Long-Range Underwater Sound Propagation: Environmental Variability, Signal Stability and Signal Coherence

Michael G. Brown
Division of Applied Marine Physics
Rosenstiel School of Marine and Atmospheric Science
University of Miami
4600 Rickenbacker Causeway
Miami, FL 33149-1098
Phone: (305) 421-4640 Fax: (305) 421-4701 Email: mbrown@rsmas.miami.edu

Award #: N000141210182
http://www.rsmas.miami.edu/people/faculty-index/?p=michael-g.-brown

LONG-TERM GOAL

Our long-term scientific goal is to understand the basic physics of low-frequency long-range sound propagation in the ocean, and the effects of environmental variability on signal stability and coherence. We seek to understand the fundamental limits to signal processing imposed by ocean variability to enable advanced signal processing techniques, including matched field processing and other adaptive array processing methods.

OBJECTIVES

The principal objective of our ongoing effort is to develop a theory of acoustic fluctuations in long-range propagation that correctly accounts for measurements. This objective is motivated by the failure (as reported by Colosi *et al.*, 1999) of traditional approaches (see, e.g., Flatté *et al*., 1979) to the study of wave propagation in random media (WPRM) to predict measured time spreads and intensity statistics in recent long-range underwater acoustic experiments. Work to date strongly suggests that acoustic fluctuations are, to a surprisingly large degree, controlled by a property (the ray-based stability parameter α or the asymptotically equivalent mode-based waveguide invariant β) of the background sound speed profile, rather than details of the sound speed perturbation. As a result, much of the recent theoretical work has been motivated by a desire to understand which wavefield properties are controlled by α or β. Over the past several years a significant part of this effort has been devoted to the analysis of measurements made during the LOAPEX experiment. A secondary objective is to better understand the limitations of the process known as noise interferometry as an ocean remote sensing tool.

APPROACH

M Brown and collaborators (primarily I Udovydchenkov at WHOI) employ a combination of ray- and mode-based theory, combined with PE simulations, to study and quantify acoustic fluctuations. Much, but not all, of the mode-based theory is based on an asymptotic analysis, as this provides a direct link to the ray-based analysis. Similarly, much, but not all, of the ray-based analysis makes use of action-angle variables, as this provides a direct link to the mode-based analysis. Another crucial connection between the ray- and mode-based analyses derives from the asymptotic equivalence of the ray stability parameter α and the modal waveguide invariant β. Throughout the past year we have continued to extend relevant theoretical developments, but we have prioritized work involving the application of theoretical results to the analysis of measurements made as part of the recent LOAPEX propagation experiment. Specific topics/questions, which have been investigated by the PI during the past two years, are listed in the following section.

WORK COMPLETED

The work listed below is in various stages of completion. The work listed in items 1 and 2 is largely complete. The work described in item 3 represents a new – and important, we believe – direction.

1. LOAPEX analysis

The PI's work (in collaboration with I Udovydchenkov at WHOI and the experimental groups at APL/UW and SIO) on the analysis of LOAPEX measurements is near completion. This effort is closely linked to earlier theoretical work on modal group time spreads work by Udovydchenkov and Brown (2008). Two papers have been written (Udovydchenkov et al., 2012a and b). The first paper focuses on near-axial modes, corresponding to small mode numbers. Those modes are the simplest to deal with from a measurement perspective, but from the perspective of scattering theory, those modes present special challenges. The second paper focuses on higher order modes. From the perspective of the scattering theory that has been developed, those modes present no special challenges, but, because the LOAPEX experiment was not designed to measure those modes, they present special signal processing difficulties. In both papers, in spite of the particular challenges present, agreement between data-based estimates of modal group time spreads and theoretical predictions is good.

2. *Communications applications of weakly dispersive modal pulses*

A modal pulse is defined as a broadband distribution of energy with fixed mode number. Weakly dispersive modal pulses are modal pulses that exhibit both negligible dispersion-induced pulse broadening and negligible scattering induced pulse broadening. In deep ocean environments, these are of two types: 1) modal pulses for which the waveguide invariant β is approximately zero; and 2) the lowest order ($m = 0$) modal pulse. Two papers have been written: 1) a theoretical paper (Brown and Udovydchenkov, 2013) describing the special properties of weakly dispersive modal pulses and their utility in communications applications; and 2) a data-based test (using LOAPEX observations) of the theory, showing excellent agreement (Udovydchenkov et al., 2013). This work is being done in collaboration with I. Udovydchenkov at WHOI.

3. *Noise interferometry*

Noise interferometry is the process by which an estimate of the transient Green's function between two locations is extracted by computing the cross correlation of simultaneous measurements of ambient noise at those locations. There are significant ocean remote sensing implications, and thus a strong motivation for better understanding noise interferometry. A theoretical study on noise interferometry in inhomogeneous environments has been completed (Brown, 2011). An important result of that study is demonstration that, in such an environment and in the geometric limit, the correlation function consists of a superposition of delayed signed step functions and logarithmic singularities. This work is continuing, with an experimental focus, in collaboration with O. Godin (CIRES/UColorado) with partial support from NSF.

RESULTS

Although our goal of developing a theory of acoustic fluctuations in long-range propagation is not yet complete, significant progress has been made. The forward scattering physics are much better understood than was the case a few years ago. An important result of the PI's work over the past few years is conceptual: the forward scattering of sound — by internal-wave-induced perturbations, for example — is largely controlled the background sound speed structure. Thus, sound scattering in environments with identical internal-wave-induced sound speed perturbations but different background speed structures may be very different. This statement is supported by observations, simulations and theoretical analysis – both ray- and mode-based.

IMPACT/APPLICATION

Our work is contributing to an improved understanding of the basic physics of low-frequency long-range sound propagation in the ocean, and the associated loss of signal stability and coherence imposed by environmental variability. This knowledge contributes to an understanding of the limitations of advanced signal processing techniques, such as matched field processing.

TRANSITIONS

Our results are being used to interpret (reinterpret, in some cases) data collected in long-range propagation experiments, e.g. AET, SPICEX, LOAPEX and PhilSea. We are unaware of transitions to system applications.

RELATED PROJECTS

The PI and collaborators listed above actively collaborate with the NPAL (North Pacific Acoustic Laboratory) groups at SIO (P. Worcester, W. Munk, B. Cornuelle, M. Dzieciuch), APL/UW (J. Mercer, B. Dushaw, R. Andrew and F. Henyey), UHawaii (B. Howe) and NPS (J. Colosi).

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PUBLICATIONS

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