

# Acoustic Clutter in Continental Shelf Environments

Nicholas C. Makris  
Chief Scientist of ONR Ocean Acoustic Clutter Program  
Massachusetts Institute of Technology, Department of Ocean Engineering  
77 Massachusetts Avenue, Room 5-222  
Cambridge, Massachusetts 02139  
Phone: (617) 258-6104 Fax: (617) 253-2350 E-MAIL: [makris@mit.edu](mailto:makris@mit.edu)

Grant Number N00014-99-1-1059

## LONG-TERM GOALS

Acoustic clutter is the primary problem encountered by active sonar systems operating in Continental Shelf environments. Clutter is defined as any returns from the environment that stand 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 with little or no bathymetric relief 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 are:

- (1) Experimental demonstration with MAE 2003 and ARE 2001 data that the primary cause of *discrete and target-like* clutter observed in the New Jersey Strataform area is due to scattering from small, isolated, but densely populated fish schools typically spanning a 100-m to 1-km diameter. These schools have similar sizes and move at rates similar to those of a slow-moving submarine.
- (2) Preparation for an at-sea experiment in a different environment, Georges Bank in the Gulf of Maine, to determine whether fish are dominant cause of clutter in any continental shelf environment, and to characterize these clutter in frequency domain by extensive time-frequency analysis.
- (3) Characterization of the temporal and spatial properties of this newly discovered biological clutter as well as correlation to oceanographic or geophysical properties of the environment.
- (4) Experimental determination of the extent to which volume reverberation from fish is responsible for the overall diffuse background reverberation that is often nominally attributed seafloor scattering.

# Report Documentation Page

Form Approved  
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE <b>30 SEP 2005</b>		2. REPORT TYPE		3. DATES COVERED <b>00-00-2005 to 00-00-2005</b>	
4. TITLE AND SUBTITLE <b>Acoustic Clutter in Continental Shelf Environments</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Massachusetts Institute of Technology, Department of Ocean Engineering, 77 Massachusetts Avenue, Room 5-222, Cambridge, MA, 02139</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES <b>code 1 only</b>					
14. ABSTRACT <b>Acoustic clutter is the primary problem encountered by active sonar systems operating in Continental Shelf environments. Clutter is defined as any returns from the environment that stand 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 with little or no bathymetric relief and to use this knowledge to develop predictive tools to enhance the detection, localization and classification of underwater targets.</b>					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>9</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

- (5) Experimental demonstration that the primary analytic tool used by the Fleet and Navy programs to predict the level of target returns, the sonar equation, is inappropriate for use in Continental Shelf environments and often overestimates the level of returns by at least an order of magnitude, i.e. more than 10 dB, but that waveguide scattering models developed in this program [P16,P19] give accurate predictions.
- (6) Development and use of a new, rapid, rigorous and unified range-dependent reverberation and waveguide target scattering model based on the parabolic equation, a Fleet standard, to quantitatively determine the fundamental physical mechanisms responsible for clutter in active sonar operation in Continental Shelf environments and to provide predictive tools to mitigate or tactically exploit clutter.
- (7) Demonstration that after substantial investigation and a major expenditure of resources, experimental evidence suggests that sub-bottom geology does not play a noticeable role in producing clutter in the Strataform area but that certain low-relief bathymetric features common in Continental Shelf environments may sometimes lead to low-level clutter.
- (8) Application of a newly developed theory by the PI and his group [P26,P27,P31-33] to explain the experimentally observed fluctuations in calibrated target returns in shallow water. This includes application of the only approach in existence for 3-D calculations of the mean forward propagated field and covariance in a random waveguide. It was recently derived by the PI and his group to help analyze MAE 2003 and ACRE 2001 data from the Acoustic Clutter Program.
- (9) Experimental demonstration that the Doppler shift and spread may provide the best method to distinguish moving targets such as submarines, underwater vehicles, and small fish schools from stationary clutter features.

## **APPROACH**

The approach is to combine the analysis of experimental data with full-field waveguide modeling of forward propagation, clutter, acoustic reverberation, and target scattering. Under the Acoustic Clutter Program the Acoustic Clutter Reconnaissance Experiment (ARE) 2001 was primarily aimed at just establishing the presence and persistence of acoustic clutter off the New Jersey continental shelf. The Main Acoustics Experiment (MAE) 2003 was designed to be very controlled, so that the actual mechanisms for the clutter could be established. It also had precise calibration so that theories and models could be accurately tested and validated. Full-field 3-D stochastic waveguide propagation and scattering models, simulations and statistical studies helped direct experiment design and support the analysis and interpretation of experiment results.

## **WORK COMPLETED / RESULTS**

MAE 2003 of the Acoustic Clutter Program, conducted from April 28 to May 24 2003, [P3] was a great success in demonstrating that discrete clutter events are consistently a major problem for active sonar operations in Continental Shelf environments, even those with little or no bathymetric relief. It was also a great success in determining that densely populated fish schools are a dominant source of acoustic clutter [P3,P13,P14,P18,P26]. Very well controlled experimental configuration of the MAE with precise calibration enabled us to probe deeply enough into the physical mechanisms and characteristics of the forward field, 3-D scattering, and background reverberation. We were also able to

develop a rigorous theoretical model for expected Doppler shift and spread to discriminate non-stationary clutter features from stationary features in a stratified ocean waveguide.

Important results from the Acoustic Clutter program are as follows:

(1) We have demonstrated that fish schools are dominant cause of acoustic clutter in continental shelf environment using data from Acoustic Clutter Experiment 2001 and 2003 [P35]. These clutter features move with similar speed as underwater targets such as submarines and their spatial coherence scale is similar to many underwater targets, so that they can be easily confused with and misidentified as submarines. We have found that the autocorrelation time scale of the clutter features caused by fish is extremely short, only between 5 to 10 minutes [P35]. We have also shown that the instantaneous spatial distribution of fish over wide areas follows a fractal or power law spectral process [P35]. This means that instantaneous structural similarity exists at all scales observed, from tens of meters to tens of kilometers, and suggests that similar underlying behavioral mechanisms are likely responsible for structures at all scales. We find the power law to be invariant regardless of whether large shoals are present or not. Quantitative knowledge of this power law now enables more accurate statistical predictions of the spatial distribution of fish populations to be made.

(2) Novel analytic expressions have been derived for the mean, mutual intensity, and spatial covariance of the 3-D acoustic field forward propagated through a random ocean waveguide containing 3-D random surface and volume inhomogeneities [P26,P32]. It enables proper modeling of scattered fields from targets and reverberation, as well as one-way transmission. The expressions include the accumulated effect of multiple forward scattering due to the random inhomogeneities. These inhomogeneities need not obey a stationary random process in space and can be of arbitrary composition and size relative to the wavelength or have large surface roughness and slope. The form of the mean forward field after multiple scattering through the random waveguide is similar to that of the incident field except for a complex change in the horizontal wavenumber of each mode. This change describes attenuation and dispersion induced by the medium's inhomogeneities, including potential mode coupling along the propagation path. Expressions for the mutual intensity and spatial covariance of the forward field are expressed in terms of both the random medium's expected modal extinction density as well as the covariance of its scatter function density, which couples each mode to all other modes due to multiple forward scattering. These are used to analytically show that 3-D scattering effects can become important for scatterers at ranges where the Fresnel width exceeds the medium's local cross-range coherence length. The expressions can also be applied to determine how the coherence of an acoustic signal received by an array of arbitrary configuration is degraded by random multiple forward scattering through the fluctuating ocean.

(3) The theory for the forward-propagated field developed by the PI and his group [P26,P32] has been applied to obtain the statistical moments of the acoustic field forward-propagated through an ocean waveguide containing 3-D random internal waves [P27,P31,P33]. The formulation accounts for the accumulated effects of 3-D multiple forward scattering. These lead to redistribution of both coherent and incoherent modal energies, including attenuation and dispersion. The mean and variance of the forward field propagating through internal waves is expressed in terms of the stochastic moments of the medium's scatter function density that is modeled using the Rayleigh-Born approximation to Green's theorem to account for random fluctuations in both density and compressibility due to internal waves. Physical and statistical properties of the internal waves are modeled with the Garret-Munk and other theoretical and empirical formulations. We simulate a typical continental-shelf environment containing random internal waves and show that when internal wave root-mean-square (RMS) height

exceeds the acoustic wavelength, the acoustic field becomes so randomized that the expected total intensity is dominated by the field variance beyond moderate ranges. This leads to an effectively saturated field that decays monotonically and no longer exhibits the periodic range-dependent modal interference structure present in non-random waveguides. We have also shown that 2-D models for the mean and variance of the acoustic field propagated through a 3-D random internal wave field then become inaccurate when the Fresnel width approaches and exceeds the cross-range coherence length of the internal wave field.

(4) We have developed a new, innovative *array invariant* source localization technique in a dispersive waveguide that requires no *a priori* knowledge of the environment [P36-P38]. The array invariant techniques enable simple, robust, and instantaneous source-range estimation in a horizontally-stratified ocean waveguide from passive beam-time intensity data obtained after conventional plane-wave beamforming of acoustic array measurements. The array invariant method is applicable for both broadband transient source signatures [P36,P38] and continuous broadband random noise signatures [P37]. The method has significant advantages over existing source localization methods such as matched field processing or the waveguide invariant. First, no knowledge of the environment is required except that the received field should not be dominated by purely waterborne propagation. Second, range can be estimated in real time with little computational effort beyond plane-wave beamforming. Third, array gain is fully exploited. The method has been applied to data from the Main Acoustic Clutter Experiment of 2003 for source ranges between 1 to 8 km, where it is shown that simple, accurate, and computationally efficient source range estimates can be made.

(6) We have combined a stochastic model for the velocities of targets with the model for scattering from a moving target submerged in a stratified ocean waveguide [P34] to estimate the Doppler shift and spread expected in long-range target detection and tracking [P28]. We have exploited the dynamic nature of moving targets to show that Doppler shift and spread can be used to discriminate moving targets such as submarines and fish school from stationary clutter features using low-frequency, long-range acoustic imaging. Our statistical Doppler model in an ocean waveguide shows that both mean radial velocity and standard deviation of a target speed can be estimated from the mean frequency shift and RMS bandwidth of the scattered field.

## IMPACT/APPLICATIONS

- We have provided temporal and spatial characteristics of clutter features caused by fish schools in continental shelf environment. From a navy sonar perspective, understanding these characteristics of clutter features will help in the development of adaptive sonar which is capable of distinguishing bioclutter features from intended, man-made targets.
- Analytic expressions have been derived for the first time to describe the mean and covariance of the acoustic field after multiple forward scattering through a random ocean waveguide with arbitrary 3-D inhomogeneities. This is extremely important for active, as well as passive, sonar systems in detecting and identifying objects in a waveguide. These statistical 3-D models have been validated with simulations of realistic continental shelf scenarios.

- The analytic expressions for the forward-propagated field can also be applied to determine how the coherence of an acoustic signal received by an array of arbitrary configuration is degraded by random multiple forward scattering through the fluctuating ocean.
- We have derived a rigorous theoretical model that quantifies the accumulated effects of multiple forward scattering through random internal wave field. We have shown that 2-D models for the mean and variance of the acoustic field propagated through a 3-D random internal wave field become inaccurate when the Fresnel width approaches and exceeds the cross-range coherence length of the internal wave field. This is extremely important for assessing the performance of Navy sonar systems in a continental shelf environment where internal waves are ubiquitous.
- We have developed a novel passive source localization method in an ocean waveguide, called the array invariant, that requires no a priori knowledge of the wave propagation environment or extensive numerical computations. The array invariant method has tremendous potential application in shallow-water surveillance missions and anti-submarine warfare.
- We have demonstrated that the Doppler shift and spread can provide a practical method to distinguish moving targets such as submarines, underwater vehicles, and small fish schools from stationary clutter features. This can be applied to Navy sonar systems to discriminate moving targets that are potential threats from stationary clutter features.

## **TRANSITIONS**

Transition of the Acoustic Clutter Program results to direct Navy programs has already begun with data acquisition by the hull mounted sonar system of a US Destroyer in the STRATAFORM area in an experiment jointly designed by the PI and NUWC Geoclutter investigator Mike Sundvik. This experimental effort used the Destroyer's sonar to probe areas where clutter was found in the initial Acoustic Clutter Reconnaissance Experiment of 2001. Both moving clutter and the same stationary calibrated targets deployed in all Geoclutter experiments were observed by the Destroyer and "tracked" in standard Navy classifiers, meaning they registered as potential moving threats, highlighting the direct relevance and impact of the proposed work to the Navy. This rapid transition is a direct result of the findings of this basic research program. Ideas and concepts transition faster than anything else. The results of this program led to a whole new NOPP funding base to use new acoustic methods to remotely detect, localize, and enumerate marine life in the ocean.

## **RELATED PROJECTS**

Other organizations participating in the Geoclutter Program are UTIG, NRL, ARL-PSU, and NUWC.

## **PUBLICATIONS**

P1. P. Ratilal, Y. Lai, D. T. Symonds, L. A. Ruhlmann, J. Goff, C. T. Holland, J. R. Preston, E. K. Scheer, M. T. Sundvik, and N. C. Makris, "Long Range Acoustic Imaging of the Continental Shelf Environment: The Acoustic Clutter Reconnaissance Experiment 2001," submitted to Journal of the Acoustical Society of America (2003).

- P2. N.C. Makris and P. Ratilal, ONR 2003 Annual Report for Post-Doctoral Fellowship Award, N000140310236.
- P3. N. C. Makris (Editor), Geoclutter Acoustics Experiment 2003 Cruise Report, MIT Cambridge MA (2001).
- P4. N. C. Makris (Editor), Geoclutter Acoustics Experiment 2001 Cruise Report, MIT Cambridge MA (2001).
- P5. P. Ratilal, Y. Lai and N. C. Makris, "Validity of the sonar equation and Babinet's principle for scattering in a stratified medium," J. Acoust. Soc. Am. (in Press for Sept or Oct 2002).
- P6. N. C. Makris, "A spectral approach to 3-D object scattering in layered media applied to scattering from submerged spheres," J. Acoust. Soc. Am. 104, 2105-2113 (1998).
- P7. N. C. Makris, F. Ingenito, W. A. Kuperman, "Detection of a submerged object insonified by surface noise in an ocean waveguide," J. Acoust. Soc. Am. 96, 1703-1724 (1994).
- P8. N. C. Makris, L. Avelino, R. Menis, "Deterministic reverberation from ocean ridges," J. Acoust. Soc. Am. 97, 3547-3574 (1995).
- P9. N. C. Makris, C. S. Chia and L. T. Fialkowski, "The bi-azimuthal scattering distribution of an abyssal hill," J. Acoust. Soc. Am. 106, 2491--2512, (1999).
- P10. C. S. Chia, L., N. C. Makris and T. Fialkowski, "A comparison of bi-static scattering from two geologically distinct abyssal hills," J. Acoust. Soc. Am. 108, 2053-2070 (2000).
- P11. Purnima Ratilal, "Remote Sensing of Submerged Objects and Geomorphology in Continental Shelf Waters with Acoustic Waveguide Scattering," MIT Doctoral Thesis, Makris Supervisor, June 2002.
- P12. Gihard Ben-Joshua, "The effects of modal dispersion in a shallow water waveguide," MIT Master's Thesis, Makris Supervisor, June 2002.
- P13. N. C. Makris, P Ratilal, D T. Symonds and R W. Nero, "Continuous wide area monitoring of fish shoaling behavior with acoustic waveguide sensing and bioclutter implications, "J. Acoustic. Soc. Am 115, 2619 (2004).
- P14. D. T. Symonds, P. Ratilal, N. C. Makris and R. W. Nero, "Inferring fish school distributions from long range acoustic images: Main acoustic clutter experiment 2003," J. Acoustic. Soc. Am 115, 2618-26199 (2004).
- P15. S. Lee, P. Ratilal, and N. C. Makris, "Explaining extended linear features observed in remote sonar images of the New Jersey continental shelf break during Acoustic Clutter Experiments in 2001 and 2003," J. Acoustic. Soc. Am 115, 2618 (2004).

- P16. T. Chen, S. Lee, Y. Lai, P. Ratilal, and N. C. Makris, "Analysis of acoustic intensity fluctuations measured after one-way transmission and bistatic target scattering on the New Jersey continental shelf during MAE 2003," *J. Acoustic. Soc. Am* 115, 2549 (2004).
- P17. N. C. Makris, P. Ratilal, Y. Lai, S. Lee, D. T. Symonds, L. A. Ruhlmann, R. W. Nero, J. R. Preston, E. K. Scheer, M. T. Sundvik, "Long-range acoustic imaging of the Continental Shelf Environment reveals massive fish schools: 2003 Main Acoustic Clutter Experiment," *J. Acoustic. Soc. Am* 114, 2375 (2003).
- P18. D. T. Symonds, P. Ratilal, R. W. Nero and N. C. Makris, "Fish schools are the dominant cause of long-range active sonar clutter in the New Jersey Continental Shelf: Quantitative correlations," *J. Acoustic. Soc. Am* 114, 2375 (2003).
- P19. Y. Lai, S. Lee, P. Ratilal, and N. C. Makris, "Comparison of modeled and measured sonar returns from calibrated targets in the Main Acoustic Clutter Experiment 2003," *J. Acoustic. Soc. Am* 114, 2312 (2003).
- P20. P. Ratilal and N. C. Makris, "Coherent versus diffuse surface and volume Reverberation in an ocean wave guide: Reverberation rings, modal decoupling, and possible fish scattering in Geoclutter 2001," *J. Acoustic. Soc. Am* 112, 2280 (2002).
- P21. N. C. Makris, P. Ratilal, Y. Lai, and D. T. Symonds, L. A. Ruhlmann and E. K. Scheer, "The Geoclutter Experiment 2001: Remote acoustic imaging of sub-bottom and seafloor geomorphology in continental shelf waters," *J. Acoustic. Soc. Am* 112, 2280 (2002).
- P22. N. C. Makris, P. Ratilal, Y. Lai, and E. Scheer, "The Geoclutter experiment: Remotely imaging sub-bottom geomorphology in shallow water," *J. Acoustic. Soc. Am* 110, 2280 (2001).
- P23. F. Ingenito, "Scattering from an object in a stratified medium," *J. Acoust. Soc. Am.* **82**, 2051 (1987)
- P24. P. Ratilal, Y. Lai and N.C. Makris, "Validity of the sonar equation and Babinet's principle for scattering in a stratified medium," *J. Acoust. Soc. Am.* **112**, 1797 (2002)
- P25. N. C. Makris, ONR 2004 Annual Report for Acoustic Clutter in Continental Shelf Environment, N000109911059
- P26. P. Ratilal and N. C. Makris, "Unified model for 3-D scattering and forward propagation in a stratified ocean waveguide with random seabed inhomogeneities," *J. Acoust. Soc. Am.* **116**, 2527 (2004).
- P27. P. Ratilal, T. Chen, and N. C. Makris, "Estimating internal wave statistics from underwater acoustic transmission scintillation measurements on the New Jersey shelf with a 3-D stochastic model," *J. Acoust. Soc. Am.* **116**, 2506 (2004)
- P28. N. C. Makris, Y. Lai, I. Bertsatos, D. Symonds, S. Lee, and P. Ratilal, "Expected Doppler shift and spread in long range scattering from fish schools on the continental shelf," *J. Acoust. Soc. Am.* **116**, 2488 (2004)

- P29. N. Donabed, P. Ratilal, and N. C. Makris, "Dominant source of background reverberation during the Acoustic Clutter 2003 experiment," *J. Acoust. Soc. Am.* **117**, 2611 (2005)
- P30. P. Ratilal, S. Lee, Y. Lai, T. Chen, D. Symonds, N. Donabed, and N. C. Makris, "Range-dependent 3D scattering and reverberation in the continental shelf environment from biology, geology and oceanography," *J. Acoust. Soc. Am.* **117**, 2611 (2005)
- P31. T. Chen, P. Ratilal, and N. C. Makris, "Mean and variance of the 3-D field forward propagated through random internal waves in continuously stratified deep and shallow water ocean waveguides," *J. Acoust. Soc. Am.* **117**, 2548 (2005)
- P32. P. Ratilal and N. C. Makris, "Mean and covariance of the forward propagated through a stratified ocean waveguide with three-dimensional random inhomogeneities," *J. Acoust. Soc. Am.*, In press (2005)
- P33. T. Chen, P. Ratilal, and N. C. Makris, "Mean and variance of the forward field propagated through three-dimensional random internal waves in a continental-shelf waveguide," *J. Acoust. Soc. Am.*, In press (2005)
- P34. Y. Lai and N. C. Makris, "Spectral and modal formulations for the Doppler-shifted field scattered by an object moving in a stratified medium," *J. Acoust. Soc. Am.* **113**, 223-244 (2003)
- P35. N. C. Makris, P. Ratilal, D. T. Symonds, S. Jagannathan, S. Lee, R. W. Nero, "Fish population and behavior revealed by instantaneous continental-shelf-scale imaging," Submitted to *Science* (2005)
- P36. S. Lee and N. C. Makris, A new invariant method for instantaneous source range estimation in an ocean waveguide from passive beam-time intensity data, *J. Acoust. Soc. Am.* **116**, 2646, (2004)
- P37. S. Lee and N. C. Makris, Range estimation of broadband noise sources in an ocean waveguide using the array invariant. *J. Acoust. Soc. Am.* **117**, 2577 (2005)
- P38. S. Lee, N. C. Makris, The array invariant, *J. Acoust. Soc. Am.*, In press (2005)