# Acoustic Clutter and Ocean Acoustic Waveguide Remote Sensing (OAWRS) in Continental Shelf Environments

Principal Investigator: Nicholas C. Makris
Massachusetts Institute of Technology, Department of Ocean Engineering
77 Massachusetts Avenue, Room 5-229
Cambridge, Massachusetts 02139
phone: (617) 258-6104 fax: (617) 253-2350 email: makris@mit.edu

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## LONG-TERM GOALS

Acoustic clutter is the primary problem encountered by active sonar systems operating in Continental Shelf environments. Clutter is defined as any return from the environment that stands prominently above the diffuse and temporally decaying reverberation background and so can be confused with or camouflage returns from an intended target such as an underwater vehicle. Many environmental factors may contribute to acoustic clutter and adversely affect the performance of tactical Navy sonar by introducing false alarms in the system. In order to develop adaptive algorithms or technology to mitigate acoustic clutter, it is critical to identify, understand, and be able to accurately model the leading order physical mechanisms which cause clutter in existing sonar systems. The long-term goal of this program is to determine and understand the physical mechanisms that cause acoustic clutter in continental shelf environments and to use this knowledge to develop predictive tools to enhance the detection, localization and classification of underwater targets.

## OBJECTIVES

The primary objectives of this program in FY2008 were to:

(1) Analyze formation processes of large oceanic fish shoals that may lead to target-like clutter.

(2) Characterize the capability of Ocean Acoustic Waveguide Remote Sensing (OAWRS) in remotely assessing populations and studying the behavior of various fish species and other marine organisms, which are the main sources of biological clutter.

(3) Determine the physical scattering mechanisms causing biological clutter and their variation with fish species, depth, size and population density.

(4) Estimating the low frequency target strength of herring (Clupea harengus) in the Gulf of Maine.

(5) Estimate velocity fields and dynamic forces driving clutter using a temporal sequence of consecutive low frequency wide-area sonar images to help distinguish biological scatterers from intended targets.

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14. ABSTRACT
**Acoustic clutter is the primary problem encountered by active sonar systems operating in Continental Shelf environments. Clutter is defined as any return from the environment that stands prominently above the diffuse and temporally decaying reverberation background and so can be confused with or camouflage returns from an intended target such as an underwater vehicle. Many environmental factors may contribute to acoustic clutter and adversely affect the performance of tactical Navy sonar by introducing false alarms in the system. In order to develop adaptive algorithms or technology to mitigate acoustic clutter, it is critical to identify, understand, and be able to accurately model the leading order physical mechanisms which cause clutter in existing sonar systems. The long-term goal of this program is to determine and understand the physical mechanisms that cause acoustic clutter in continental shelf environments and to use this knowledge to develop predictive tools to enhance the detection, localization and classification of underwater targets.**

15. SUBJECT TERMS

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(6) Conduct a joint experiment with the Mexican Navy in the Pacific Ocean to quantify hurricane destructive power with ocean acoustic measurements.

(7) Test the hypothesis that inexpensive underwater acoustic measurements can be used to determine the wind speed and classify the destructive power of a hurricane with greater accuracy than standard satellite remote sensing techniques and with at least the same accuracy as hurricane hunting aircraft.

(8) Improve the techniques of underwater imaging by developing a maximum likelihood method for estimating remote surface orientation from measurements of surface radiance.

(9) Study the problem of source localization in a fluctuating waveguide containing random internal waves.

(10) Study the temporal coherence of an acoustic field after multiple forward scattering through random three-dimensional (3D) inhomogeneities in an ocean waveguide.

(11) Develop and apply a theory for the nonlinear scattering of sound in the presence of inhomogeneities and apply it to underwater detection of submerged objects and objects buried in sediment.

## APPROACH

We have developed a method known as Ocean Acoustic Waveguide Remote Sensing (OAWRS) that instantaneously detects, locates and images underwater targets over thousands of square kilometers in continental-shelf environments [1]. Using the OAWRS approach, we found that fish shoals were the primary sources of clutter in long-range sonar systems in shallow water continental shelf environments. The OAWRS approach demonstrates that discrete clutter events are consistently the major clutter problem in a region with significant bathymetric relief and variable oceanography as well as in a region with flat bathymetry.

The OAWRS approach was first demonstrated in April-May 2003 off the US Continental Shelf south of Long Island, NY in an area known as the Mid-Atlantic Bight. With a single transmission of a one-second duration Linear Frequency Modulated (LFM) waveform, OAWRS surveyed an area on the order of a typical US east coast state such as Connecticut or New Jersey, as shown in Fig. 1A. The imaging is effectively instantaneous because the entire region is surveyed in less time than it takes a marine organism to traverse a single OAWRS resolution cell [1].  The OAWRS approach was used again in conjunction with the National Marine Fisheries Service (NMFS) Annual Herring Survey of the Gulf of Maine and Georges Bank to study diurnal variation in clutter associated with herring spawning in September-October 2006 [2].

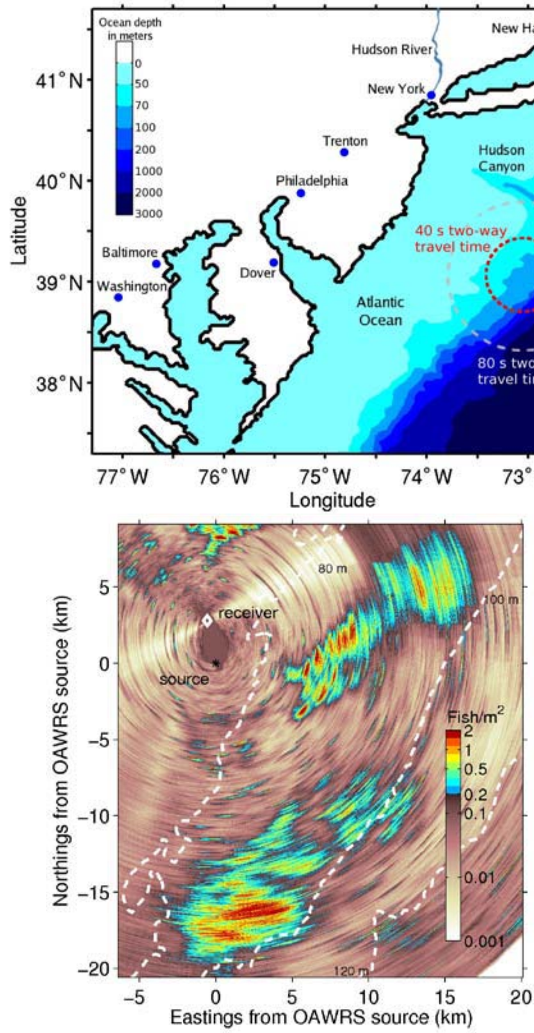


***Fig. 1. (A) Areal coverage of a single OAWRS transmission during the 2003 survey in the US east coast continental shelf. A region of 60 km diameter was surveyed every 40 s, or 120 km every 80 s, depending on ping repetition rate and recording time. (B) Instantaneous OAWRS image of fish population density showing fish shoals near the continental shelf edge 100 km south of Long Island New York, on the morning (10:36 EDT) of May 15, 2003. Dashed lines mark depth contours. Receiver array resolution decreases as viewing directions go from normal (broadside) to parallel (endfire) to the array axis, leading to blurring of the eastern portion of the northeastern shoal. Population density estimation employs waveguide propagation and scattering models, correction for OAWRS areal resolution, and calibration with local CFFS measurements as described in the Appendices.***

## WORK COMPLETED/RESULTS

Bioclutter and Remote Sensing of Fish Populations: Clutter emergence in low frequency sound was quantified for the first time by using OAWRS in Georges Bank (Fig. 2), a region with varied bathymetry and oceanography. It was also shown that fish shoals can be a major clutter problem in not only flat bathymetries, but also in varied bathymetries such as the one in the Gulf of Maine. By quantifying the formation process of vast oceanic herring (Fig. 3) shoals during spawning, it was shown that a rapid transition from disordered to highly synchronized behavior occurs as fish population density reaches a critical value, and organized group migration occurs after this transition [2]. The spawning process was found to follow a regular diurnal pattern in space and time which proved to be difficult to detect without continuous wide-area sensing abilities (Fig. 2 A-B).

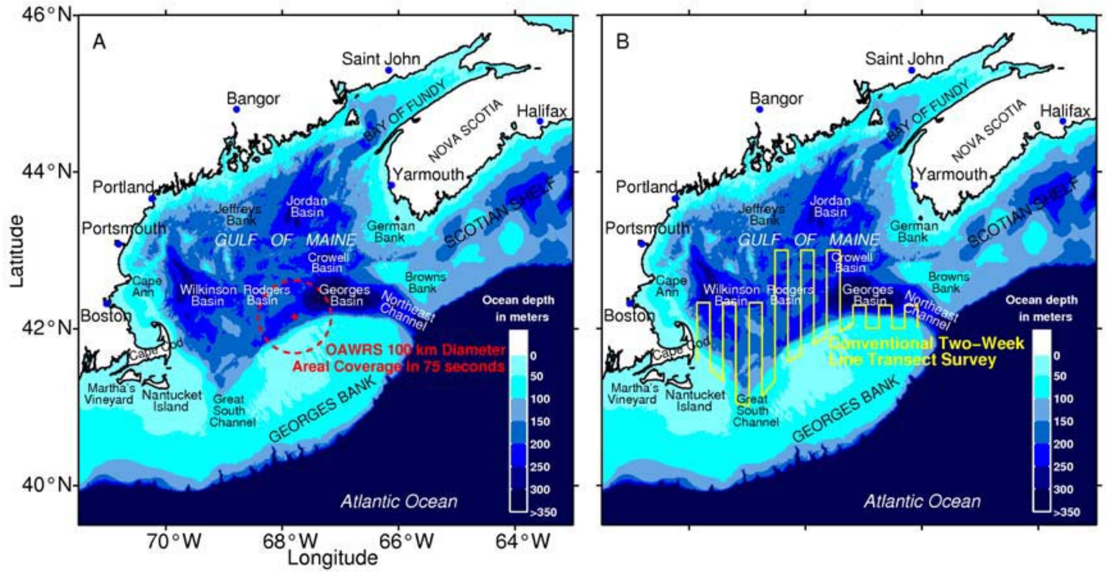


*Fig. 2. (A) Areal coverage of a single OAWRS transmission in the 2006 survey in the Gulf of Maine. A region of 100 km diameter is surveyed every 75 s. (B) Line transects of National Marine Fisheries Service (NMFS) two-week survey are shown in yellow.*

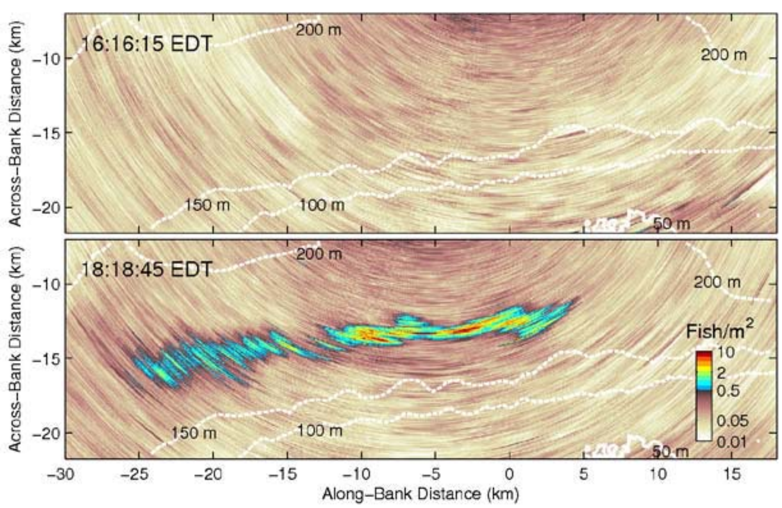


*Fig. 3. Instantaneous OAWRS snapshots showing pre-spawning shoal formation in the evening of October 3, 2006. Dashed lines mark depth contours. Population density estimation employs waveguide propagation and scattering models, correction for OAWRS areal resolution, and calibration with local CFFS measurements as described in the Appendices. The positive vertical axis points 16° counter-clockwise of true north.*

To assess the performance of OAWRS in identifying biological clutter, we modeled the scattering from biological targets and inverted for their physiological characteristics from experimental data collected during the Gulf of Maine 2006, as well as the earlier 2003 experiment. Using this technique we showed that target strength of herring is more than 10 dB greater than expected from shallow neutral buoyancy depth models. The high target strength of fish shoals compared to the expected values can be a source of error in distinguishing man-made targets from biological clutter. We also developed a potential method for remotely sensing physiological characteristics of fish with OAWRS that may be helpful in species classification [3]. For fixed fish length and depth, acoustic scattering at and near swimbladder resonance is a strong function of swimbladder volume (Fig. 4), which can vary significantly across species and so be used for classification. Swimbladder volume can also be used to estimate neutral buoyancy depth, where a fish's weight is balanced by its buoyancy. At any given depth, neutral buoyancy usually requires the swimbladder to occupy roughly 5% of the total fish volume, where more air is required to maintain this ratio as depth increases due to the compressive effects of increasing overburden pressure.

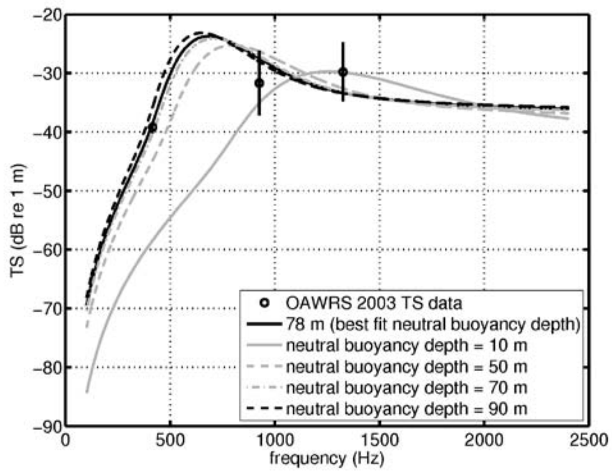


***Fig. 4: Target strength data corresponding to the mean scattering cross-section of a shoaling fish in OAWRS 2003 constrained by local CFFS are shown as black circles, with standard deviations as black error bars. These means and standard deviations are from sample means and variances of 181 independent samples at 415 Hz, and 46 independent samples at 925 Hz and 1325 Hz. The standard deviations are: 0.7 dB at 415 Hz, 5.5 dB at 925 Hz, and 5 dB at 1325 Hz. Target strength versus frequency curves for 5 different neutral buoyancy depths are computed with a Love's model, a US Navy standard for low frequency fish scattering, by depth-averaging the expected scattering cross section of an individual fish over the layer observed by CFFS for the Gaussian length distribution (standard deviation 15% of the 28.6 cm mean) determined by CFFS. The least-squares best-fit buoyancy depth between measured data to Love-model target strength is given by the black solid line. If the shoaling fish observed in the 2003 OAWRS experiment in the 70-90 m layer were neutrally buoyant closer to the surface (grey line), they would scatter far too weakly below 1.4 kHz to be consistent with the measured OAWRS and CFFS data.***

The low-frequency target strength of shoaling Atlantic herring (Clupea harengus) in the Gulf of Maine during Autumn 2006 spawning season is estimated from experimental data acquired simultaneously at multiple frequencies in the 300 to 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 systems (CFFS), (3) fish length distributions obtained from trawl samples and CFFS, and (4) local low-frequency transmission loss measurements [4]. Using multiple frequencies, we are able to do spectral characterization of targets, which can be used for clutter mitigation. The estimated target strength is higher than previously known that will result in high returns than expected for Navy sonars.

We showed in the Gulf of Maine as well as in the New Jersey Continental shelf that clutter features can move with similar speed as underwater targets such as submarines, so that they can be easily confused with and misidentified as man-made targets [3]. In order to study the dynamics of clutter in OAWRS imagery, we have developed and applied a Minimum Energy Flow (MEF) method which is capable of estimating both incompressible and compressible motion from image sequences [5]. The method is also used to compute forces which drive the velocity field, and predict its evolution.

To estimate the statistics of the velocity and position of groups of self-propelled underwater objects, such as fish schools and swarms of Autonomous Underwater Vehicles (AUV's), a method has been developed using OAWRS and the theory for scattering from a moving object in a stratified medium [6]. Knowledge of the velocity statistics of aggregations of underwater scatterers may offer new possibilities for target classification and clutter mitigation. We show that it may be possible to obtain very accurate, long-range (tens of kilometers) estimates of the velocity and position of a single target moving with fixed speed and direction in an ocean waveguide given an appropriately designed signal. Similarly for a group of underwater targets, it may be possible to accurately estimate the statistics (mean and standard deviation) of their velocity and position provided the range-velocity ambiguity function is sufficiently sampled, e.g. given a large enough number of targets.

Quantifying Hurricane Destructive Power with Undersea Sound: Inexpensive underwater acoustic measurements can be used to determine the wind speed and classify the destructive power of a hurricane with greater accuracy than standard satellite remote sensing techniques. This is demonstrated by correlating the underwater sound intensity of hurricane Gert with meteorological data acquired by aircraft transects and satellite surveillance [13]. The intensity of low frequency underwater sound measured directly below the hurricane is found to be approximately proportional to the cube of the local wind speed, or the wind power. We have shown that passive underwater acoustic intensity measurements may be used to estimate wind speed and quantify the destructive power of a hurricane with accuracy similar to that of aircraft measurements.

To obtain more data relating undersea sound and wind power in hurricanes, Professor Makris initiated and is currently leading a joint scientific collaboration with Mexico's Navy (Secretaria De Marina). Professor Makris worked for several years with various ONR Latin America Station Chiefs and Program Managers and the US Embassy in Mexico City, to establish relationships with Mexico and obtain support from the Admiral commanding the Directorate of Oceanography, Hydrology and Meteorology. Another follow-up experiment in the same geographical location has been designed and two more sensors will be deployed in Spring 2010.

Acoustic Propagation (Multiple Forward Scattering) Through a Fluctuating or Randomly Inhomogeneous Ocean: We derived an analytical expression for the temporal coherence of an acoustic field after multiple forward scattering through random three-dimensional (3D) inhomogeneities in an ocean waveguide [9]. 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.

Analytical expressions have been derived for the attenuation and dispersion of the acoustic field forward propagated through fish shoals and wind-generated bubble clouds in an ocean waveguide [10]. It is found that at swim bladder resonance, fish shoals may sometimes lead to measurable attenuations in the forward field. The attenuation at off-resonant OAWRS frequencies, however, is typically negligible as shown both by the present theory and experimental data. The modeled attenuation due to random wind-generated bubble clouds is found to be highly sensitive to the choice of cutoff radius, which determines whether resonant bubbles are included in the bubble spectra. It is also found that bubble clouds generated under high wind speeds lead to additional dispersion and attention of the transmitted signal. These expected distortions can significantly degrade standard coherent processing techniques in ocean acoustics, such as the matched filter, if not taken into account.

The scintillation statistics of broadband acoustic transmissions are determined as a function of signal bandwidth $B$, center frequency $f_c$, and range with experimental data in the New Jersey continental shelf [11]. Acoustic signals transmitted through an ocean waveguide typically scintillate in both time and space upon reception due to multimodal propagation and random variations of the medium and its boundaries. Quantitative knowledge of these received signal fluctuations is often essential in the design of ocean acoustic experiments and in the analysis of subsequent measurements. The received signal intensity is shown to follow the Gamma distribution implying that the central limit theorem has led to a fully saturated field from independent multimodal propagation contributions. A computationally efficient numerical approach is developed to predict the mean intensity and the corresponding broadband transmission loss of a fluctuating, range-dependent ocean waveguide by range and depth averaging the output of a time-harmonic stochastic propagation model. This model enables efficient and accurate estimation of transmission loss over wide areas, which has become essential in wide-area sonar imaging applications.

The bias and covariance of maximum likelihood estimates (MLEs) are expanded in inverse order of sample size or signal-to-noise ratio (SNR), where the first-order term in the covariance expansion is the Cramer-Rao lower bound (CRLB). We derive an analytical expression for the second-order covariance of MLEs obtained from general complex Gaussian data vectors. We then show that this expression can be used to specify necessary conditions for accurate estimation in many practical problems where both the mean and the variance of the measurement are functions of the estimation parameters [12]. The results provided in this research help quantify the effects of ocean fluctuations on localization performance by calculating the theoretical limits for a deterministic and a highly random waveguide.

Detection of submerged objects and bottom imaging: A theory is developed for nonlinear scattering of sound in the presence of inhomogeneities that can be used in detection of man-made submerged targets at higher resolution and depth [7]. The second-order nonlinear wave equation for a medium with inhomogeneities is derived, and the general solution in the form of an integral is provided, which is evaluated for a number of canonical cases. It is shown that: (i) three distinct physical mechanisms may lead to a second-order scattered field, (ii) the relative contribution from each mechanism depends on the acoustic properties and geometry of the inhomogeneites, (iii) it is possible to probe for mechanical properties of the inhomogeneities for only one of these mechanism at frequencies only existing in the second-order scattered field but not the linear incident field. This theory is used in detecting and discriminating submerged and buried objects in ocean sediments.

To improve underwater imaging, a maximum likelihood method for estimating remote surface orientation from measurements of surface radiance is developed, where the images are corrupted by signal-dependent noise [8]. Necessary conditions on experimental sample size are determined so that the variance of the estimate falls within a specified design threshold. This is accomplished by adjusting the sample size so that (1) the variance of the estimate asymptotically attains the Cramer-Rao Lower Bound (CRLB), and (2) the estimate has a CRLB that falls within the design threshold. It is also shown that to estimate remote surface orientation it is in general necessary to observe the surface from at least three distinct non-coplanar directions.

## IMPACT/APPLICATIONS

- We have determined key physiological characteristics of Atlantic herring, such as neutral buoyancy depth, in the New Jersey continental shelf, using an analytical model for the fish TS and measurements of low frequency TS obtained in the MAE 2003 experiment. Our method now enables assessment of the impact of bioclutter on the performance of OAWRS in a variety of continental shelf environments around the world.

- We have developed a new technique that uses a temporal sequence of consecutive low frequency wide-area sonar images to estimate the flow fields of clutter from OAWRS images. This technique provides us spatio-temporal characteristics of clutter dynamics that are vital to distinguish biological scatterers from intended targets.

- We have developed an analytical tool to estimate instantaneous clutter velocity distributions in a single wide area sonar image through Doppler.

- We have proposed and developed a method to estimate hurricane destructive power using underwater noise measurements obtained from relatively inexpensive underwater hydrophones. This method can be used in hurricane prone areas around the world, in place of prohibitively expensive specialized hurricane hunting aircrafts.

- We have developed a partnership with the Mexican Navy to conduct scientific experiments in their waters to study ocean acoustic hurricane quantification. We will deploy sensors off the Mexican Isla Socorro, which experiences more hurricanes than anywhere else on earth. When retrieved in 2010, these will be used to test the ability to accurately quantify hurricane destructive power with acoustics.

- We have developed a theory for nonlinear scattering of sound in the presence of an inhomogeneity insonified by two plane waves at slightly different frequency, Our theory can be used in detection and discrimination of objects buried in seafloor sediments, by simultaneously using the high penetration of the incident low frequency waves and the high resolution of the sum frequency wave.

## TRANSITIONS

Transition of the Acoustic Clutter Program is already significant as documented by the great amount of Naval Research now focusing on clutter issues in active sonar which was spearheaded and guided by this Acoustic Clutter Program. Our hurricane work can be transitioned into development of ocean based early warning systems off USA, Mexico and other coastal regions around the world frequented by hurricanes.

## RELATED PROJECTS

Other organizations participating in the Geoclutter Program are Northeastern University, National Marine Fisheries Service, Institute of Marine Research Norway, NRL, ARL-PSU, MAI, UNH, RESON, SNWSC, and NFESC.

## RECENT RELEVANT PUBLICATIONS


1. N.C. Makris, P.Ratilal, D. Symonds, S. Jagannathan, S. Lee and R.W. Nero, “Fish Population and Behavior Revealed by Instantaneous Continental Shelf-Scale Imaging,” Science, 311, 660-663.

2. Nicholas C. Makris, Purnima Ratilal, Srinivasan Jagannathan, Zheng Gong, Mark Andrews, Ioannis Bertsatos, Olav Rune Godoe, Redwood W. Nero, J. Michael Jech, "Critical Population Density Triggers Rapid Formation of Vast Oceanic Fish Shoals", Science, Vol. 323, No. 5922, 1734-1737 (March 27, 2009).

3. S. Jagannathan, D. Symonds, I. Bertsatos, T. Chen, H. T. Nia, A. D. Jain, M. Andrews,Z. Gong, N. Donabed, R. Nero, L. Ngor, J.M. Jech, O.R. Godø, S. Lee, P. Ratilal and N.C. Makris, “Ocean Acoustic Waveguide Remote Sensing (OAWRS) of Marine Ecosystems,” accepted to be published in Mar. Ecol. Prog. Ser.

4. Z. Gong, M. Andrews, S. Jagannathan, O.R. Godø, R. W.Nero, J. M. Jech, N.C. Makris and P. Ratilal, “Atlantic Herring Low Frequency Target Strength and Abundance Estimation:OAWRS 2006 Experiment in the Gulf of Maine,” submitted to J. Acoust. Soc. Am.

5. S. Jagannathan, B.K.P. Horn, P.Ratilal, N.C.Makris, “Velocity Estimation and Prediction from Time Varying Density Images,” submitted to IEEE Trans. Pattern Analysis and Machine Intelligence.

6. I. Bertsatos and N.C. Makris, “Instantaneous Velocity estimation of Fish Groups by Ocean-Acoustic Waveguide Remote Sensing Doppler Analysis,” submitted to J. Acoust. Soc. Am.

7. H. T. Nia, P. Ratilal, N. C. Makris, “Nonlinear Scattering of Sound in the Presence of Inhomogeneities,” submitted to Phys. Rev. E.

8. N.C. Makris and I. Bertsatos, “Estimating surface orientation from fluctuating intensity,” to be submitted to Optics Letters.

9. T. Chen, P. Ratilal, N. C. Makris, "Temporal Coherence After Multiple Forward Scattering Through Random Three-dimensional Inhomogeneities in an Ocean Waveguide," J. Acoust. Soc. America 124, 2812-2822 (2008).

10. T. Chen, S. Jagannathan, P. Ratilal, N. C. Makris, “Attenuation due to Fish Shoals and Wind-generated Bubble Clouds After Multiple Forward Scattering,” submitted to J. Acoust. Soc. Am.

11. Andrews, T. Chen, and P. Ratilal, “Empirical dependence of acoustic transmission scintillation statistics on bandwidth, frequency and range in New Jersey continental shelf”, J. Acoust. Soc. Am. 125, 111-124 (2009).

12. Ioannis Bertsatos, Michele Zanolin, Purnima Ratilal, Tianrun Chen, and Nicholas C. Makris, "General Second-Order Covariance of Gaussian MLE Applied to Passive Source Localization in a Fluctuating Ocean Waveguide," to be submitted to J. Acoust. Soc. Am.

13. J. D.Wilson and N.C. Makris, "Quantifying hurricane destructive power, wind speed and air-sea material exchange with natural undersea sound," Geophys. Res. Lett. 35, L10603 (2008).