Vertical Structure of Shadow Zone Arrivals: Comparison of Parabolic Equation Simulations and Acoustic Data

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LONG-TERM GOALS

As part of the North Pacific Acoustic Laboratory (NPAL) program, the long-term goals of this project are to understand the physics of long-range, broadband propagation in deep water and the effect of oceanic variability on acoustic propagation.

OBJECTIVES

Observations made during the Acoustic Thermometry of Ocean Climate (ATOC) experiment show that acoustic energy penetrates significantly deeper in the water column below the lower turning points of the predicted acoustic ray paths than expected from diffraction alone [1]. This energy appears anomalously deep in the water column, but the measured travel times correspond well with timefronts predicted to have cusps several hundred meters above the depth of the receivers.

The objective of this particular effort is to examine the vertical structure of these "shadow-zone arrivals" and to determine the relative roles of different sources of oceanic variability such as internal waves, ocean spice, and reflections off the base of the oceanic mixed layer in contributing to the vertical scattering.

APPROACH

In June 2004, two source moorings and a set of hydrophone arrays were deployed in the North Pacific Ocean as part of the SPICEX experiment. (SPICEX was one component of the larger 2004 NPAL experiment, which also included the Long-range Ocean Acoustic Propagation EXperiment (LOAPEX) and the Basin Acoustic Seamount Scattering EXperiment (BASSEX).) The two closely spaced vertical line arrays (VLAs) together virtually spanned the full ocean depth, enabling observation of the vertical structure of the timefront arrivals.

The two source moorings were located at ranges of 500 km and 1000 km from the VLAs, each supporting acoustic sources at both 750 meters, the approximate depth of the sound channel axis, and

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14. ABSTRACT
As part of the North Pacific Acoustic Laboratory (NPAL) program, the long-term goals of this project are to understand the physics of long-range, broadband propagation in deep water and the effect of oceanic variability on acoustic propagation.

15. SUBJECT TERMS

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3000 meters, slightly above the surface conjugate depth. Receptions from all four sources were analyzed to determine the level of scattering into the shadow zone.

The experimental data were calibrated and compared with parabolic equation propagation simulations [2] based upon hydrographic measurements taken at the time of the deployment in June 2004 as well as during LOAPEX in September 2004 [3]. Three different environments were considered: a range-dependent profile developed using underway CTD (UCTD) measurements taken at the time of the experimental deployment, the mean sound-speed profile, and a mean sound-speed profile perturbed to stochastically simulate the oceanic sound-speed perturbation due to internal waves [4].

The evolution of monthly incoherent averages of acoustic timefronts from June to November 2004 was investigated to determine the effect of the seasonally dependent upper-ocean sound-speed structure on deep shadow-zone arrivals.

This work is funded as a graduate student traineeship award, and formed the basis of Lora Van Uffelen's Ph.D. dissertation, which she successfully defended on August 24, 2009. The dissertation advisory committee, Dr. Peter Worcester (chair), Dr. Bruce Cornuelle, Dr. Daniel Rudnick, Dr. Walter Munk and Dr. William Kuperman, all of the Scripps Institution of Oceanography, Dr. Kathleen Wage of George Mason University, and Dr. William Coles of the electrical engineering department at the University of California, San Diego, all provided advice and guidance as committee members. Dr. Matthew Dzieciuch of the Scripps Institution of Oceanography also contributed.

WORK COMPLETED

The focus of prior analysis of long-range propagation data has been acoustic travel time, with less attention paid to the intensity of arrivals; however, absolute intensities are essential to make meaningful comparisons between acoustic receptions and between receptions and simulated data. The absolute intensities of both acoustic data from SPICEX and parabolic equation simulations were calculated enabling direct intensity comparisons of incoherent averages of hydrophone data with Monte Carlo parabolic equation simulations incorporating several realizations of stochastic internal-wave fields.

Previous analysis of the SPICEX acoustic timefront data included incoherent averages of acoustic receptions recorded during a single day, which coincided with the collection of the oceanographic environmental data. This analysis was extended to include monthly incoherent averages of acoustic timefronts from June to November 2004 for better statistical characterization.

Depth-dependent energy profiles of individual lower cusps of monthly incoherent timefront averages were calculated to determine the effect of the seasonally dependent upper-ocean sound-speed structure on deep shadow-zone arrivals.

Acoustic ray propagation simulations through an unscattered sound-speed profile define the expected depth of the timefront cusps, i.e., the upper limit of the acoustic shadow zone. The upper turning points of the rays associated with the deep cusps were determined to indicate the depths at which the acoustic rays are most sensitive to scattering due to internal waves [5].

Temperature fluctuation data from Seabird MicroCAT (Conductivity And Temperature) sensors affixed to the VLA mooring were compared with the empirical Garrett-Munk internal-wave energy spectrum [6] to determine which energy level (if any) appropriately describes the data.

RESULTS

Acoustic data received during SPICEX clearly show vertical extension of timefront cusps well below depths of lower cusps predicted by deterministic rays propagated through a range-independent sound-speed environment (Figure 1).

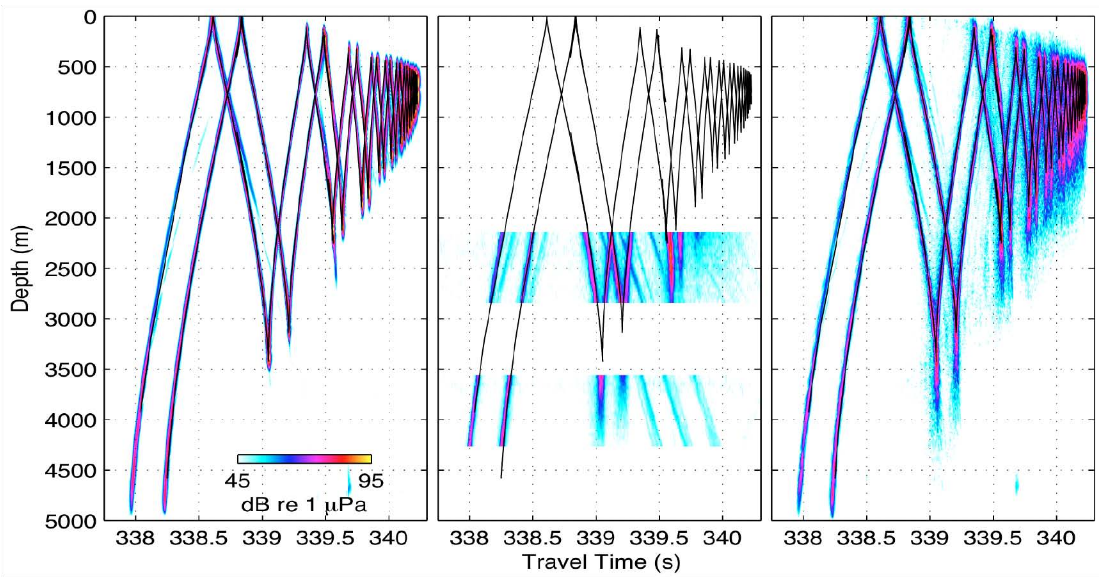

Figure 1: Acoustic ray propagation simulation from an axial source at 500-km range to VLA receivers overlaid on parabolic equation simulation for a range-independent profile (left), a profile including scattering consistent with the Garrett-Munk internal-wave energy spectrum (right), and an incoherent average of acoustic receptions received on the VLA in the month of June 2004 (middle). The incoherent average of the measured receptions has been aligned with the predicted timefront. Three steep arrivals corresponding to rays that reflect from the sea surface and seafloor are clearly evident in the receptions between 339 and 340 seconds, but will not be studied here.

Parabolic equation simulations incorporating sound-speed fluctuations consistent with the Garrett-Munk internal-wave energy spectrum at full strength (1 GM) appropriately describe the scattering into the acoustic shadow for data collected during times for which environmental data are available. Temperature fluctuation data from MicroCAT sensors mounted on the VLA are also consistent with an internal-wave energy level of 1 GM, although instruments located above 200 m indicate higher variability (Figure 2).

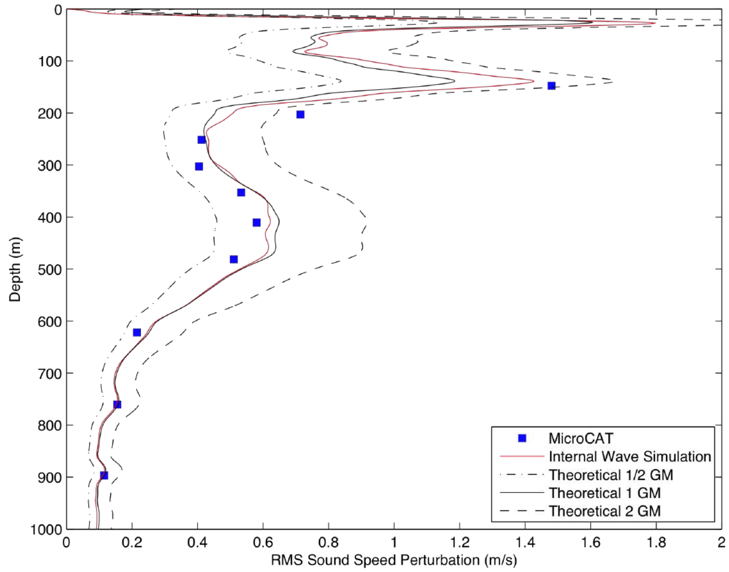

Figure 2: Rms sound-speed perturbation based on data from MicroCAT sensors on the VLA compared with rms sound-speed perturbations generated for 1-GM stochastic internal-wave simulations. Calculated rms sound-speed perturbations based on the theoretical variance of the Garrett-Munk spectrum for energy levels of ½ GM, 1 GM, and 2 GM are also included.

Incoherent monthly averages of acoustic timefronts demonstrate that the depth of the pair of lower cusps arriving immediately after 339 seconds on Figure 1 increases from June to November and displays dramatic deepening in the month of November. A magnification of the second lower cusp in the pair is shown in Figure 3.

A more quantitative measure of the vertical extension of the cusp is the energy profile of the cusp. The top panels of Figure 4 show the energy in each of the cusps in this pair as a function of depth. Energy profiles for the monthly timefront averages are compared with energy profiles for unscattered and internal-wave scattered simulations based on both June and September sound-speed environments.

The unscattered energy profile is characterized by a diffraction pattern culminating in a distinct peak, below which it quickly decays. The energy profiles of the internal-wave simulations do not exhibit this intense peak but have a more scattered profile, which distributes the energy to greater depths. The acoustic data for the months of June through October generally fall between the internal wave predicted energy profiles for the June and September sound-speed environments, and the month of November is an outlier.

No environmental data are available for the month of November, however, historical data predict that a steep temperature gradient, referred to as the summer thermocline develops from June through September as the surface waters warm and subsides dramatically in November as the surface cools and the heat content of the warm surface waters is distributed to greater depths. The changes in depths of the cusps are likely due to the changing sound-speed profile and are therefore deterministic.

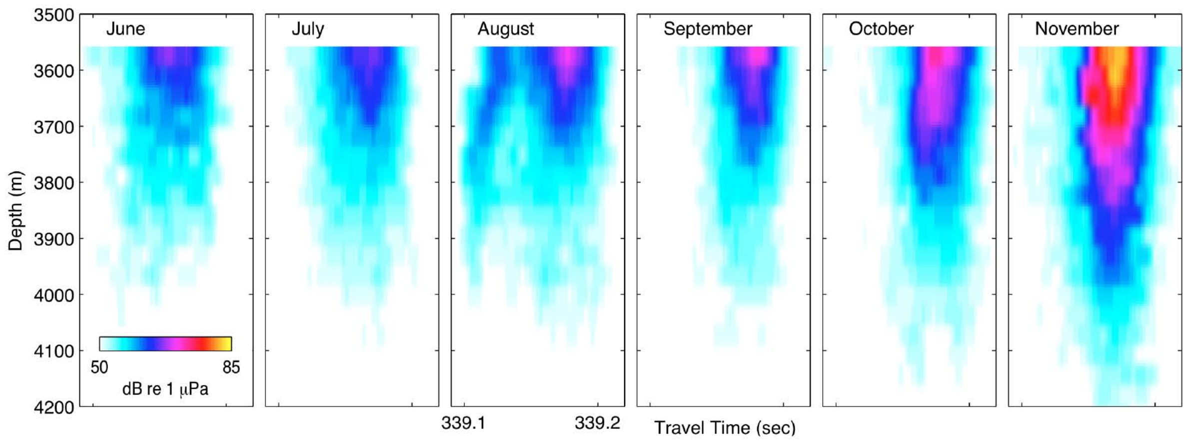

Figure 3: Monthly incoherent average of measured acoustic intensities (dB re 1 μPa) as a function of travel time and hydrophone depth for the second cusp on the 500-km timefront shown in Figure 1.

Energy profiles of the first two pairs of cusps on the 1000-km timefront (not shown) are also included in Figure 4. The lower panels, showing the second pair of cusps, exhibit similar behavior to those in the first pair of cusps on the 500-km timefront with a dramatic increase in energy in the month of November.

The first pair of cusps on the 1000-km timefront, shown in the middle panels of Figure 4, exhibit very different behavior. The upper phones display the highest energy content in June and the energy level progressively decreases in subsequent months, however the lower phones have the lowest energy in June. June therefore displays the most unscattered profile, with a strong peak that decays quickly, whereas later months, such as November, have more vertical energy profiles, indicating increased scattering. The effect is also present in the internal-wave simulations for June compared with September.

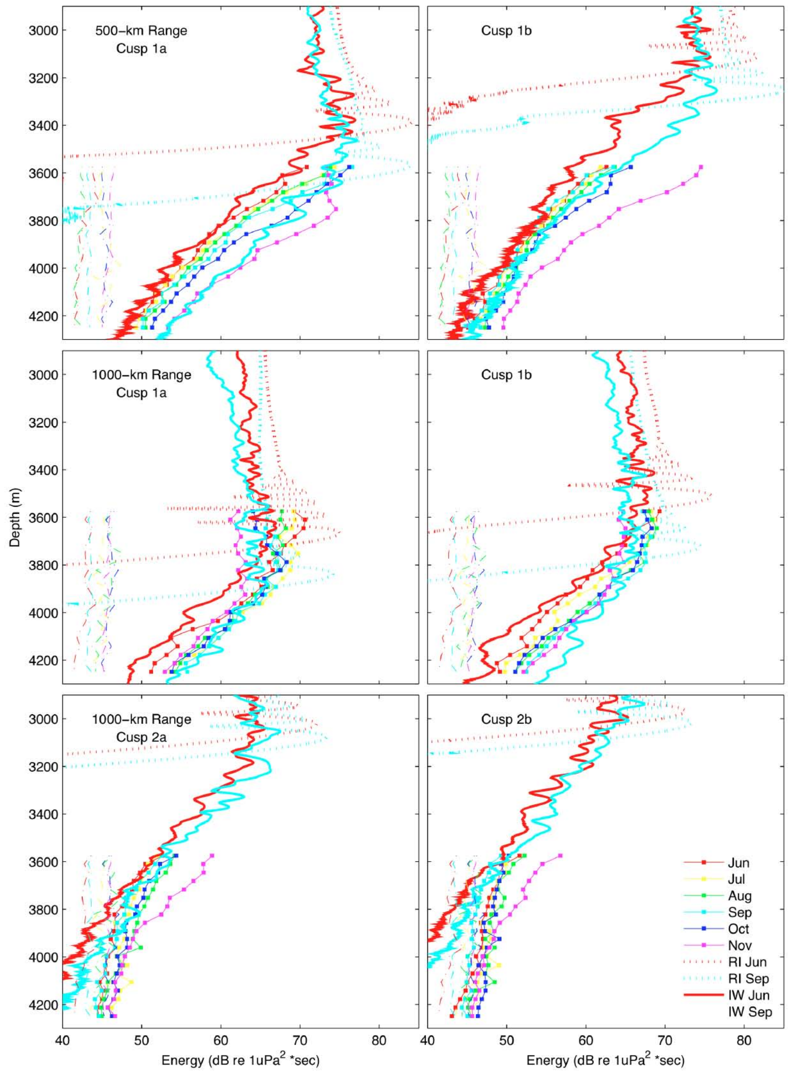

Figure 4: Energy in the first (left) and second (right) cusps in set 1 on the 500-km timefront (top), set 1 on the 1000-km timefront (middle), and set 2 on the 1000-km timefront (bottom). Hydrophone data are shown for June through November for the 20 phones on the lower segment of the DVLA. Noise levels for each month are depicted by dashed lines colored to correspond with the acoustic data. Energy calculated for range-independent and internal-wave PE simulations for both June and September profiles are included.

The difference between this set of lower cusps and the two discussed previously is that the upper turning points for this set of ray arrivals are shallower (on the order of 20 m for the June profile). The June rays likely demonstrate less scattering by internal-wave fluctuations because they turn very near the sea surface, where internal-wave sound-speed perturbations approach zero. Conversely, in November the rays are likely refracting off the base of the remnant summer thermocline, where gradients are strong and internal-wave variability is high, giving the more scattered profile indicated by slower decay in energy with depth that is observed.

The energy profile of cusps arriving later in the timefront pattern (not shown), resulting from lower-angle rays with deeper upper turning points, display less seasonal dependence than the earlier arrivals with upper turning points in the upper ocean.

In summary, the relationship between time of year and shadow-zone extension is not direct. Shadow-zone arrivals refer to energy that arrives below the cusps of unscattered arrivals, so the depth at which an arrival is considered a shadow-zone arrival can change dramatically based on the shape of the sound-speed profile. The depth to which the timefronts extend as the seasons change is a complex combination of deterministic changes in the depths of the lower cusps as the range-average profiles evolve and of the amount of scattering, which depends on the depths of the upper turning points and the mean vertical gradients at those depths.

IMPACT/APPLICATIONS

This research has the potential to affect the design of deep-water acoustic systems, whether for sonar, acoustic communications, acoustic navigation, or acoustic remote sensing of the ocean interior.

RELATED PROJECTS

A large number of investigators and their students are currently involved in ONR-supported research related to the NPAL project. The Principal Investigators include R. Andrew (APL-UW), A. Baggeroer (MIT), F. J. Beron-Vera (UMiami), M. Brown (UMiami), J. Colosi (NPS), B. Dushaw (APL-UW), N. Grigorieva (St. Petersburg State Marine Technical Univ.), K. Heaney (OASIS), F. Henyey (APL-UW), B. Howe (APL-UW), J. Mercer (APL-UW), A. Morozov (WRC and WHOI), V. Ostachev (NOAA/ETL), D. Rudnick (SIO), E. Skarsoulis (IACM/FORTH), R. Stephen (WHOI), A. Voronovich (NOAA/ETL), K. Wage (George Mason Univ.), and M. Wolfson (APL-UW).

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PUBLICATIONS

Van Uffelen, Lora J., Worcester, Peter F., Dzieciuch, Matthew A., Rudnick, Daniel L. (2009). "The vertical structure of shadow-zone arrivals at long range in the ocean," J. Acoust. Soc. Am. **125**, 3569-3588. [published]

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