiple scattering becomes important for groups with very high target strengths and very high population densities, but these high target strengths and high densities combination are unrealistic for Atlantic herring schools.

- *Analytic model for field moments from scatterer distribution when single scattering dominates*

For cases when the single scatter approximation is sufficient, an analytic model has been developed to rapidly estimate the coherent and incoherent intensities for population density estimates. The intensities are expressed in terms of the characteristic function of the statistical distribution of fish shown in Fig. 1(c). Here, the mean fish density in depth from Fig. 1 (b) is used as the statistical distribution. The incoherent intensity found analytically closely matches that found using the Monte-Carlo numerical model in Fig. 1(f). This work has been written into a journal article and submitted for publication [4].

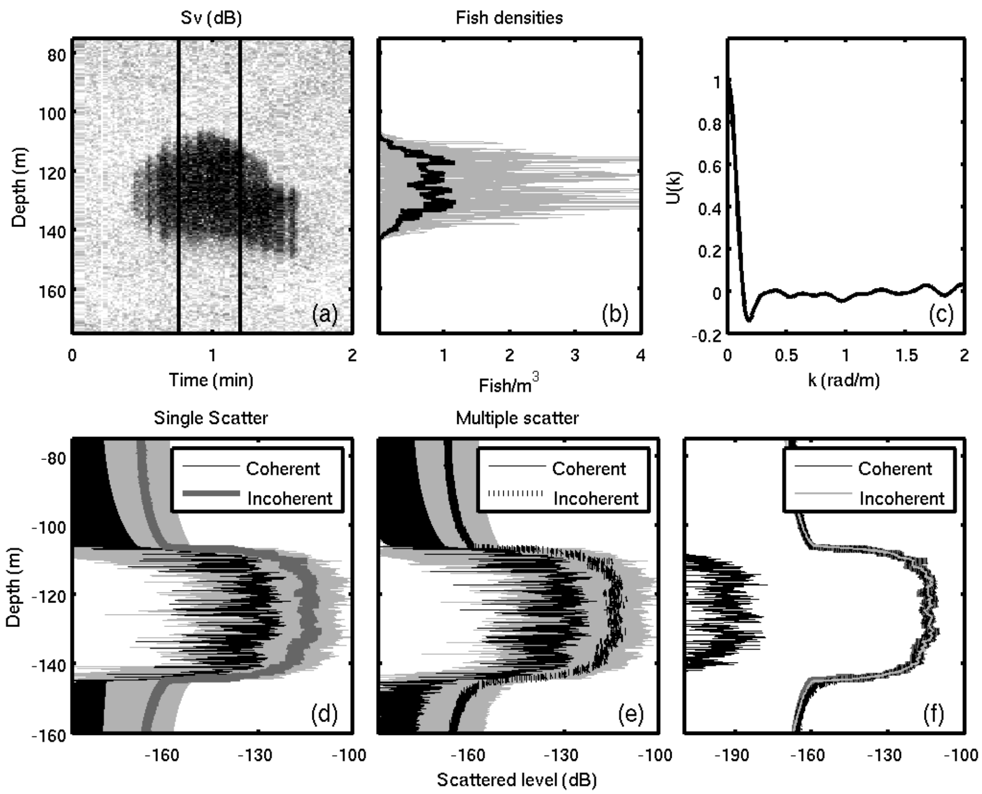

Fig. 1: Matched filtered coherent and incoherent intensity levels scattered from a group of fish. Echosounder data in terms of volumetric scattering strength Sv is illustrated over depth for several measurements in time (a). This is converted to fish densities in gray (b) using an estimated mean target strength of -39.6 dB for Atlantic Herring assuming single-scattering, the mean over the 25 measurements is shown in black. Output of the Monte-Carlo model simulating the matched filtered returns from this group are illustrated using the (d) single-scatter approximation and (e) including multiple scattering. For each, the individual matched filtered signals are shown in light gray, with the sample mean square, or coherent intensity, and sample variance, or incoherent intensity. Panel (f) compares the incoherent intensities from the numerical simulations in (d) and (e) to the coherent and incoherent intensities found using the analytic model. The characteristic function for this spatial distribution used in the analytic model is illustrated in (c).

Currently, research is underway to apply the numerical model in an *ocean waveguide* to simulate the multiple scattering effects in wide area sonar systems, such as OAWRS. Further research goals will use the model to simulate OAWRS in an ocean waveguide randomized by internal waves, more fully describing the imaging system in its random environment.

3. Develop scattering model for vertically extended targets in range-dependent waveguides

The standard approach often used for modeling the scattered field from large objects in a multi-modal ocean waveguide is that developed by Ingenito in 1987. In this approach, the incident field at the target center is decomposed into modal plane waves. The object's plane wave scatter function is used to couple the incident and scattered modes that are then propagated to a receiver. The Ingenito waveguide scattering model can be applied to large objects but they have to be contained within an iso-speed layer because of modal plane wave decomposition. The Ingenito model can lead to substantial errors in estimating the scattered field level of vertically extended targets with significant variation in sound speed across the target depth. Furthermore, since it is based on normal mode theory, the Ingenito approach cannot be used to model scattering from objects in range-dependent environments.

An analytic and numerical model has been developed to calculate the scattered field from vertically extend targets in range-dependent ocean waveguides by application of Green's Theorem. The Kirchoff's approximation is applied to estimate the locally scattered field at the target surface as a function of the incident field. The model is therefore directly applicable to objects that satisfy the rigid or pressure-release boundary conditions. The scattered field from the target in the far-field is then estimated by propagating the locally scattered fields at each depth of the target in the range- and depth-dependent waveguide and coherently summing these at the location of the receiver.

This vertically extended target waveguide scattering (VETWS) model is implemented for the BBN target, a passive acoustic reflector often deployed in experiments for active sonar calibration and to enable accurate geographic charting of sonar imagery. The BBN target is a 30 m long air-filled rubber cylindrical target deployed vertically in the water column, and it satisfies a pressure release boundary condition. Numerical implementation of the model is achieved with both the normal mode model for range-independent scenarios, and with the parabolic equation model for range-dependent environments. The VETWS model was validated against the Ingenito's waveguide scattering model for a BBN target contained in the iso-speed water column layer of a Pekeris waveguide. Good agreement between the two models is expected since the object is placed in an iso-speed layer.

Calculations with both models was also carried out in a waveguide with a highly refractive sound speed profile, where there is substantial change in the water-column sound speed over the BBN target depth. The models disagree both in phase and amplitude. The Ingenito model can either over-estimate or under-estimate the scattered field level by more than 10 dB at around 20 km range. For the Ingenito model the interference pattern for the scattered field level depends on the modal interaction of the Green's function with range at the target center, whereas for the VETWS model the interference pattern depends on the modal interaction integrated over the entire depth extent of the target. This result indicates that refraction of the incident field along the target depth needs to be properly accounted for in order to accurately estimate the scattered field level from vertically extended targets in general ocean waveguides. These and other examples are presented and summarized in Ref. 5 that was recently submitted for publication.

Our future goal is to calibrate the VETWS model with scattered field data from BBN targets deployed in the Gulf of Maine during OAWRS 2006 experiment and in the New Jersey continental shelf during the Geoclutter 2003 OAWRS experiment. These are the only unclassified data sets using a long range sonar with BBN targets, making this calibration of extreme importance to understanding scattering in ocean waveguides.

IMPACT/APPLICATIONS

We have determined the dominant physical mechanism by which fish schools cause clutter in Navy sonar systems as scattering arising from their air-filled swimbladders. We also verified with data that the frequency dependence in scattering from fish swimbladder is well modeled as a resonant spheroidal bubble. Furthermore, a multi-frequency Navy sonar system that spans from several hundred Hz to a few kHz will be very effective in distinguishing fish clutter from underwater vehicles.

RELATED PROJECTS

Research on several of the areas listed above are being conducted in collaboration with Nicholas Makris and his team at MIT and J. Michael Jech of NEFSC-NOAA. The results of this research also supports the National Oceanographic and Partnership Program (NOPP) on fish sensing and imaging.

PUBLICATIONS

1. A. Galinde, N. Donabed, S. Lee, N. Makris and P. Ratilal, "Range-dependent waveguide scattering model calibrated for bottom reverberation in continental shelf environments," *J. Acoust. Soc. Am*., Vol. 123, 1270-1281 (2008).

2. Z. Gong, M. Andrews, D. Cocuzzo, S. DasGupta, S. Jagannathan, D. Symonds, I. Bersatos, T. Chen, H. Pena, R. Patel, O.R. Godoe, R.W. Nero, J.M. Jech, N.C. Makris and P. Ratilal, "Altantic herring low frequency target strength and abundance estimation: OAWRS 2006 Experiment in the Gulf of Maine," submitted to *Can. J. Fish. Aquat. Sci.* (Oct. 2008).

3. M. Andrews, T. Chen and P. Ratilal, "Broadband transmission statistics and match filter degradation in the New Jersey Continental shelf," under review in *J. Acoust. Soc. Am*. (submitted Mar. 2008).

4. M. Andrews, Z. Gong, D. Cocuzzo, and P. Ratilal, "High-resolution population density imaging of random scatterers through cross-spectral coherence in matched filter variance," under review in *IEEE Geosci. Remote Sensing Letters* (submitted Mar. 2008).

5. E. Kusel and P. Ratilal, "Model for scattered field from vertically extended targets in range-dependent ocean waveguides," under review in *J. Acoust. Soc. Am*. (submitted Sep. 2008).

6. S. Jagannathan, D. Symonds, I. Bersatos, T. Chen, M. Andrews, Z. Gong, N. Donabed, H. Nia, A. Tan, L. Ngor, R. Nero, M. Jech, O. Godoe, S. Lee, P. Ratilal, and N. Makris, "Ocean acoustic waveguide remote sensing of marine ecosystems," under review in *Mar. Ecol. Prog. Ser*., invited paper (submitted Mar. 2008).

7. T. Chen, P. Ratilal and N. Makris, "Temporal coherence after multiple forward scattering through random three-dimensional inhomogeneities in an ocean waveguide," *J. Acoust. Soc. Am*., Vol. 124 (to appear in Oct. 2008).