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Determining the Characteristics and Mechanisms for 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 clutter and environmental reverberation in instantaneous-wide-area underwater acoustic imaging and surveillance systems. This understanding is used to develop operational and signal processing techniques to distinguish 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 matched-filtering broadband data from imaging systems in fluctuating and dispersive ocean waveguides.

APPROACH

The research effort involves developing and enhancing physics-based theoretical models for multi-static scattering from groups of fish, marine mammals and other biological organisms, geology and extended targets, and environmental reverberation in *range-dependent* ocean waveguides. The data from the ONR-sponsored experiments in the Gulf of Maine in 2006 and on the New Jersey Strataform in 2003 measured with instantaneous-wide-area ocean acoustic waveguide remote sensing systems (OAWRS) are processed and analyzed.

WORK COMPLETED AND RESULTS

1. Estimating low-frequency target strength and abundance of shoaling Atlantic herring in the Gulf of Maine during the Ocean Acoustic Waveguide Remote Sensing 2006 Experiment

The low-frequency target strength of shoaling Atlantic herring (Clupea harengus) in the Gulf of Maine during the autumn 2006 spawning season is estimated from experimental data acquired simultaneously at multiple frequencies in the 300-1200 Hz range using (1) a low-frequency ocean acoustic waveguide remote sensing (OAWRS) system, (2) areal population density calibration with several conventional

fish finding sonar (CFFS) systems, and (3) low-frequency transmission loss measurements. The OAWRS system's instantaneous imaging diameter of 100 km and regular updating enabled unaliased monitoring of fish populations over ecosystem scales including shoals of Atlantic herring containing hundreds of millions of individuals and stretching for many kilometers along the northern flank of Georges Bank, as confirmed by concurrent trawl and CFFS sampling. High spatial-temporal coregistration was found between herring shoals imaged by OAWRS and concurrent CFFS line-transects, which also provided local areal population densities, as well as depth and length distributions of the fish populations.

The mean scattering cross-section of an individual shoaling herring is found to consistently exhibit a strong, roughly 20 dB/octave roll-off with decreasing frequency (see Fig. 1) in the range of the OAWRS survey over all days of the roughly 2-week experiment, consistent with the steep roll-offs expected for sub-resonance scattering from fish with air-filled swimbladders given measured fish length, depth distribution, and experimentally inferred swimbladder volumes based on Love's model, which indicate the herring remain negatively buoyant in layers near the seafloor for extended periods. These findings published in Ref. [1] suggest that OAWRS can provide valuable evidence for remote species classification over ecosystem scales since significant variations in the frequency dependence of target strength are expected across species due to differences in resonance [2,3]. 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.*

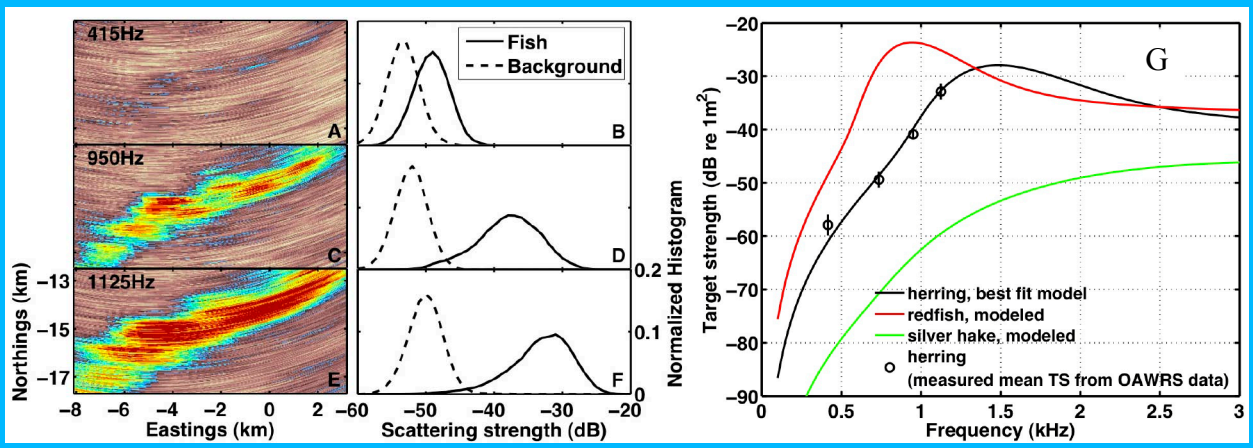

Figure 2: (A,C,E) OAWRS images of the ocean environment acquired simultaneously at 3 distinct imaging frequency bandwidths centered at 415, 950 and 1125 Hz. (B,D,F) Corresponding histogram of intensity levels scattered from areas containing Atlantic herring and outside (background). (G) Dramatically different resonance frequency responses across species and size aid in remote classification over wide areas with OAWRS.

2. Development of a theoretical model for the statistical moments of the multiply scattered, matched filtered field from a random distribution of scatterers in a range-dependent fluctuating dispersive ocean waveguide

A numerical Monte-Carlo model has been developed to determine the statistical moments of the broadband matched filtered scattered fields from a three-dimensional random spatial distribution of random scatterers in a random range-dependent ocean waveguide [4]. The model includes multiple scattering from the scatterer group and employs the complex scatter function to account for attenuation and dispersion due to scattering from an individual. The model uses a range-dependent acoustic propagation model (RAM) based on the parabolic equation to simulate acoustic field propagation in a range-dependent ocean waveguide. By incorporating randomness in the waveguide environment and the dynamic scatterer group, the model can account for statistical fluctuations typically present in data from any active sonar system. The model developed here is the only model to simultaneously analyze multiple scattering and attenuation from a scatterer group imaged at long ranges in an ocean waveguide with a broadband pulsed system, employing the waveguide Green's function for propagation and the matched filter to localize scatterers in range. The model can analyze bistatic scattering from the scatterer group in any direction including the forward.

The model has been applied to investigate OAWRS population density imaging of shoaling Atlantic herring during the 2006 Gulf of Maine Experiment. We show that high-resolution population density imaging of fish populations can be achieved with high accuracy in a random range-dependent ocean waveguide with an OAWRS system. Multiple scattering, attenuation and dispersion are found to be negligible at the OAWRS imaging frequencies ranging from several hundred Hertz to a few kHz employed in the experiment and for the herring densities observed. For fish groups typically observed with OAWRS, that extend tens to thousands of times the wavelength of the imaging system, we show that the incoherent intensity dominates the scattered returns, and that coherent multiple scattering effects, such as resonance shifts and sub-resonance local maxima, are negligible or absent. These latter effects can be significant only for small highly dense fish groups on the order of the acoustic wavelength. An optimal mean charting speed required to accurately localize a fish group in horizontal range from its time-dependent broadband matched filtered scattered field in a random range-dependent ocean waveguide is found to be approximately equal to the minimum of the measured mean water-column sound speed profile. When combined with the incident field, the model can accurately characterize attenuation in forward propagation through a fish group. The model also showed that extinction due to scattering can negate the effects of multiple scattering, both effects being cumulative over the range extent of the fish group. The net attenuation through the fish group required an accurate characterization of swimbladder resonance damping [4].

3. Broadband acoustic transmission scintillation statistics in the Gulf of Maine

Over 3000 broadband acoustic transmissions in the Gulf of Maine during the OAWRS 2006 experiment have been statistically analyzed as a function of the signal bandwidth, center frequency and source-receiver ranges for transmissions in the three octave band frequency range from 300 to 1200 Hz. It was found that the fluctuations in the signal intensity level follow the exponential-Gamma distribution parameterized by the number of coherence cells or statistically independent fluctuations in the signal, μ, and mean intensity $\overline{I}$, which are functions of range, bandwidth (B), and center frequency (f_c). Our analysis indicates the standard deviations of the 1 second duration broadband signals range from 2 to 5 dB, with standard deviations (1) inversely proportional to the signal bandwidth, and (2) proportional to the center frequency. The lower frequency broadband signals undergo less fluctuation

from propagation than higher frequency signals with the same bandwidth. The statistics of the broadband data were verified with a range-dependent numerical Monte-Carlo propagation model implemented with the parabolic equation that randomized the acoustic signals along the propagation path by incorporating linear internal waves in the model. Results from the model indicate that the standard deviation of a monotonic signal propagated beyond a 3 km distance attains a 5.6 dB value and becomes independent of range. For a broadband signal, the standard deviation attains a peak at approximately 3 km and subsequently decreases with range, implying that the waveguide has become more deterministic when the signal has propagated through several internal wave correlation lengths. At any given range beyond 3 km, the standard deviation of the broadband signal was found from the model to be inversely proportional to the signal bandwidth and proportional to the center frequency, consistent with our findings from the data. The Monte-Carlo propagation model enables reliable estimation of broadband transmission scintillation characteristics and can be applied for efficient design of acoustic systems. We are presently preparing a journal article for publication on this topic.

4. Instantaneous whale localization from passively recorded vocalizations by a towed horizontal receiver array using the array invariant method

A large number of loud, low-frequency acoustic calls produced by marine mammals, most likely from humpback whales (Megaptera novaeangliae), were coincidentally recorded on a towed hydrophone array during the Gulf of Maine 2006 Experiment. Spectral analyses show that most of these calls were broadband non-linear down-sweep signals with short time durations, typically lasting about 1 to 2 seconds, and in the frequency range from 300 Hz to 600 Hz. Individual calls exhibited significant variation in time-frequency characteristics and followed irregular temporal pattern. The calls may have propagated hundreds of meters to hundreds of kilometers in the ocean waveguide from the whale locations to the receiving array. We have begun to examine the possibility of localizing and tracking the humpback whales from their vocalizations received passively on the towed array by application of the array invariant method, developed by Lee and Makris (JASA 2006). The array invariant method has significant advantages over existing passive source localization methods, such as matched field processing (MFP), and waveguide invariant, because it does not require a priori knowledge of environmental parameters, and fully exploits the coherent gain possible with receivers of finite spatial aperture. It uses the fact that the maximum beam-time intensity migrates along an angle that is invariant to environmental parameters but follow a known and unique dependence on source-receiver range to localize the underwater sound source. The array invariant approach had been demonstrated previously for broadband sources with known linear broadband signatures in a horizontally stratified waveguide. Here we extend the approach to localizing sources with unknown and complex signatures in a range-dependent waveguide in the presence of ambient noise and in-band interfering sources.

The research approach combines theoretical modeling with experimental data analysis. A theoretical model that simulates the time-frequency characteristics of the whale call, propagated through a range-dependent ocean waveguide randomized by internal waves, received on an array of 64 hydrophones has been developed. The effects of environmental reverberation with significant energy in the bandwidth of the whale call modeled as interfering colored noise are added to the whale signal. An adaptive matched filter designed to maximize the SNR for each whale call has been developed. The array invariant approach for estimating the whale range from the beamformed data is then examined as a function of signal to noise ratio of the whale call, and range and depth of the whale. Preliminary analysis indicates the array invariant can passively localize the range of the whales in the ocean waveguide for ranges exceeding 50 km and for a wide range of whale depths.

The array invariant approach will next be applied to the measured whale call data to passively localize their ranges. The longer term goal of this research will be to test the hypothesis of whether whales can lead to clutter in long range wide area Navy underwater surveillance systems.

IMPACT/APPLICATIONS

We have determined the dominant physical mechanisms by which fish schools cause clutter in Navy sonar systems as scattering arising from their air-filled swim bladders. We also verified with data that the frequency dependence in scattering from fish swimbladder is well modeled as arising from 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.

PUBLICATIONS / REFERENCES

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HONORS/AWARDS/PRIZES

My graduate student Duong Tran won a Best student paper award for the following presentation at the Acoustical Society of America Meeting in Portland, Oregan.

D. Tran, Z. Gong, M. Andrews, P. Ratilal, N. Makris, "Atlantic herring low frequency target strength estimation from ocean acoustics waveguide remote sensing (OAWRS) data in the Gulf of Maine over 10 days of observation," J. Acoust. Soc. Am, 125(4), 2549-2549.