PENNSTATE
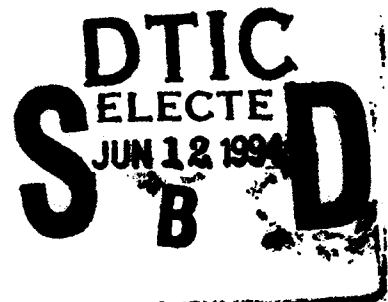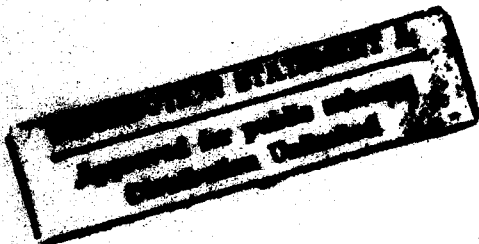
Applied Research Laboratory

FINAL REPORT

OFFICE OF NAVAL RESEARCH
FUNDAMENTAL RESEARCH INITIATIVES
N00014-90-J-1365

DTIC
ELECTE
JUN 12 1994
S B D

1 October 1989 - 31 May 1994

29 94-17984

94 6 10 090

DTIC QUALITY INSPECTED 1

OFFICE OF NAVAL RESEARCH
FUNDAMENTAL RESEARCH INITIATIVES
N00014-90-J-1365

FiNAL REPORT

1 October 1989 - 31 May 1994

Applied Research Laboratory
The Pennsylvania State University
P.O. Box 30
State College, PA 16804

Table of Contents

A Statistical Solution to Shallow Water Propagation that Includes Chaos

N00014-90-J-1365
Martin A. Mazur and Diana F. McCammon
The Pennsylvania State University
Applied Research Laboratory
P. O. Box 30
State College, PA 16804
Tel: (814) 863-4782 (Mazur) (814) 863-4159 (McCammon)
email: internet: mam@arlvax.arl.psu.edu

Objective: Ray tracing in range dependent environments generally leads to chaotic ray paths [1]. However, Collins and Kuperman [2,3] have recently shown that ray chaos can be overcome by recasting ray tracing in terms of Fermat's principle of minimum propagation time. The objective of this research is to expand this idea by applying a variety of techniques from optimization theory and the theory of two-point boundary value problems to the calculation of eigenrays in range dependent environments.

Background: In classical ray tracing, eigenrays between a source and receiver are determined by an initial value or 'shooting' approach. The launch angles of rays from a source point are varied until the rays intersect the receiver end point. In range dependent environments, the ray paths are generally chaotic [1]. This puts a fundamental limit on the accuracy of ray tracing, even with perfect knowledge of environmental conditions. Because of the extreme sensitivity of chaotic ray paths to initial conditions, the calculation of eigenrays in range dependent environments quickly becomes impossible. Recently, Collins and Kuperman [2,3] have shown that ray chaos can be overcome by recasting the problem in terms of Fermat's principle of minimum propagation time. The problem then becomes amenable to techniques of optimization theory and the theory of two-point boundary value problems. In [3], the travel time integral was minimized using an optimization technique called simulated annealing. A relaxation technique for the solution of two-point boundary value problems, the 'bending' method, was also investigated. Simulated annealing produces stable eigenrays, but is computationally inefficient. The relaxation technique is very fast but extremely sensitive to the quality of the initial guess and can fail to converge.

Current Research: Accomplishments and Goals. In our research we are investigating using the Rayleigh-Ritz method to minimize the travel time integral. In this technique, a candidate eigenray is represented as a finite linear combination from among a complete set of basis functions. The coefficients of these functions are adjusted until the travel time is minimized. The number of coefficients is then increased until the desired accuracy is achieved. Using this technique, we have calculated stable eigenrays in a range dependent sound speed profile that is notable for producing extremely chaotic ray paths when the shooting method is used. Figure 1 shows some rays emanating from a source point as calculated using the shooting method. The launch angles of these rays are all within 10^{-5} degree of the launch angle of the eigenray connecting (0,0.2) and (100, 0.2) calculated using simulated annealing [3]. The eigenray calculated using the Rayleigh-Ritz method is indistinguishable from this eigenray and is shown in bold. The sound speed profile is $c(r,z) = c_0 (1 + \alpha \cos K_r r \cos K_z z)$ where $c_0 = 1.5$ km/s, $\alpha = 0.02$, $K_z = 2\pi/0.5$ km^{-1} and $K_r = 2\pi/20$ km^{-1}.
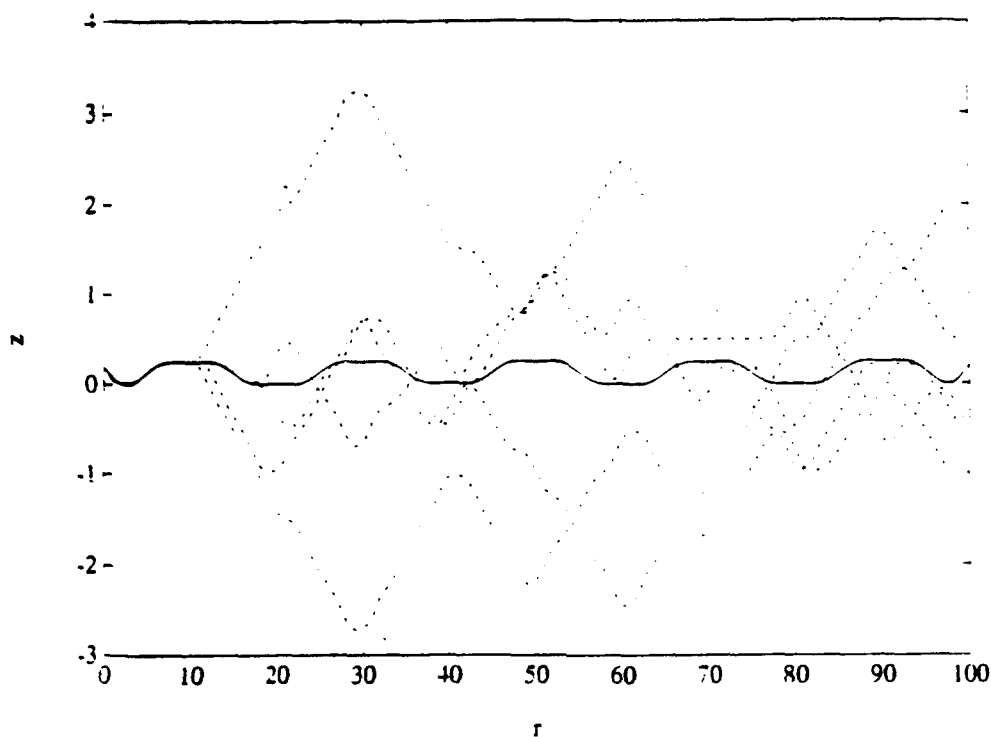
Figure 1. Rayleigh-Ritz Eigenray and Chaotic Shooting Rays

We have used both sine functions and 'hat' functions as basis functions. The sine function basis set is particularly useful for the following reasons: (1) The resulting representation for an eigenray is economical. In our example, the eigenray is represented well by 16 coefficients. This compares with having to optimize over hundreds of grid points in the simulated annealing and relaxation techniques. (2) In environments where the rays oscillate, the coefficients found in the calculation of an eigenray can be useful in formulating initial guesses for the coefficients of longer range rays.

Our immediate goal is to submit for publication in JASA a paper detailing our results to date. Mr. Mazur will continue the research started under this grant to complete his doctoral thesis. This research will include investigations of other optimization techniques and comparisons of their usefulness in terms of ease of implementation, speed, and adaptability to environments with boundary interactions.

References

[1]   D. R. Palmer. M. G. Brown. F. D. Tappert. H. F. Bezdek, "Classical Chaos in Nonseparable Wave Propagation Problems". Geoph. Res. Let., v. 15 No. 6, 569-572 (1988).

[2]   W. A. Kuperman and M. D. Collins. "Finding eigenrays by optimization with application to tomography and overcoming chaos". J. Acoust. Soc. Am 93 2425 (1993).

[3]   M. D. Collins and W. A. Kuperman. "Overcoming ray chaos", to appear in June 1994 J. Acoust. Soc. Am.

Conferences Attended and Contributed Talks: Martin A. Mazur attended the 124th Meeting of the Acoustical Society of America held in New Orleans, Louisiana from October 31 to November 4, 1992. He delivered a talk related to this research effort entitled *Does ray chaos in range dependent environments disappear when higher-order approximations are made?*

Graduate Students: Martin A. Mazur is a graduate student supported by this research effort. He is a US citizen. His expected date of graduation if June, 1995. The title of his Ph.D. thesis is *Novel Approaches to Mitigating the Effects of Chaos in the Calculation of Acoustic Eigenrays in Range Dependent Environments*. The thesis will be theoretical with significant numerical portions. The objective of the thesis is to develop and compare a variety of techniques which can be used to mitigate or overcome ray chaos when calculating eigenrays in range dependent environments. The theoretical underpinnings of these techniques will also be developed.

High Frequency Surface Scattering Statistics (N00014-90-J-1365)

Richard Lee Culver
The Pennsylvania State University
Graduate Program in Acoustics
State College, PA   16804
(814) 867-0150
Email: rlc@abe.arl.psu.edu
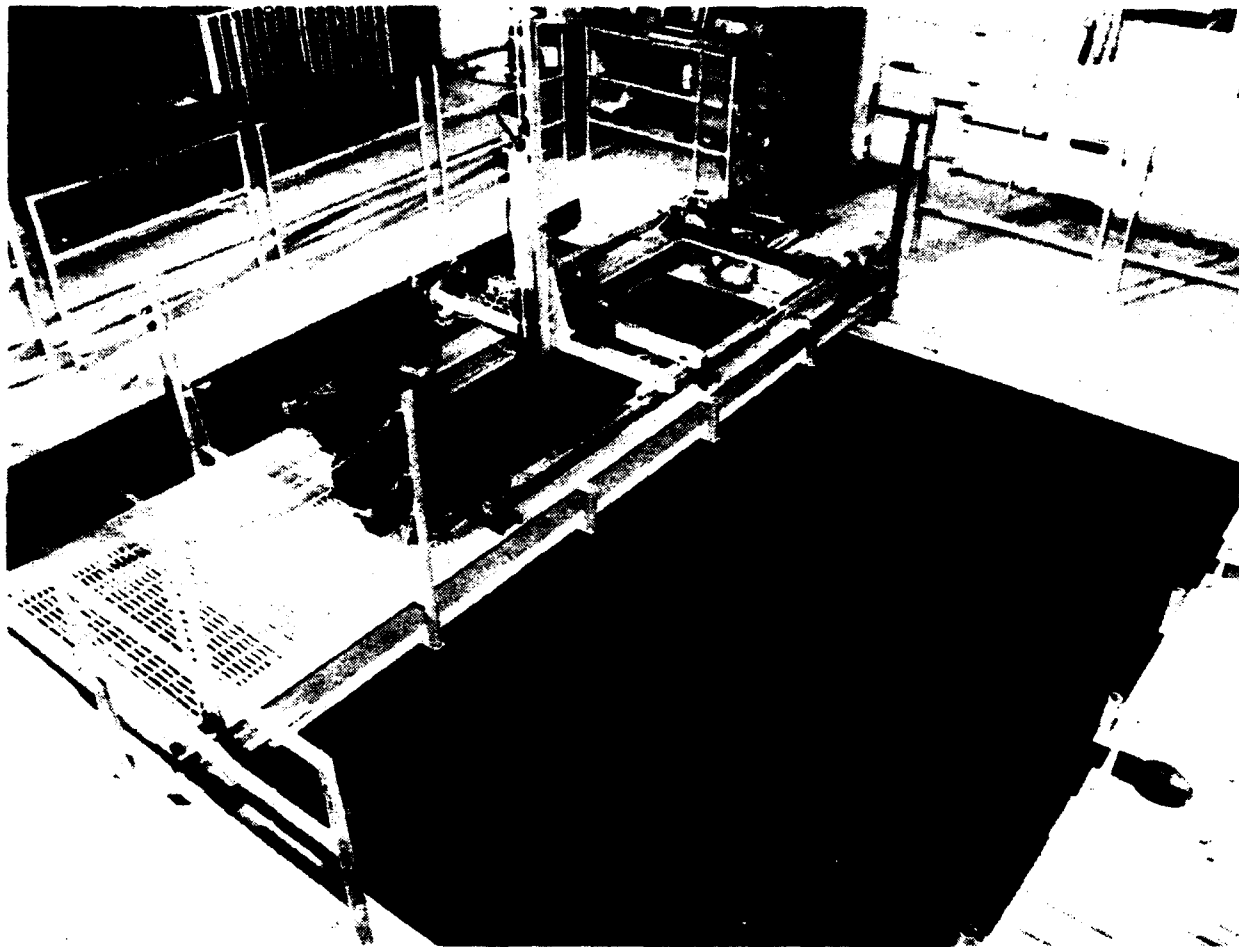
FY93 Accomplishments

- Completed development and testing of a five axis transducer positioning system for use in the new 29'x23'x18' acoustic measurement water tank (pictured above).

- Designed and built a very high speed (1 ms) transmit/receive (T/R) switch for monostatic acoustic measurements.

- Non-Rayleigh scattering encountered using a single frequency sinusoidal surface when returns from several aspect angles are combined.

Papers, Talks and Conferences

- P.D. Neumann and R.L. Culver, *Statistical characteristics of bistatic surface scatter,* presentation made at the Acoustical Society of America meeting, Ottawa, Canada, 17-21 May 1993.

- Symposium on Coastal Oceanography and Littoral Warfare, San Diego, CA, 2-5 August 1993.

- R.L. Culver and P.D. Neumann, *High Frequency Bistatic Ocean Surface Scattering,* invited paper, Acoustical Society of America semi-annual meeting, Denver, Colorado, 4-8 October 1993.

- K.M. Becker, *Construction and calibration of an underwater acoustic transducer,* invited article, Scientific American, mailed February 1994.

- R.L. Culver and K.M. Becker, *A computer-controlled 5 axis transducer positioning system,* under preparation.

Graduate Students Supported

Kyle M. Becker (US citizen)	Expected graduation date: 12/94 (MS Acoustics)
Experimental/theoretical thesis:	*The relationship between surface characteristics and scattering strength statistics*

Thesis objective: The objective of Kyle's work is to determine the physical mechanisms or surface properties which cause ocean surface scattering strength distribution to deviate from exponential. As part of his research, he designed, built and tested the transducer positioning system. He is currently designing random but statistically stationary surfaces, measuring the statistics of monostatic scattering from the surfaces, and relating the elevation statistics of the surfaces to the scattering statistics.

Todd A. Mathias (US citizen)	Expected graduation date: 12/95 (MS Acoustics)
Experimental/theoretical thesis	*A Stud· of Bistatic Surface Scattering Statistics*

Thesis objective: The objective of Todd's work is to investigate high frequency bistatic surface scattering strength. As part of his research, Todd is developing the computer interface to the transducer positioning system. During the year ahead, Todd will extend Kyle's work to bistatic geometries (transmitter and receiver not at the same location) and utilize a higher frequency transducer in order to investigate the effects of scale.

Transitions, Application of this Research

Because I also direct the 6.2 Torpedo Environments project (RO35H01) which provides high frequency environmental acoustic information to the Advanced Undersea Weapons G&C Block (OT3A), I am able to focus my 6.1 Fundamental Initiatives research on an issue which is critically important to shallow water undersea weapon development, non-Rayleigh boundary scattering. On the other hand, I am also in a position to integrate results of the 6.1 research into a 6.2 program for application and evaluation, and when warranted, transition to 6.3 undersea weapons or MCM programs.

My Fundamental Initiatives-sponsored work is only 3 years old, and during the last three years we have interrupted our measurement program to develop important tools. A linear actuator-based transducer positioning system capable of translation in 3 dimensions and rotation in azimuth and elevation was designed and built because meaningful false alarm statistics require 10^3 to 10^4 independent measurements for each geometry. A transmit/receive (T/R) switch (which blocks out the power amplifier during receive) capable of 1 ms switching speeds was designed and built because such a device is not commercially available. A 40 dB gain in SNR was achieved. Finally, the work has been moved to a 29'x23'x18' water tank located in the new ARL building, completed only this past fall. While the old tank was adequate, the new tank provides a greater opportunity for the work to expand.

The significant outcome of the work thus far has been the finding that non-Rayleigh statistics are obtained when scattering strengths obtained from different aspects of a strongly polarized surface are combined. This has led to speculation that non-Rayleigh scattering from the ocean boundaries might be caused by patches of strong (or coherent) scattering intermingled with areas which scatter more weakly. Such surfaces have been dubbed *confused-coherent* by D.F. McCammon, who was a co-PI when this work was began and continues to be involved.

The current effort is to fabricate a series of new surfaces and evaluate the *confused-coherent* hypothesis. Dr. Steve Stanic of NRL/Stennis has agreed to provide information about bottom relief obtained from his experiments, which will guide selection of the surface characteristics. A multi-axis milling machine at ARL can form surfaces with specified elevation spectra. Measurements will be made with both monostatic and bistatic geometries

This work could one day be applied to undersea weapon development in the following way. It is known that boundary scattering can mask target echoes in shallow water. Our work to characterize non-Rayleigh surface scattering can help us understand the statistics of shallow water boundary reverberation. An effort under the 6.2 Torpedo Environments Project will attempt to distinguish target echoes from boundary reverberation based upon their different statistics.

A Higher Order Stochastic Model for Surface Backscatter in High Sea States

Kenneth E. Gilbert and Lucy J. Kulbago
Applied Research Laboratory and the Graduate Program in Acoustics
The Pennsylvania State University
P. O. Box 30
State College, PA 16804
Telephone: (814) 863-8291

Objective: To incorporate into an existing plane-wave surface scattering model the improvements necessary to model backscatter in high sea states and shallow water where the insonifying field departs significantly from a plane wave. Work to date has dealt with high sea states since experimental data is available.

Background: In the previous year a stochastic oceanic bubble layer model was developed in which the statistics of the microbubble distribution are controlled by turbulence in the inertial subrange (Kolmogorov turbulence). In FY93 surface backscatter was computed using the stochastic bubble layer model and a first-order scattering method (Plane-Wave Born Approximation--PWBA)[1] as well as a higher-order scattering method (Distorted-Wave Born Approximation--DWBA)[2]. The results indicate that, in high sea states, turbulent transport of microbubbles has two major effects on the backscatter from the bubble layer. First, the chaotic nature of turbulence leads to a sound speed that varies stochastically in space and time but that has a characteristic wave-number spectrum. As a consequence, the backscatter from the layer has a characteristic dependence on the frequency. Second, the bubble layer, although stochastic, is a region where the sound speed is on average less than in bubble-free water. In high sea states the average sound speed reduction is sufficient to cause significant near-surface upward refraction for low grazing angles. In such situations, the insonifying field is not well represented by a plane-wave. Therefore we have considered a higher-order scattering model that takes into account both the average and stochastic properties of the microbubble distribution. It is shown that with measured oceanographic inputs (i.e., no adjustable parameters) the model gives a good account of the measured backscatter data of Ogden and Erskin[3].

Approach: To account for a non-planar incident wave, we use the so-called "Distorted-Wave Born Approximation" (DWBA). With the DWBA the plane-wave insonifying field is replaced by the solution for a wave propagating in the average sound-speed profile in the bubble layer. In Figure 1, we compare the effective insonifying fields for plane waves (PWBA) and distorted waves (DWBA) for conditions typical of a high sea state (WS= 30 kt). It is evident from Figure 1 that for low grazing angles and high sea states there are significant differences between the plane-wave solutions and the corresponding distorted-wave solutions. The effect of the distortion of the plane wave is to enhance the effective near-surface field at low frequencies (f$\lesssim$ 300 Hz) and to suppress it at higher frequencies (f $\gtrsim$ 300 Hz).

Results: Figure 2 compares the predicted scattering strength-versus-frequency with the Ogden-Erskin empirical fits to Critical Sea Test data for several grazing angles. Two distorted wave calculations are shown: An exact numerical solution that shows resonance effects and a WKB

frequencies. this modification of the plane-wave result is in qualitative agreement with the measured backscatter. Current research is directed toward a better estimate for the average insonifying field in order to improve the agreement with measured surface backscatter for high sea states and low grazing angles.

References

[1]   Kenneth E. Gilbert, A stochastic model for scattering from the near-surface bubble layer, J. Acoust. Soc. Am. **94**, 3325-2352 (1993).

[2]   Lucy J. Kulbago and Kenneth E. Gilbert, "Surface scattering: The role of turbulent mixing of microbubbles," to be published in a refereed book of the Proceedings of the International Conference on Theoretical and Computational Acoustics, Mystic Connecticut, July 5-9, 1093.

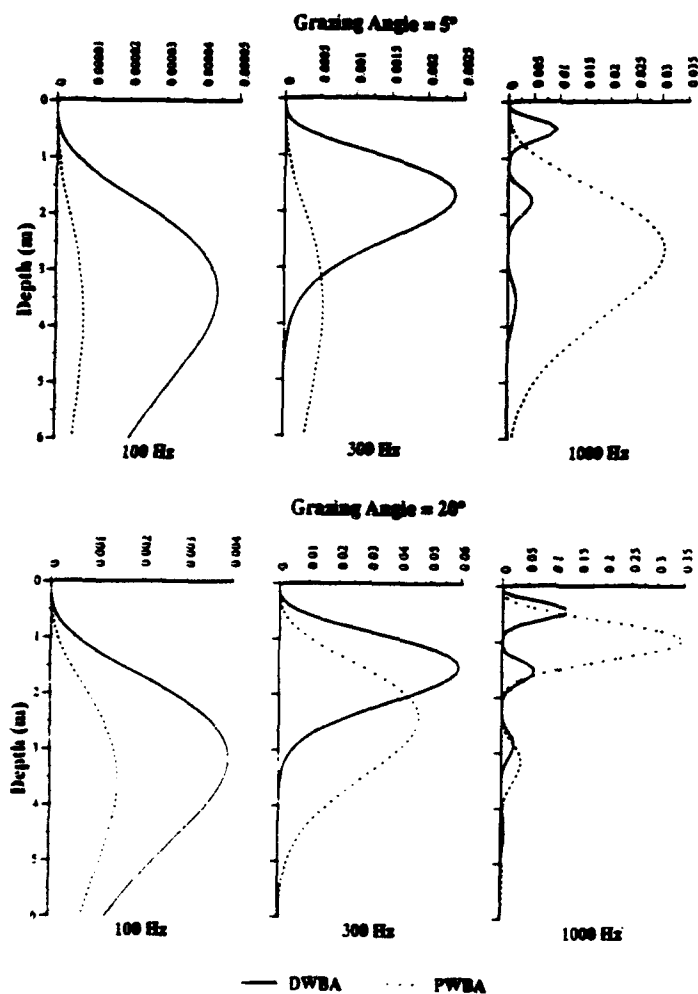[3]   P. M. Ogden and F. T. Erskin. Naval Research Laboratory Rpt. NRL/FR/5160-92-9377.

Figure 1. Comparison of the effective insonifying field for plane waves (PWBA) and for distorted waves (DWBA). Relative to the plane-wave result, distortion of the incident wave enhances the insonification at low frequencies and suppresses it at high frequencies.
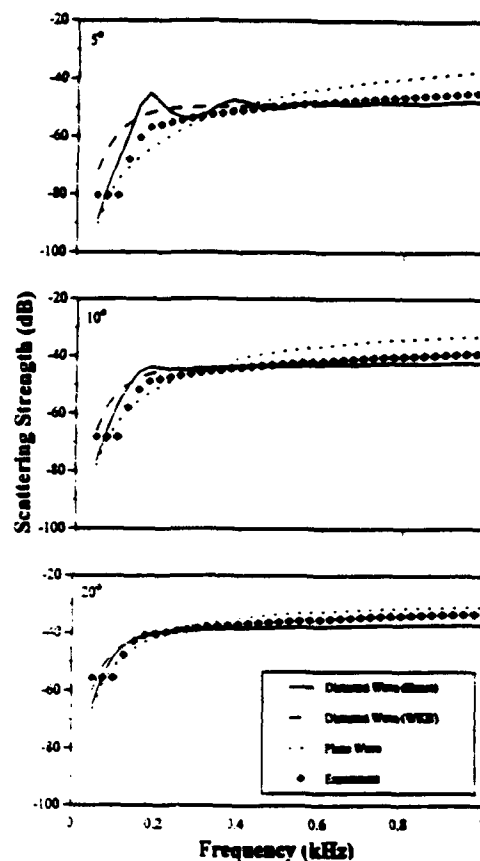
Figure 2. Scattering strength versus frequency at several fixed grazing angles. The solid line is a distorted-wave Born approximation calculation (DWBA) using an exact numerical solution for the distorted incident wave. The long dashed line is a DWBA calculation using a WKB approximation for the distorted incident wave. The short dashed line is a plane-wave Born approximation calculation (PWBA). The diamonds are the Ogden-Erskin empirical fit to the Critical Sea Test data.

Activity Report for FY93 (1 Oct 1992 - 30 Sept 1993)

1. Papers in refereed publications

Kenneth E. Gilbert, A stochastic model for scattering from the near-surface oceanic bubble layer, J. Acoust. Soc. Am. **94**, 3325-2352 (1993).

Kenneth E. Gilbert and Xiao Di, " A fast Green's function method for outdoor sound propagation," J. Acoust. Soc. Am. **94**, 2343-2352 (1993).

Xiao Di and Kenneth E. Gilbert, "An exact Laplace transform formulation for a point source above a ground surface," J. Acoust. Soc. Am., **93**, 714-720 (1993).

2. Papers submitted to refereed journals

K. Attenborough, S. Taherzadeh, H.E. Bass, R. Raspet, G.R. Becker, A. Gudesen, A. Chrestman, G.A. Daigle, A.L'sperance, Y. Gabillet, K.E. Gilbert, Y.L. Li, M.J. White, P. Naz, J.M. Noble, H. van Hoof, "Benchmark cases for outdoor sound propagation models," submitted to the Journal of the Acoustical Society of America (This paper involves an international collaboration on an extensive set of benchmark calculations. The names are in alphabetical order.)

3. Books or chapters, authored or edited

Kenneth E. Gilbert and Lucy J. Ameling, "Surface scattering: the role of turbulent mixing of microbubbles," to be published in a refereed hard-cover book of the Proceedings at the International Conference on Theoretical and Computational Acoustics, Mystic Connecticut, July 5-9, 1993.

4. Technical reports written

Kenneth E. Gilbert and Ralph R. Goodman, "Acoustic backscatter from the near-surface oceanic bubble layer," contribution to Applied Research Laboratory Review (1993).

Xiao Di and Kenneth E. Gilbert, "An analytic conformal mapping for sound propagation over terrain," NCPA Report No. XD 1-93, University of Mississippi (Jan. 1993)

5. Invited papers or talks

Xiao Di and Kenneth E. Gilbert, "Application of numerical grid generation to sound propagation over irregular terrain," invited paper presented at the 124th meeting of the Acoustical Society of America, New Orleans, Louisiana, 31 October - 4 November, 1992.

6. Contributed papers or talks

Kenneth E. Gilbert, "Stochastic scattering model predictions for reverberation from the near-surface oceanic bubble layer," presented at the 124th meeting of the Acoustical Society of America, New Orleans, Louisiana, 31 October - 4 November, 1992.

9

Xiao Di and Kenneth E. Gilbert, "A phase screen approach to sound propagation through small-scale turbulence, presented at the 124th meeting of the Acoustical Society of America, New Orleans, Louisiana, 31 October - 4 November, 1992.

Kenneth E. Gilbert and Xiao Di, "Some recent developments in parabolic equation methods for outdoor sound propagation," presented at the 26th panel meeting of the NATO Research Study Group 11, Quebec, Canada, October 26-29, 1992.

Kenneth E. Gilbert and Lucy J. Ameling, "Surface scattering: the role of turbulent mixing of microbubbles," presented at the International Conference on Theoretical and Computational Acoustics, Mystic Connecticut, July 5-9, 1993.

Xiao Di, Kenneth E. Gilbert, and Lucy J. Ameling, "A fast phase-screen method for sound propagation through a turbulent atmosphere," 125th meeting of the Acoustical Society of America, Ottawa, Canada, 17-21 May 1993.

7. Conferences attended

124th meeting of the Acoustical Society of America, New Orleans, Louisiana, 31 October - 4 November, 1992.

NATO Research Study Group 11, 26th panel meeting, Quebec, Canada, October 26-29, 1992.

Benthic Boundary Layer Special Research Program Workshop I. NRL-Stennis Space Center, MS, October 29-30, 1992. Sponsored by Office of Naval Research

Benthic Boundary Layer Special Research Program Workshop II. NRL-Stennis Space Center, MS, January 7-8, 1993. Sponsored by Office of Naval Research

Critical Sea Test 7 Data Review Workshop, Applied Physics Laboratory, Johns Hopkins University, February 3, 1993. Sponsored by Office of Naval Research

125th meeting of the Acoustical Society of America, Ottawa, Canada, 17-21 May 1993.

Review of Army Battlefield Acoustics Program, May 24-24, 1993 Penn State University. Sponsored by the Army Research Laboratory and the Army Research Office.

8. Patent applications
None

9. Honors (promotions, awards, etc.)

Elected Chairman of the Technical Committee on Underwater Acoustics

Elected Vice President of the Pennsylvania Chapter of the Acoustical Society of America

Appointed to membership on the Technical Committee on Acoustical Oceanography.

Organizer and session chairman tor two special sessions of the 126th meeting of the Acoustical Society of America

10. Graduate Students

Name: Lucy J. Kulbago
Citizenship: U.S.
Type of thesis: theoretical
Thesis title: Acoustic backscatter from the near-surface oceanic bubble layer
Objective: Incorporate into an existing plane-wave surface scattering model the improvements necessary to model backscatter in high sea states and shallow water where the insonifying field departs significantly from a plane wave. Work to date has dealt with high sea states since experimental data is available.

Name: Timothy J. Kulbago
Citizenship: U.S.
Type of thesis: theoretical/numerical
Thesis title: Wavelet analysis of acoustic backscatter from the benthic boundary layer.
Objective: Use wavelet analysis of acoustic backscatter from shallow water bottoms to extract additional information relative to conventional processing. In particular investigate use of frequency dispersion characteristics to identify sediment types and to identify manmade scatterers in the bottom.

Name: Rodney R. Korte
Citizenship: U.S.
Type of thesis: theoretical/numerical
Thesis title: A fast Green's function algorithm for sound propagation in range-dependent ocean environments
Objective: Generalize a Green's function method developed originally for atmospheric acoustics (propagation in a half-space) for application to ocean acoustics (waveguide propagation) with the inclusion of the effects of elasticity and porosity. Because of the its speed.the method should be extremely useful for high-frequency, broadband calculations required in shallow water acoustics and mine countermeasures.

Name: Scott D. Hansen
Citizenship: U.S.
Type of thesis: experimental
Thesis title: An atmospheric turbulence model derived from inversion of sound propagation measurements in an acoustic shadow zone.
Objective: Make accurate measurements of the sound field in an acoustic shadow zone where the sound field is due primarily to scattering from atmospheric turbulence. Use generalized non-linear inversion techniques to extract an acoustically-based empirical model for near-ground turbulence in the atmosphere.

11. Postgraduate Students

None

12. Transitions

The oceanic bubble layer scattering model developed by Dr. K.E. Gilbert on 6.1
funding in FY92 and FY93 has been incorporated by Dr. D.F. McCammon into the
operational reverberation model used by the Naval Air Weapons Center (Harsh
Environment Low Frequency Reverberation Model). As further advances are made
on the 6.1 research model, the improvements will be incorporated into the
operational model.

BROADBAND OCEAN ACOUSTIC TOMOGRAPHY
(N00014-90-J-1365)
Leon H. Sibul

The Pennsylvania State University

Applied Research Laboratory

P.O. Box 30, State College, PA 16804

(814)863-0312

LHS2@PSU.EDU

OBJECTIVE

To investigate the use of the broadband ambiguity function, the wavelet transform and tomographic concepts for characterization of time-varying ocean medium inhomogeneities. To extend classical acoustic tomographic concepts, that essentially assume a time invariant or a slowly varying medium, to tracking the location and velocities of ocean inhomogeneities. The technique uses backscattering of broadband active acoustic signals from moving inhomogeneities. The resulting inverse problem is solved by inverting multidimensional wavelet transforms.

PROGRESS:

We have shown that many important imaging problems including radar, sonar, medical imaging of distributed objects, remote sensing of the earth, oceans, and atmosphere, tomography, and time-varying channel identification fall into the conceptual framework of the theory of generalized inverses of linear operators. The general problem can be stated in terms of the following operator equation

$$Tx = r, \tag{1}$$

where r is the received or sensed signal and T is a linear operator that acts on x (an unknown image or medium characterization). T is described by a known measurement system or probing signal. The problem is to invert this operator equation to determine the unknown medium characterization x. However, the inverse of T may only exist in the sense of a generalized inverse. We show that a fundamental theorem for generalized inverses establishes the basic processing structure for remote sensing and tomography problems. While keeping the generality of inverse problems in mind we have focused our research on estimation of broadband and narrowband (NB) spreading functions for characterization of randomly time-varying propagation and scattering media. The key step in processing is calculation of the adjoint of the operator T.

The adjoint operator associated with the NB delay-Doppler spreading function estimation is a *generalized Gabor transform* of the received signal with respect to the transmitted signal. In the wideband case, the adjoint operator is a *wavelet transform* of the received signal with respect to the transmitted signal (mother wavelet). In both cases, the processor output is a group theoretic convolution of the spreading function with the appropriate autoambiguity
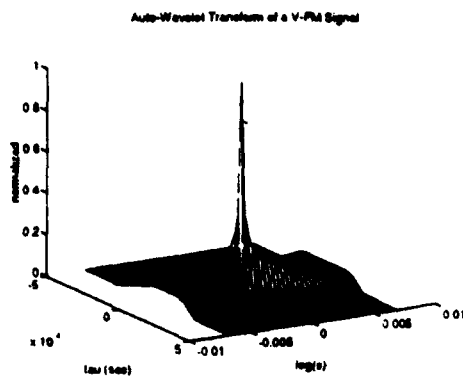
1a.
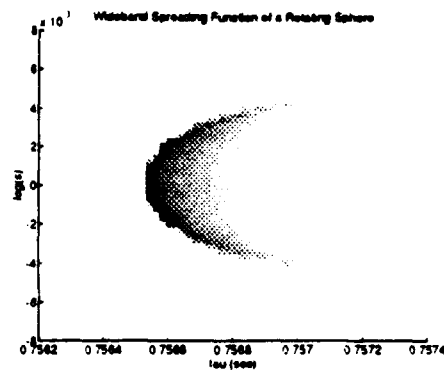
1b.
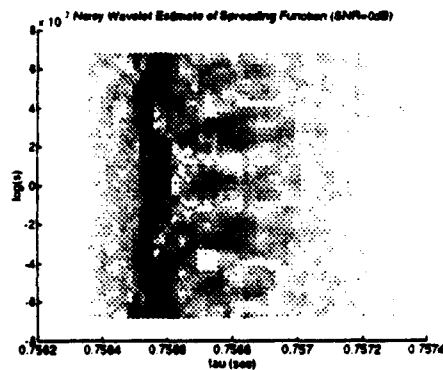
1c.

Figure 1. Imaging and Parameter Estimation of a Rough Rotating Sphere.

function. We used the resolution of identity (or Shur-Frobenius-Godement theorem) to show that autoambiguity functions are reproducing kernels for some subspaces of finite energy spreading functions. This fact is used to design probing signals that can give good estimates of appropriately limited spreading functions without forming the inverse operator. Required signal resolution properties are determined from above fundamental theoretical results.

The above described theoretical results were applied to imaging and parameter estimation of rough rotating spheres and layers of randomly moving distributed scatterers. Rough rotating spheres approximate many moving inhomogeneities such as rotating eddies, clouds of bubbles and other objects in the medium that are observed from a moving platform. Key processing steps are illustrated on Figure 1. An overhead view of the wideband spreading function of a rough rotating sphere is shown on Figure 1b; it is imaged by a wideband V-FM signal that has the autowavelet transform (autoambiguity function) shown on Figure 1a. The observed image at the 0 dB SNR is shown on Figure 1c. We have developed a generalized Hough transform technique to accurately estimate the parameters of the rotating sphere from the noisy and blurred image (Figure 1c).

PAPERS PUBLISHED IN REFEREED JOURNALS

[1]   J. A. Tague and L. H. Sibul, "Matrix Representation of Propagation and Scattering Operations," *Signal Processing*, Vol. 29, No. 3, December 1992, pp 299-307.

[2]   R. L. Culver, L. H. Sibul, D. W. Ricker, D. F. McCammon, "High Frequency Requirements for Shallow Water ASW," *U.S. Navy Journal of Underwater Acoustics*, October 1992.

[3]   M. P. Mahon, L. H. Sibul, and H. M. Valenzuela, "A Sliding Window Update for the Basis Matrix of the QR Decomposition," *IEEE Transactions on Signal Processing*, Vol. 41, No. 5, pp 1951-1953, May 1993.

[4]   R. K. Young, L. G. Weiss, and L. H. Sibul, "Multisensor Processing for Underwater Vehicles," *J. Underwater Acoustics*, Vol. 43, No. 1, pp 167-178, January 1993.

ACCEPTED FOR PUBLICATION IN REFEREED JOURNALS

[1]   A. N. Mirkin and L. H. Sibul, "Application of the Maximum Likelihood Criterion to Multiple Source Localization in an Inhomogeneous Medium," accepted for publication in *J. Acoust. Soc. Am.*, February 1994.

[2]   L. H. Sibul, L. G. Weiss, and T. L. Dixon, "Characterization of Stochastic Propagation and Scattering via Gabor and Wavelet Transforms," accepted for publication in the *Journal of Computational Acoustics*, June 1994.

[3]   L. G. Weiss, R. K. Young, and L. H. Sibul, "Wideband Processing of Acoustic Signals Using Wavelet Transforms, Part I: Theory," to appear in *J. Acoust. Soc. Amer.*

CHAPTERS IN BOOKS

[1]   N. K. Bose and L. H. Sibul "Multidimensional Signal Processing: Sensor Array Processing," chapter in *Electrical Engineering Handbook*, CRC Press, Inc., 1993.

[2]   L. H. Sibul, R. K. Young and M. L. Fowler, "Optimum Signal Processing and Medium Characterization in the Time-Frequency and Wavelet Transform Domains," in *Acoustics Signal Processing for Ocean Exploration*, edited by José M. F. Moura and Isabel M. G. Lourtie, Kluwer Academic Publishers, Dordrecht, Netherlands 1993.

INVITED TALKS

[1]   L. H. Sibul, "Wavelet Transforms and Their Applications," University of Tartu, February 11, 1993, Tartu, Estonia.

[2]   L. H. Sibul, "Wavelet Transforms and Their Applications," Technical University of Tallinn, February 17, 1993, Tallinn, Estonia.

[3]   L. H. Sibul, "Signal Processing - Detection, Thresholding, Signal Ambiguity Functions, Adaptive Algorithms, and Parameter Estimation," presented at Advanced Defense Development Laboratory, May 10-15, 1993, Chinhea, Korea.

CONTRIBUTED TALKS (Also published in Conference Proceedings)

[1]   T. L. Dixon[*], L. H. Sibul, and R. K. Young, "Systems Identification via Regularization of the Wideband Inverse Problem," *Proceedings of Conference on Information Sciences and Systems*, Johns Hopkins University, Baltimore, MD, March 24, 1993.

[2]   A. P. Chaiyasena[*] and L. H. Sibul, "Group Representation Theory and Signal Ambiguity Functions," *Proceedings of Conference on Information Sciences and Systems*, Johns Hopkins University, Baltimore, MD, March 24-26, 1993.

        [*] Presenter

CONFERENCES ATTENDED

[1]   T. L. Dixon, L. H. Sibul and A. P. Chaiyasena attended *Conference on Information Sciences and Systems*, Johns Hopkins University, Baltimore, MD, March 24-26, 1993.

GRADUATE STUDENTS

1.   A. Peter Chaiyasena.
        Ph.D in Mathematics
        "Group Theoretic Foundations of Wavelet Transforms and Signal Ambiguity   Functions"

Objective:

Develop unified group theoretic foundation to wavelet and other group theoretic transforms, wide-
and narrow-band ambiguity functions and Wigner transforms. An important concept that we exploit
in this study is that both the narrowband and wideband ambiguity functions are coefficients of the
unitary representations of their respective groups. Wide-band ambiguity functions are coefficients of
the affine group and narrowband ambiguity functions are coefficients of the Heisenberg group. This
fact provides insight into important concepts of admissible signals, ambiguity conservation, and
ambiguity function invariance properties that are important for signal design. This study uses
contractions of the groups to study the relations between Heisenberg and affine groups from which
approximations of wideband ambiguity functions by computationally efficient narrowband ambiguity
functions can be established. Theoretical.

Student Nationality: American
Graduated, May 1993

2.   Kenneth L. Hillsley
        Ph.D in Electrical Engineering
        "Wavelet Transform-based Wideband Tomographic Reconstruction of Stochastic Media"

Objective:

The objective of this research is to solve the inverse problem of reconstructing position and velocity
components of turbulent inhomogeneities by developing a wideband, wavelet transform-based,
tomographic reconstruction theory. By considering wideband processing with the powerful technique
of tomographic imaging, it will be possible to obtain high-resolution reconstructions of multiscale
time-varying inhomogeneities. The interplay between wideband processing and the wavelet transform
is an emerging area of research. The unique ability of wavelet transforms to efficiently and
accurately characterize wideband and nonstationary signals over broad parameter ranges make wavelet
transforms a natural analytical tool for the reconstruction problem. Theoretical and numerical.

Student Nationality: American
Expected date of graduation: May 1995

3.   Teresa L. Dixon
       Ph.D in Electrical Engineering
       "Wideband Imaging of Distributed Objects Using Wavelet Transforms and Generalized
       Inverse Theory"

<u>Objective:</u>

The objective of this research is to use the theory of generalized inverses and wavelet transform
theory to establish optimum processing structure for active acoustic remote imaging of time varying
distributed objects, and randomly time-varying propagation and scattering channels. Results from
wideband ambiguity function and wavelet transform theory are used to establish theoretical limitations
on imaging and parameter estimation of distributed objects. Theoretical results are verified by
computer experiments. Theoretical and numerical.

Student Nationality: American
Expected date of graduation: August 1994.

TRANSITIONS

Results of this research are continuously transitioned to the Shallow Water Torpedo Detection and
Classification 6.2 Program and the Shallow Water Advanced Technology Demonstration (6.3A)
Program. An estimator/correlator signal processing technique, that was initially researched in this
program, will be implemented and tested in the Shallow Water Detection and Classification project.
Research results from this project are used for the Mine Countermeasure Program, condition based
maintenance and non-destructive testing. Leon Sibul has conducted many seminars and workshops,
and given presentations to transition research results for the 6.2 community.

Former students who are applying research results to industrial and Navy projects are:

Dr. Mark L. Fowler	IBM Federal Systems
Dr. Adam N. Mirkin	NUWC, Newport, RI
Dr. Dennis W. Richardson	IBM Federal Systems
Dr. John A. Tague	University of Ohio, Athens, OH
Dr. Guy R. Sohie	GE Corporate Research Center, Schenectady, NY

A Mid-Frequency Sound Speed Measurement Instrument
N00014-90-J-1365

Ralph R. Goodman, William Thompson, Jr.
Applied Research Laboratory
P. O. Box 30
State College, PA 16804
Telephone: (814) 863-8140, (814) 863-4156

An approach to the problem of real-time monitoring, with fine spatial resolution, small changes in the speed of sound in water, such as might be associated with air-bubble filled water near the ocean's surface, is being investigated. The thought is that the input electrical impedance or admittance of an electroacoustic transducer, which is a function of the acoustic radiation loading on its active face, can be made an even more sensitive function of that loading by, in effect, amplifying the loading. This can be accomplished by locating the transducer at one end of a planar (one dimensional) waveguide, filled with the water to be evaluated, and terminated at the other end by some impedance. The input impedance of the waveguide then constitutes the radiation load on the transducer.

Initially it was thought that a one-quarter wavelength long waveguide terminated with a very large impedance would provide the most sensitive situation for observing small changes in the sound speed of the entrained water. However, some experiments using a small, but low frequency, bender-type piezoceramic transducer positioned at one end of a thick-walled, cylindrical, aluminum tube which was terminated at the end opposite the transducer by a thick aluminum plate, once again revealed the impracticality of trying to create a rigid boundary in a fluid medium. An unusual observation during these experiments was the appearance of a second resonance, i.e., a second peak in the input conductance, at a frequency lower than the fundamental mechanical resonance of the transducer without the waveguide. Since this additional resonance is wholly an artifact of the presence of the waveguide, the possibility of exploiting it as a barometer of changes in the water's sound speed is being examined.

A mathematical model of the waveguide-loaded transducer has been developed and calculations of the input conductance of the transducer do reveal two resonances, the lower frequency one being a consequence of the mass-like reactance of the waveguide input impedance (assuming the termination impedance of the waveguide is also mass-like, as probably was the case for the experiments alluded to, and assuming the length of the waveguide is a small fraction of a wavelength, as was the case) canceling the stiffness-like impedance of the transducer at a frequency below the fundamental mechanical resonance. More importantly, further calculations show that the frequency of this auxiliary resonance, a quantity that should be able to be measured quite readily, varies as much as 19% for a 20% variation in the speed of sound of the entrained water and in a very linear manner.

The cylindrical waveguide used in the experiments actually had a number of axially oriented slots cut through the wall of the tube to permit free flooding of the tube. These slots seemed to have no consequence upon the existence of this additional resonance but would, of course, permit the water to change as an apparatus was towed through the ocean. The largest of the

19

small bender type transducers used had a fundamental resonance at about 2500 Hz and the auxiliary resonance occurred as low as 1400 Hz. The entire transducer and waveguide assembly fit in a cylindrical envelope about three inches in diameter by no more than five inches in length.

Acoustic Wave Propagation Across Turbulent Media

Dr. Henry McDonald
Applied Research Laboratory
The Pennsylvania State University
P.O. Box 30
State College, PA 16804
(814) 863-3040
hmd@arlvax.arl.psu.edu

Problem

The propagation of acoustic waves through turbulent fluid media has attracted a good deal of theoretical attention. This is so because of the number of areas of engineering interest where this phenomena is present. As an example, in undersea applications, the distortion of acoustic wave fronts via turbulence has a clear relevance to the operation of sonar arrays. The processes of refraction, advection, and scattering in a moving, turbulent flow field can grossly distort, even render completely incoherent, an incident acoustic wave. As such, an understanding of the mechanisms of this distortion in the context of turbulence is required. Early on, the interest in such phenomena was primarily concerned with the effects of large scale turbulence on atmospheric and oceanic acoustics. In terms of theoretical treatment, most of the early work involved a statistical approach to the problem in which the effect of turbulence was accounted for by a modified refractive index. More recently, a deterministic approach has been utilized in which acoustic waves are propagated through instantaneous realizations of turbulent flows. Statistics are then determined by compiling results from a large number of such realizations. This more recent work, however, has been largely limited to isotropic turbulence. Clearly, for practical reasons, it would be useful to extend this methodology to non-isotropic turbulence. That is the ultimate goal of this project.

Approach

In this work, the deterministic approach is followed. As such, the problem essentially becomes a two-part problem: first, the instantaneous turbulent flow fields are generated, and, second, the acoustic waves are computationally propagated through a number of these "frozen" flow fields. Until recently, work on this problem has concentrated on the first part. Specifically, the capability has been developed to generate two- and three-dimensional realizations of homogeneous isotropic turbulence. The generation process essentially begins with the specification of a turbulent kinetic energy spectrum. This spectrum is then discretized into a finite number of wave modes. An orientation for each wave vector is then randomly assigned according to probability densities that will yield a uniform distribution in wave number space. Complex amplitudes for each of the wave vectors in the discrete spectrum are then randomly chosen such that the incompressibility and reality constraints are satisfied. Longitudinal and lateral correlation functions compiled from 25000 such realizations are shown in figure 1.

Currently, work on the project is centered on the second aspect of the problem; namely, the acoustic wave propagation. The equation governing the propagation of acoustic disturbances in a randomly inhomogeneous medium is the so-called stochastic Helmholtz equation. Two common approaches to the solution of this equation are: the geometric acoustics approximation (allowing for the use of ray tracing techniques) and the parabolic

approximation. Both approaches are currently being implemented. Presently then, the main thrust is the verification of these basic elements against previous work (analytical, computational and experimental).

Future Work (to be completed with current funding)

As stated in the first paragraph, the primary objective of this work is the extension of these deterministic techniques to non-isotropic turbulent flows. This will necessarily require a complete rethinking of the first part of this work, namely, the generation of the individual realizations of the turbulence. The intention is to utilize the so-called maximum entropy family of probability density functions to construct random velocity fields satisfying an arbitrary number of moments of the velocity. With this approach, for example, given a Reynolds stress tensor for an arbitrary turbulent flow, it would be possible to construct individual realizations of the turbulence. Upon constructing a large number of such realizations, and ensemble averaging the moments, the specified Reynolds stress tensor will be recovered. In this way it is felt that information from many standard turbulence models could be used for construction of the flow field realizations. The number of moments to be specified will then be related to the level of closure of the particular turbulence model.
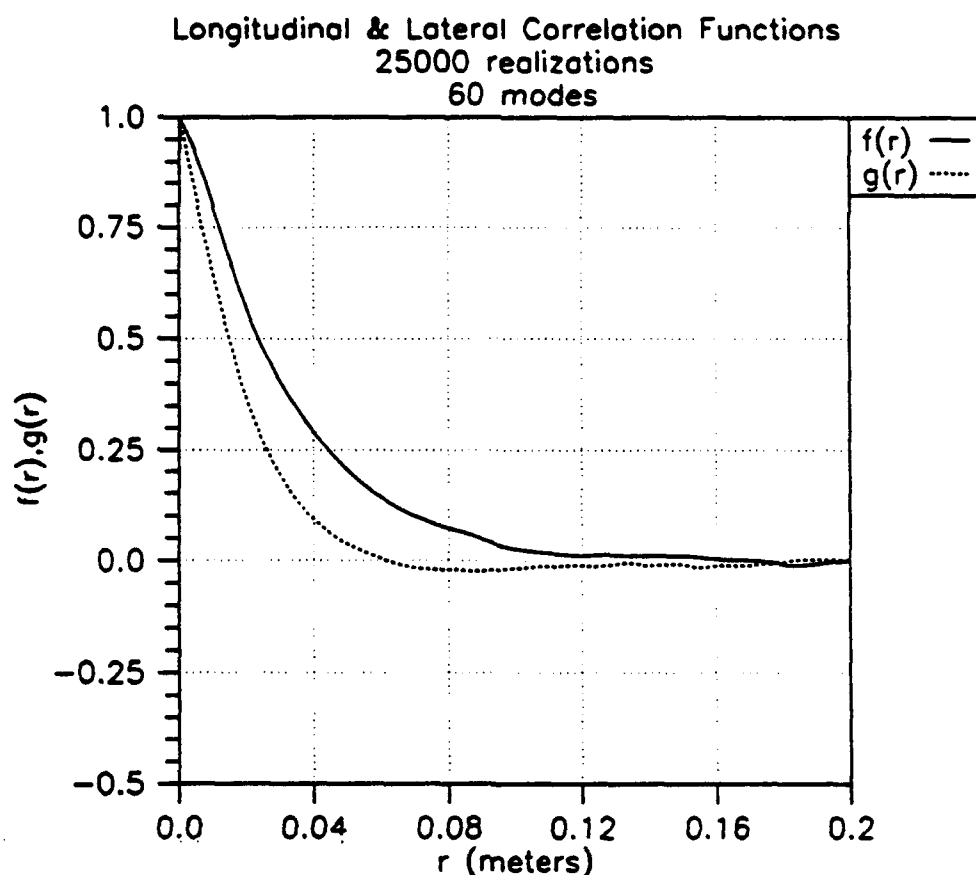

Figure 1. Longitudinal and lateral correlation functions for 25000 realizations of homogeneous, isotropic turbulence computed using random Fourier modes.

Active Dynamic Measurement of Material Fatigue
David C. Swanson, PhD
The Applied Research Laboratory
The Pennsylvania State University
P.O. Box 30, State College, PA 16804
(814) 865-2448
drdave@sabine.acs.psu.edu

Prediction of the strength (or failure) of materials has always been one of the most fundamental elements of engineering. A vast body of knowledge exists about the strength of materials as well as the failure mechanisms under static loads. However, structures under relatively low static loads (compared to their material yield strengths) are known to develop cracks and fail after a period of time when structural vibration is present. Some common examples of these structures are gears, airplane engine pylons, Naval aircraft tailhooks and landing gear, and even machine tools. In recent years, the use of ultrasonic non-destructive testing has allowed the detection of small cracks in materials. But, by the time a crack is large enough the reflect an ultrasonic wave, much of the structural strength may already be lost. This research develops a technique for monitoring the growth of cracks in a material using a simple but precise measurement of fatigue-related changes in the structural damping.

Any growth in the number of dislocations should also increase the mechanical damping due to wave scattering by the dislocations as well as increase the electrical resistance. Note that at absolute zero temperature most metals can form a perfect crystal and become superconducting. The increases in electrical and mechanical damping as well as increases in material stiffness should be usable by a sensor system designed to monitor fatigue. According to C.R. Barrett, W.D. Nix, and A.S. Tetelman, *The Principles of Engineering Materials*, (Prentice-Hall, 1973), p258., the movement and presence of dislocations both generate and interfere with vibration waves, but the effect of the drag forces is small compared to other mechanisms. Therefore, as a structure in the process of failure is subjected to vibrations, the time to failure should decrease while the mechanical damping and stiffness should increase.

A simple but crude experiment apparatus is shown in Figure 1 below. A 3/8" by 0.030" by 30" long band of high carbon steel rated at 1125 lbs. breaking strength is notched leaving only about 1 mm. One end is rigidly attached while the other end is placed in tension through a stiff spring in the apparatus. The purpose of the spring is to keep the band in near constant tension as the band stretches in the notched area. With no vibration applied, the band generally lasts many hours before breaking - if it breaks at all. With a small amount of random vibration applied, bands with identical notches and tension consistently break between 30 minutes and slightly over 2 hours time. Tension is held nearly constant by initially "tuning" the band's fundamental frequency to the same value for each test and by carefully producing identical notch widths. Also a spring can be seen at the right end in Figure 1 which helps keep tension constant during the fatigue process.
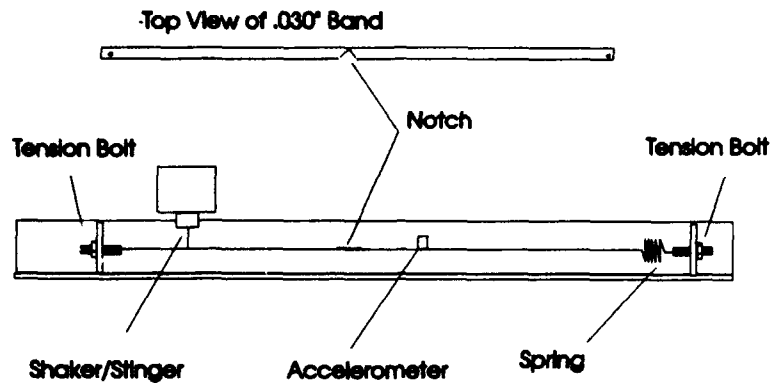
Apparatus for Measuring Damping

Figure 1   Damping measurements are achieved by observing the Q of structural resonances

     A broadband random noise signal is applied to the shaker which excites the band via the stinger as seen in Figure 1. An accelerometer senses the response of the band during the fatigue test. The positions of the shaker and accelerometer have a profound affect on the measured transfer function, but not on the measured changes in damping. Figure 2 shows two typical transfer function frequency responses taken just after initial setup and after approximately 90 minutes of vibration excitation.
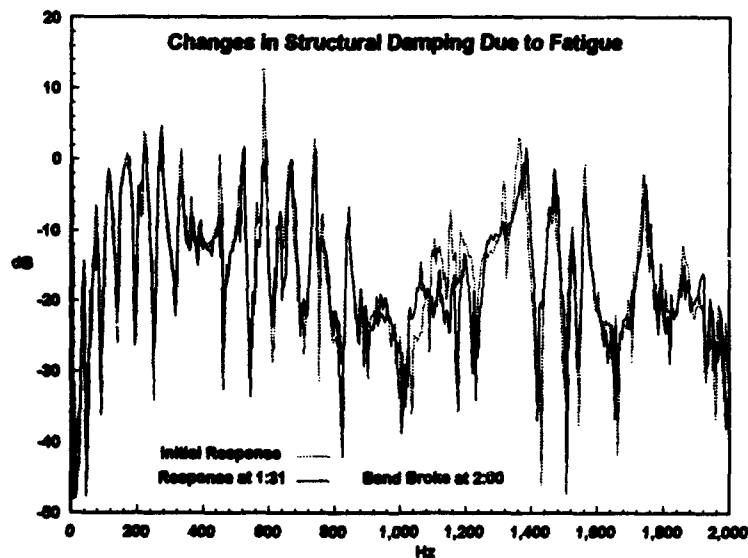
Figure 2   Very small increases in material stiffness and larger increases damping are observable over the 90 minute test.

Active Dynamic Measurement of Material Fatigue
David C. Swanson, PhD
The Applied Research Laboratory
The Pennsylvania State University
P.O. Box 30, State College, PA 16804
(814) 865-2448
drdave@sabine.acs.psu.edu

Patent Applications: ARL Invention Disclosure No. 638 "Nondestructive Material Fatigue Measurement Apparatus", October 5, 1993, David C. Swanson.

Graduate Students:

1)   Mr. Douglas Koehn, USA, MS graduation expected Fall 1994, Experimental, "Vibration-Induced Material Fatigue Measurement Using Modal Damping"

Objective: The thesis defines the known fundamental physical mechanisms for sonic fatigue of materials and their relationship to damping. A simple apparatus is constructed for transfer function measurements of a notched band under static and dynamic loads. Photo-micrographs compare physical observations of crack formation and growth to corresponding structural damping measurements. The trend in damping changes during failure will be evaluated as a precursor to structural failure.

2)   Mr. Sevag Arzoumanian, USA, MS graduation expected Fall 1995, Experimental, "Active Vibration-Induced Fatigue Mitigation"

Objective: This thesis applies active vibration control using adaptive self-optimizing algorithms to stop crack growth in a seeded fault area. Since the adaptive control "error" sensor cannot be placed directly in the fault area, the complete dynamics of the notched band will be examined to develop a "remote error" sensor system consisting of an array of accelerometers. The response of the adaptive controller will be used to simultaneously monitor structural integrity and to develop a material condition prognosis system linked with an active fatigue control methodology.

REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	31 May 1994	Final - 1 Oct 1994 - 31 May 1994

4. TITLE AND SUBTITLE

Fundamental Research Initiatives
Final Report

5. FUNDING NUMBERS

N00014-90-J-1365

6. AUTHOR(S) M. A. Mazur, D. F. McCammon; R. L. Culver; K. E. Gilbert, L. J. Kulbago; L. H. Sibul; H. McDonald; D. C. Swanson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Applied Research Laboratory
The Pennsylvania State University
P. O. Box 30
State College, PA 16804

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
Ballston Tower 1
800 N. Quincy St.
Arlington, VA 22217-5660

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Final report on High Frequency Surface Scattering Statistics, A Higher Order Stochastic Model for Surface Backscatter in High Sea States, Broadband Ocean Acoustic Tomography, A Mid-Frequency Sound Speed Measurement Instrument, Acoustic Wave Propagation Aross Turbulent Media, and Active Dynamic Measurement of Material Fatigue.

14. SUBJECT TERMS

surface scattering, backscatter, high sea states, tomography, sound speed instrumentation, turbulent media, material fatigue

15. NUMBER OF PAGES

26

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified		