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

Lora J. Van Uffelen
Scripps Institution of Oceanography
University of California, San Diego
9500 Gilman Drive, Mail Code 0238
La Jolla, CA 92093-0238
phone: (858) 822-4908 fax: (858) 534-6251 email: lvanuffe@ucsd.edu

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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 is expected from diffraction alone [1]. This energy appears anomalously deep in the water column, but the measured travel times seem to 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 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 speed channel, and 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

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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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The experimental data was compared to parabolic equation propagation simulations based upon hydrographic measurements taken at the time of the deployment [2]. Three different environments were considered: a range dependent profile developed using underway CTD (UCTD) measurements taken at the time of the experimental deployment and during the related LOAPEX experiment, the mean sound speed profile, and a mean sound speed profile perturbed to statistically simulate the oceanic sound speed perturbation due to internal waves [3].

Internal waves may account for much of the vertical extension. Previous work on the SLICE89 data has shown that internal waves break down the geometrical optics timefront pattern and broaden the timefront at the finale [4]. It has also been hypothesized that reflections off the base of the mixed layer may cause a steepening and deepening of acoustic rays which increases with the number of reflections from the base of the mixed layer [5]. Spicy fronts within mixed layer may also contribute to scattering into the geometric shadow zone. Simulations have been performed to predict this scattering, but have not been compared to acoustic data [6].

It seems likely that several mechanisms could in fact be important, depending on the upper turning depths of the ray paths. If so, one would expect the shadow zone arrivals to be a function of ray path and of the structure of the upper ocean. Since high-quality acoustic data is available for several months during the life cycle of the oceanic mixed layer, the effects of the changing mixed layer sound speed will be evident in the changes in the acoustic timefronts. Estimates of the changing sound speed environment will be made using UCTD measurements taken on the SPICEX deployment cruise in June and the LOAPEX cruise in September. Simulations based on these changes will help elucidate the extent to which the variability can be attributed to the changes in the mixed layer sound speed structure

This work is being funded as a graduate student traineeship award and the members of my thesis advisory committee, Dr. Peter Worcester, 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 are all offering advice and guidance as committee members. Dr. Matthew Dzieciuch of the Scripps Institution of Oceanography has also contributed.

WORK COMPLETED

Because acoustic travel time is the primary observable utilized in ocean acoustic tomography, previous analysis of long-range propagation data has focused on acoustic travel time, with less attention paid to determining the intensity of arrivals. Determining the absolute intensities of both acoustic data and parabolic equation simulations is necessary to make meaningful comparisons between acoustic receptions as well as between receptions and simulation data.

Much of the effort in FY07 was directed at determining the absolute intensities of the acoustic data from both the axial HLF-5 and abyssal WRC sources based upon calibration of the sources and hydrophones as well as the gain due to signal processing performed on the data. Improvements were also made in determining the acoustic travel time.

Recent efforts have focused on determining absolute intensities for the parabolic equation simulations in order to make direct comparisons and quantification of scatter into the acoustic shadow zone. Updated simulations using absolute intensities were compared to acoustic data.

The evolution of the timefronts throughout the 6-month deployment was examined, and receptions in June and September were compared to parabolic equation simulations performed based on estimated sound speed environments formulated using UCTD and CTD measurements collected on the SPICEX deployment cruise and the LOAPEX cruise, respectively. Although the sources were no longer transmitting in March, simulations were also performed for a March profile, based on SeaSoar measurements collected by Dr. Daniel Rudnick, to simulate the effect of a deep spring mixed layer.

RESULTS

Intensities for the acoustic data from all four acoustic sources seem reasonably situated between what would be expected for spherical spreading and what would be expected for spherical spreading to 5000 meters (the approximate ocean depth) and cylindrical spreading for the remainder of the transmission range. Figure 1 shows a sample reception from the 500-km range HLF-5 source. The upper portion of the timefront is separated in travel time from the lower portion because the shallow portion of the VLA (SVLA) was located approximately 5-km nearer to the source than the deep VLA (DVLA).

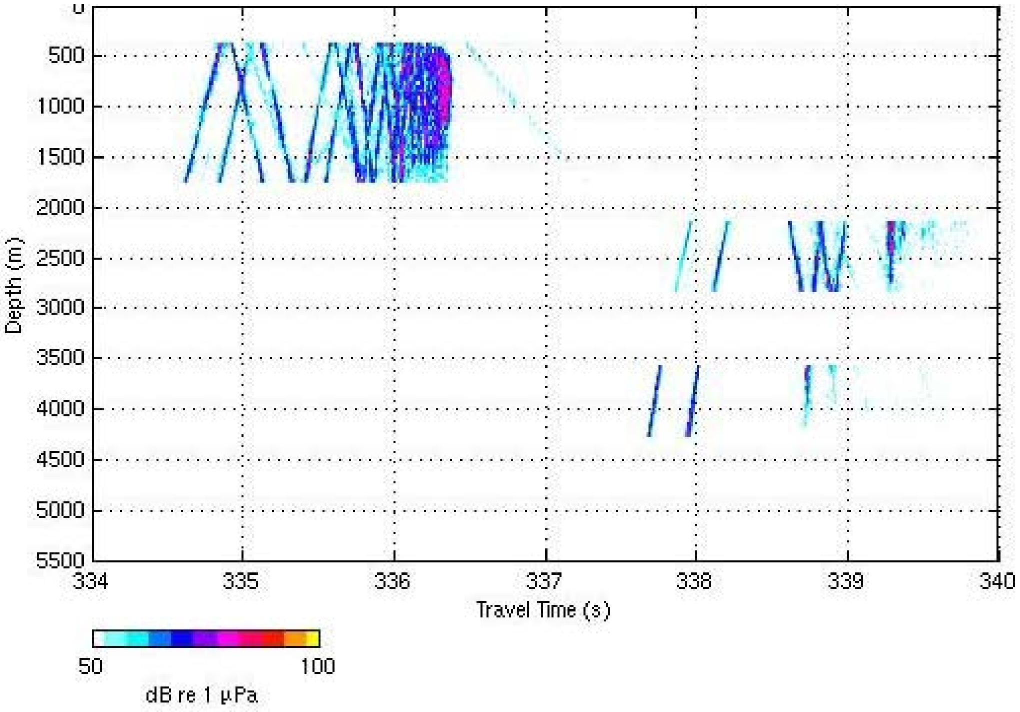

Figure 1: Timefront plot for a single June 11, 2004 acoustic reception from the 500-km range HLF-5 source. Data is calibrated to be in units of dB re 1 μPa. Arrivals on the SVLA precede arrivals on the DVLA in travel time due to the physical separation of the moorings.

No significant changes in vertical extension into the shadow zone were seen to evolve during the 6-month transmission period, although there was not a significant deepening of the mixed layer during the period of acoustic transmissions. The parabolic equation simulations also did not appear to show significant deepening of the timefronts other than what would be expected due to the change in turning depths due to the differing sound speed profiles, although closer evaluation needs to be done.

Figure 2 shows a 1-day average (6 transmissions) of the calibrated intensity for selected hydrophones on the DVLA as a function of travel time for receptions from the HLF-5 acoustic source located 500-km distant. The acoustic data shown in red can be thought of as an average of horizontal slices of timefronts similar to the one presented in Figure 1. The peaks of the hydrophone data were time-aligned with the first peak of the simulation at the deepest phone to obtain a coherent average of data receptions.

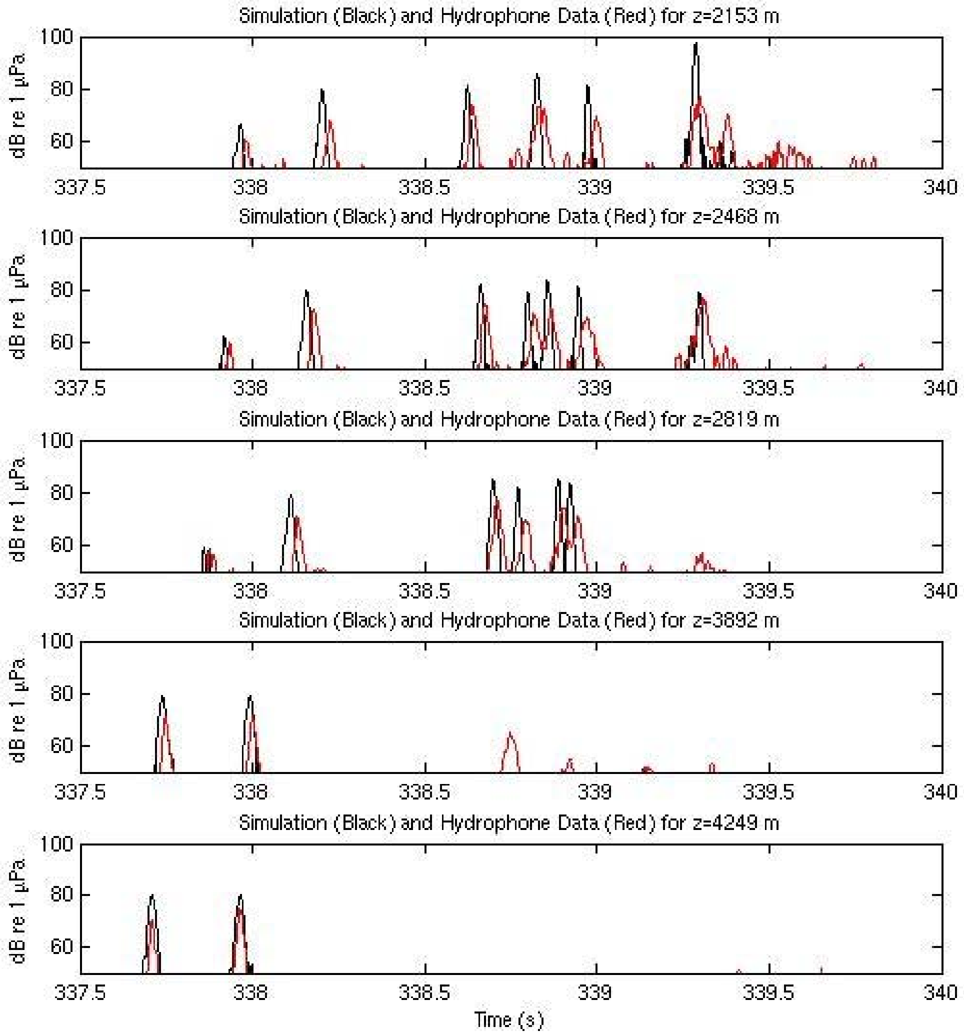

Figure 2: Comparison of parabolic equation simulations (black) and a hydrophone data (red) at selected hydrophone depths from the DVLA. Data shown is a coherent 1-day average of HLF-5 receptions from the 500-km source.

Comparisons of calibrated acoustic data with corresponding range-dependent parabolic equation simulations verified that the shadow zone extensions that were observed previously are a real phenomenon and not merely an artifact of dynamic range or noise effects. This is clearly visible on the lower hydrophones shown in Figure 2. The red peak on the hydrophone at 3892 meters (4th plot from the top) clearly shows an arrival at approximately 338.75 seconds, which is not even hinted at by the predictions. This peak is clearly a shadow zone arrival.

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), S. Flatté (UCSC), 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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