

Fluctuations of Broadband Acoustic Signals in Shallow Water

Mohsen Badiey

College of Earth, Ocean, and Environment

University of Delaware

Newark, DE 19716

Phone: (302) 831-3687 Fax: (302) 831-3302 Email: badiey@udel.edu

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<http://oalab.cms.udel.edu>

LONG-TERM GOALS

The long-term goal of this project is to obtain quantitative understanding of the physical mechanisms governing broadband (50 Hz to 50 kHz) acoustic propagation, reflection, refraction, and scattering in shallow water and coastal regions in the presence of temporal and spatial ocean variability.

OBJECTIVES

The scientific objective of this research is to understand acoustic wave propagation in a dynamic environment in two frequency bands: Low (50 Hz to 500 Hz) and Mid-to-High (500 Hz to 25 kHz). The goal for the low frequency band is to assess the effects of internal waves on acoustic wave propagation, with an emphasis on the mechanisms that cause significant acoustic temporal and spatial intensity fluctuations. The goal for the mid-to-high frequency band is to assess the effects of water column and dynamic sea surface variability, as well as source/receiver motion on acoustic wave propagation for underwater acoustic communications, tomography, and other applications.

APPROACH

The project combines theoretical, experimental, and modeling efforts to improve our understanding of broadband acoustic wave propagation in a dynamic shallow water environment. Studies in the low frequency band have been focused on data from the SW06 experiment with both stationary and moving sources [1] to investigate different mechanisms that can explain acoustic intensity fluctuations in the presence of internal waves. A 3-D propagation model has been utilized and detailed 3-D environmental data required as input to the model has been constructed using temperature and radar image data. Improvements have been made to take into account the curvature of the internal wave fronts.

Studies in the mid-to-high frequency band have utilized data collected at KAM08 [2] as well as additional data from recent KAM11 [3] experiment. The effects of sea surface and water column

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variability on acoustic wave propagation have been investigated using both Parabolic Equation (PE) and ray-based models.

WORK COMPLETED

1) Low Frequency Acoustic Wave Propagation

A 3-D parabolic approximation model was developed to study both stationary and moving sources propagation scenario in the presence of internal waves. A detailed 3-D environment was reconstructed based on shipboard radar images and temperature data collected at various locations along the acoustic track [4]. For both stationary and moving sources, model-data agreement was considerably improved when the curvature of the internal wave fronts was included in the model compared to straight wave front assumption [5]. Model results are promising; not only it can reproduce the mechanisms (focusing-defocusing, interference, etc.) of the acoustic intensity fluctuation, but is also able to quantitatively predict the time and location of specific details given a high quality reconstruction of 3-D environment as parameter.

2) High Frequency Acoustic Wave Propagation

We recently participated in the Kauai Acomms MURI 2011 (KAM11) experiment in Kauai, Hawaii. During the joint efforts with the Marine Physical Laboratory (MPL) - Scripps Institution of Oceanography and the Woodhole Oceanographic Institution (WHOI), the Ocean Acoustics Laboratory - University of Delaware deployed two-tripod systems multiple times as well as conducting environmental measurements. We have continued our analyses of the data from KauaiEx 2003, MakaiEx 2005, KAM08, and now the recently acquired KAM11 data to assess the effects of the environment on the acoustic wave propagation. For modeling, time-evolving rough sea surfaces used as boundaries in the PE model were re-generated using waverider buoy data from KAM08. Results from the PE model runs are being closely compared with data and specific features relevant to the acoustic communication research are being studied in detail.

3) Instrumentation

In KAM11 we collected extensive acoustic data using our two autonomous high frequency acoustic transceiver tripod systems. The system includes a modular high-frequency hydrophone array (1-8 elements), a mid-frequency (10 kHz) and a high frequency (25 kHz) transducer, a central electronics unit in underwater pressure housing, deep sea batteries, and a scaffold tripod (height 5.1m) for seafloor deployment. Three deep sea batteries can provide approximately 72 hours continuous recording time.

RESULTS

A. Low Frequency Acoustic Wave Propagation in Presence of Shallow Water Internal Waves

To examine the angular dependence of acoustic propagation in an environment with internal wave, during the SW06 experiment in New Jersey shelf, an acoustic source (J15 projector) was towed by the R/V Sharp, which was following the front of an internal wave packet (Fig. 1a). The source was transmitting broadband acoustic signals (50-450 Hz) in different angles with respect to the internal wave front (Zones 1-5). Signals received on WHOI Vertical Linear Array were analyzed and modeled.

A 3-D environment was reconstructed based on the shipboard radar images of R/V Sharp and R/V Oceanus and temperature data collected on three thermistor strings [4]. Recent study has shown the

importance of the ducting by curved internal waves [5]. Here, the reconstruction of the 3-D environment also includes the linear interpolation of the thermistor data along the curved internal wave front and then confirming the results on the surface by using the radar images obtained during the acoustic transmissions. Figure 1(b) shows the reconstructed temperature field at 30 m (near the thermocline), between the source (J15 aboard R/V Sharp) and the vertical receiver array (Shark array) with radar image overlay. Note that the data is extended beyond these two points based on additional thermistors along the propagation path between the fixed source (NRL300) and the receiver array.

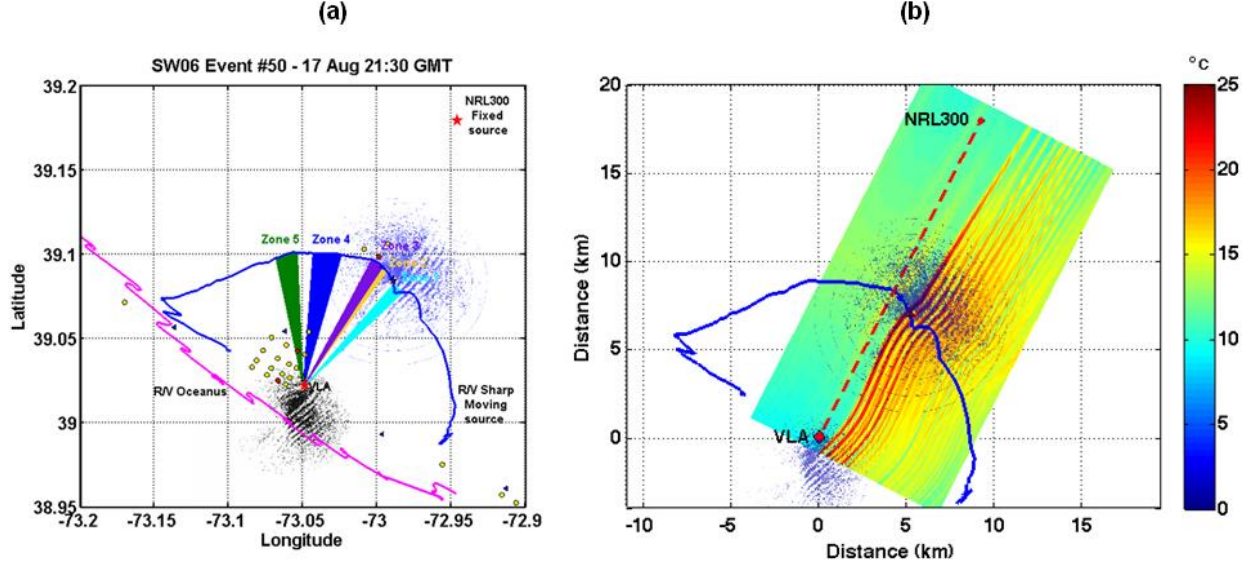


Figure 1: (a) Ship tracks of R/V Sharp (acoustic source) and R/V Oceanus, location of VLA receiver, environmental moorings (red and yellow dots), radar images from R/V Sharp and R/V Oceanus at 21:30 GMT on August 17, 2006, and 5 Zones are depicted on the image corresponding to the schedule of transmissions during this period, with silence in between the identified time zones. (b) Reconstructed environment at 21:30 GMT at depth 30 m. Note the curvature of the internal wave fronts.

Figure 2(a) shows the depth-integrated intensity of the received acoustic signals on the vertical array versus the estimated angles between acoustic track and internal wave fronts (see Fig. 1a). Note that positive angle means the acoustic signal propagates towards the tail of IW package. The intensity fluctuation varies in each zone. This is verified against the theoretical predictions of the angular dependence of the field based on the interactions with IW front [6]. A three dimensional PE is used with the interpolated 3-D environmental data explained above to model this propagation scenario.

Figure 3 shows the top view of the depth integrated acoustic intensity (color) from 3-D PE modeling result with temperature contour (black line overlay) at 30 m depth. A focusing occurrence at 21:53:00 GMT (Zone 2) is predicted by the model in Fig. 3(a). The model also shows a strong horizontal Lloyd's mirror interference pattern at 22:00:00 (Fig. 3b), similar to the data observed [7]. The occurrence of focusing at geotime about 22:21:30 (Zone 3) observed in the data was well predicted by the model. The model also shows that when the focusing occurred, the acoustic energy was concentrated at the lower part of the water column, which was largely due to the depression of the thermocline caused by the arrival of internal waves. The PE modeling results match the data well for Zones 2 and 3. Results of model-data comparison for the depth-integrated intensity in all 5 zones are

shown in Fig. 4. The model results generally agree with the experiment data except for Zone 4 that falls into the intermediate range of azimuthal relationship shown in Fig. 2(b).

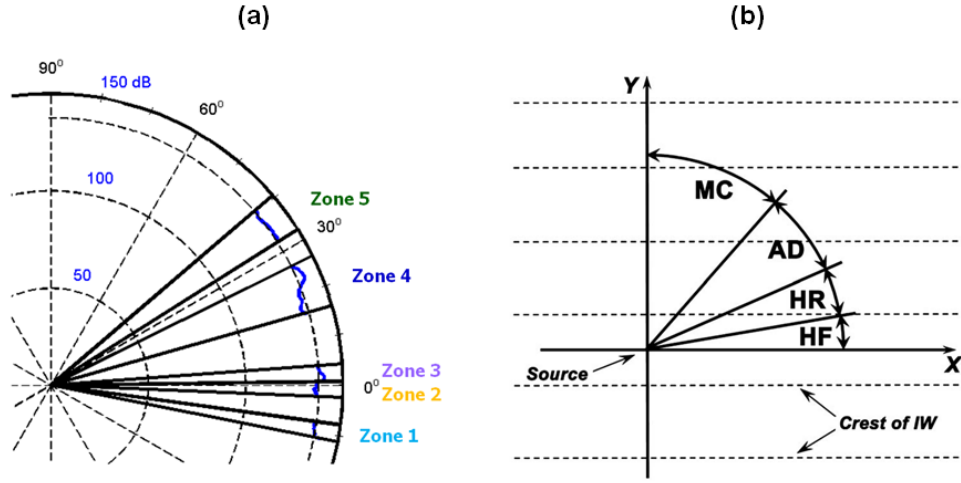


Figure 2: (a) Data of depth-integrated intensity and estimated angle for each zone. (b) Mechanisms of internal wave effect depend on the angle between the internal wave and the acoustic track. HR=horizontal refraction, AD=adiabatic, and MC=mode coupling.

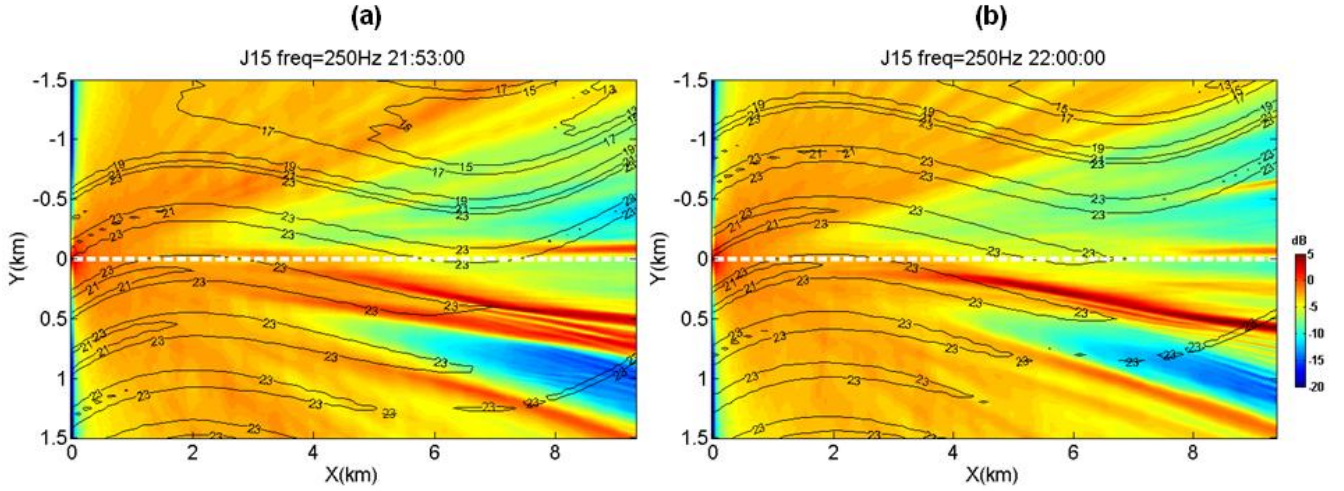


Figure 3: 3-D PE modeling results showing the acoustic intensity (in color) and the temperature contour (black line overlay) at depth 20 m. Source is located at point (0,0) and white dashed lines indicate the acoustic track. Model results show (a) focusing mechanism and (b) strong horizontal Lloyd mirror interference pattern.

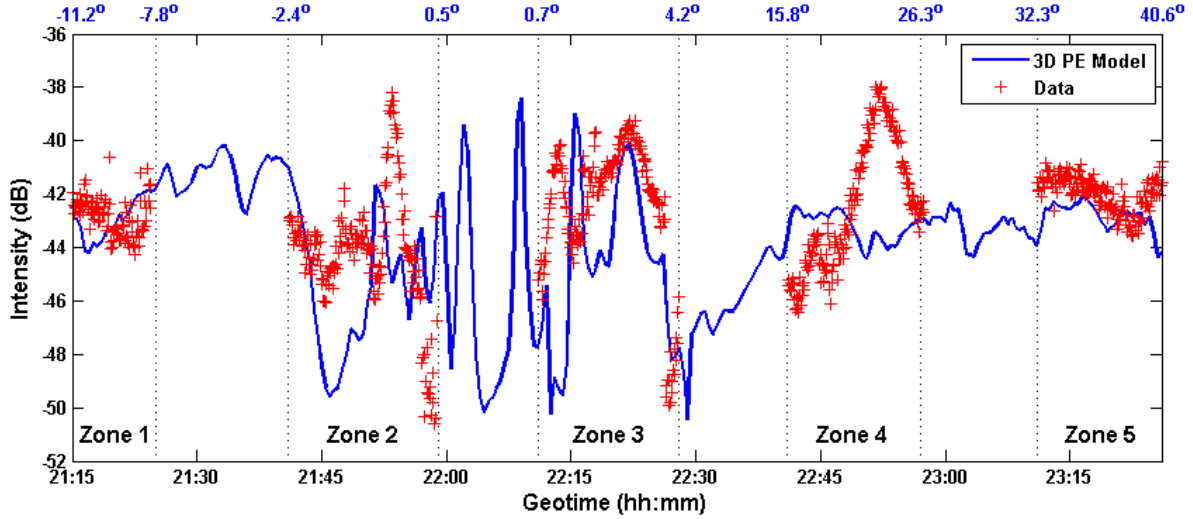


Figure 4: Model-data comparison of the depth-integrated intensity for transmission in Zones 1 to 5 shown in Fig. 1(a). At Zones 2 and 3 the model results are in very good agreement with data. At Zone 4, the model could not reproduce the peak intensity observed in data due to lack of detailed environmental data during this propagation period.

B. High Frequency Acoustic Propagation in Shallow Water

Surface waves are among several environmental parameters that can have significant influence on acoustic propagation in shallow water. To study the effects of surface wave roughness we have developed PE and Ray models in conjunction with a 2-D time-evolving sea surface boundary to analyze the results obtained during a highly calibrated field KAM11 experiment. In this section we first present our recently obtained experimental data followed by results from our recent modeling efforts.

I. KAM11 Experiment

KAM11 Experiment was conducted off the western side of Kauai, Hawaii, from June 23 to July 12, 2011 in a water depth of about 100 m. The experiment focused on collecting acoustic and environmental data to study the effects of ocean variability on high frequency acoustic propagation affected by the temporal and spatial changes in the water column and the sea surface [8, 9]. It is shown that the ocean variability impacts arrival rays differently depending on their travel paths. The measurements from KAM08 and KAM11 provide data for these studies. In KAM11 we also transmitted reciprocal high frequency broadband (between 7-13 kHz) signals between 2 bottom-mounted tripods to assess the effects of surface wave directionality on the propagation. These transmissions were conducted during highly calibrated setting where detailed environmental data were collected simultaneously.

Figures 5 (b) and (c) show the received signals at the ship-deployed monitoring hydrophone for 30 s transmissions from UD Tripod I (left) and Tripod II (right), respectively. Deterministic fringe patterns due to reflection/scattering from the sea surface are observed in each case that could be related to the directionality of the surface waves.

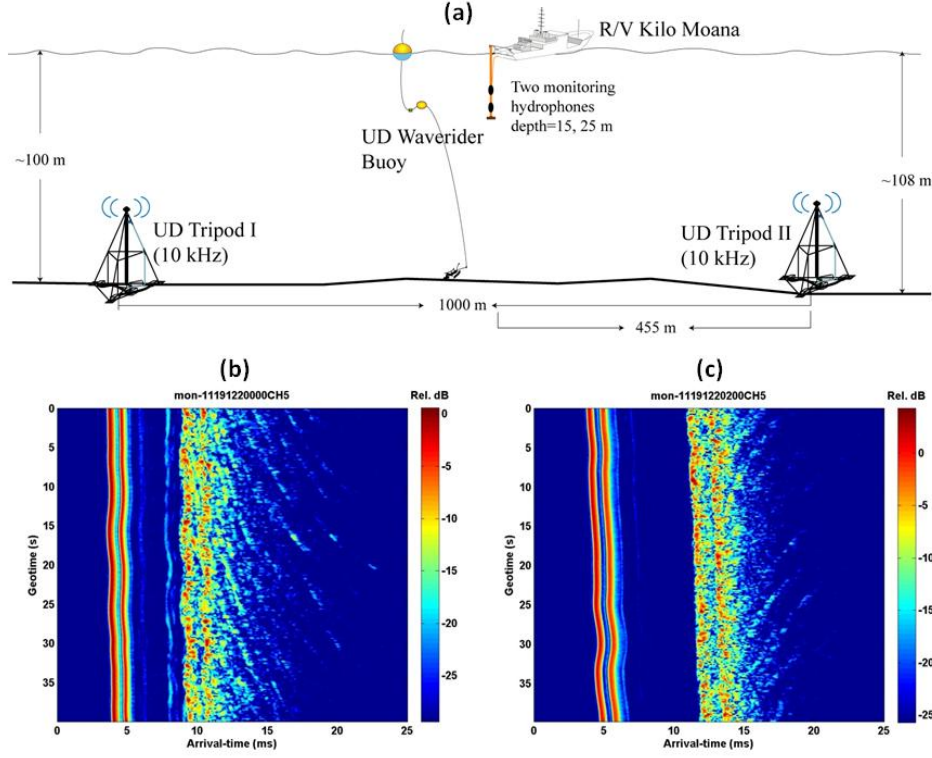


Figure 5: Reciprocal arrival time of a broad band signal (7-13 kHz) during KAM11 experiment from July 10 21:00 to July 11 3:00, 2011 (UTC) (a) Schematic of the experimental setting. In addition to the receivers located at each tripod on the seafloor, there are two ship-deployed hydrophones located near the sea surface at 15 and 25 m below the sea surface respectively. (b) and (c) subplots show the received signals from left (Station 05 in Ref. [3]) and right (Station 07 in Ref. [3]) sources transmitting from the sea floor. Deterministic features on the single bounced surface return shown as deterministic periodic stripes are showing the interaction between acoustic signals and the surface waves. The time difference between subplots (b) and (c) was two minutes.

II. Parabolic Equation Model Results

While we have some newly obtained data from KAM11 experiment that was conducted a couple of months ago, the modeling results shown in here are related to the KAM08 experiment. We have used the waverider buoy data from KAM08 to model the time-evolving rough surfaces and input the modeled rough surfaces into a PE model [10]. To better understand the variations resulted from the evolving sea surface, we compared individual acoustic paths to respective neighboring paths for collected and modeled data. We also computed ensemble averages over a variety of averaging periods to determine the relationship between short and long periods. Furthermore, we also examined channel updating and coherence time by correlating individual paths against each other.

PE model runs generally follow the patterns of the collected data (Fig. 6). The direct and bottom-reflected paths arrived at the receiver at the same time, and are denoted by "1+2" in Fig. 6. The surface-reflected and surface-bottom paths arrivals are close to each other, and are labeled as 3 and 4, respectively. For both data and model, some periods display stronger surface-direct signals, while other periods display stronger surface-bottom signals. After the main surface arrivals (denoted by the dotted

lines in Fig. 6), we observe a dispersal of intensity over arrival time and geotime due to scattering that occurs between broadband signals and the rough sea surface.

Figure 7 displays the same data as Fig. 6 but averaged over the 30 s geotime window. For both data and model, the relative intensity decreased from -8 dB to -25 dB between 9 and 11.4 ms. This shows that the PE with rough evolving sea surface is able to approximate the collected data relatively well.

We are currently considering the role that high wave-numbers play in extending the surface scattering. Furthermore, we are examining the effects bubbles play on near-surface scattering by combining the rough surface PE model with a range-dependent bubble model and comparing those runs with data collected under high sea states where the bubbles are most likely to generate.

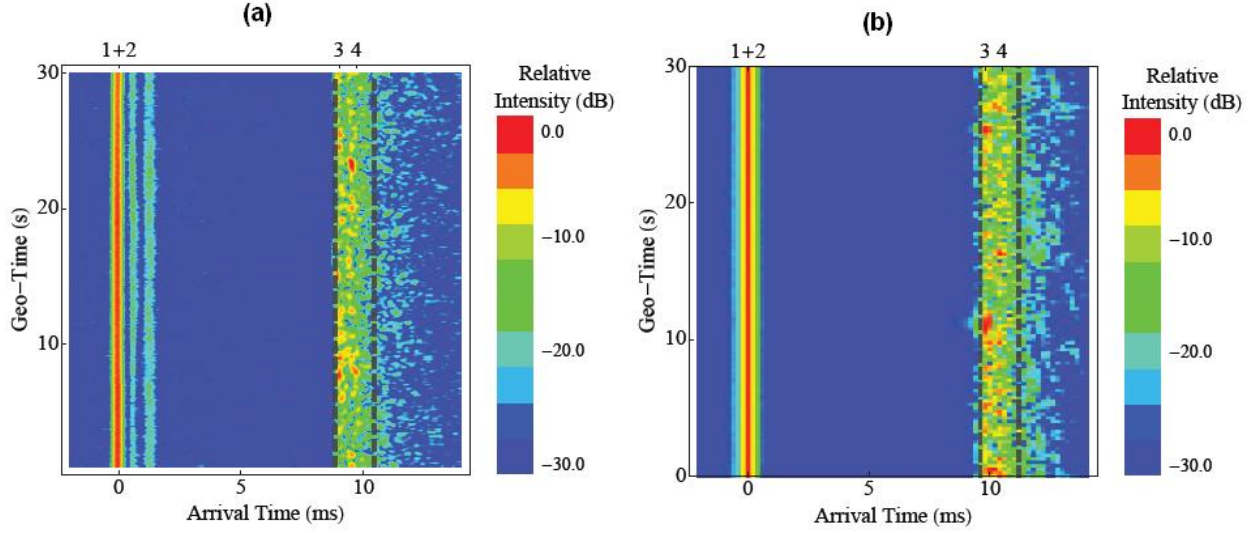


Figure 6: Impulse Intensity as a function of arrival time and shown over a 30s geotime period for Tripod data (a) and PE model (b). Dotted black lines indicate portions of returns used for correlation analysis.

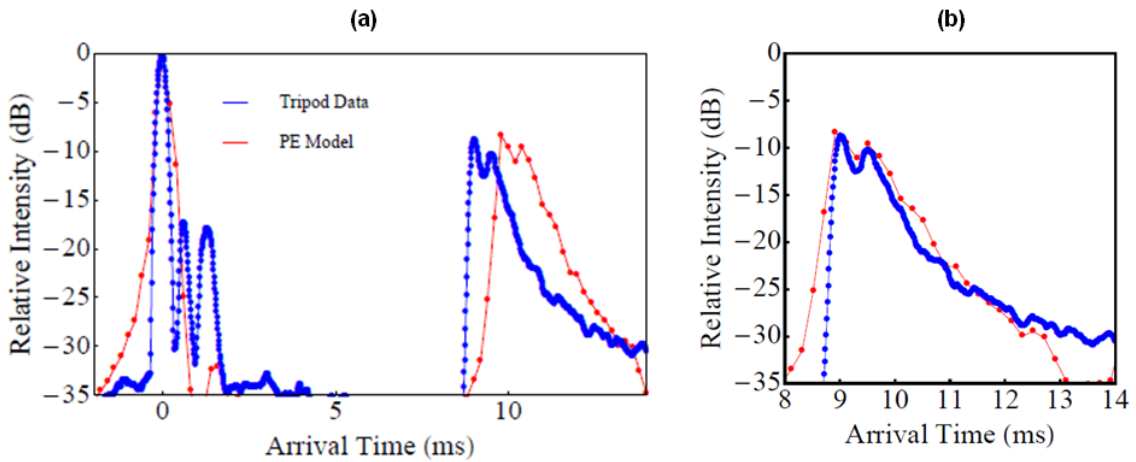


Figure 7: 30s Ensemble averages of impulse intensity as a function of arrival time, with artificially aligned surfaces in zoom.

IMPACT/APPLICATIONS

The low frequency component of our research contributes to the understanding of acoustic propagation in complex shallow water regions. We have developed a model to explain the mechanisms of acoustic intensity variation caused by internal solitons. The high frequency part of our research has contributed to the understanding of the effects of surface wave roughness on sound propagation, which in turn affects the performance of acoustic communication signals.

RELATED PROJECTS

In our low frequency band research, we have been working with Dr. J. Lynch from Woods Hole Oceanographic Institute (WHOI) and Dr. B. Katsnelson from University of Voronezh, Russia. For the research work in the high frequency band, we are collaborating with colleagues from Scripps Institution of Oceanography (Dr. W. Hodgkiss and Dr. H.-C. Song), Naval Post Graduate School (Dr. K. Smith), and Heat, Light, and Sound Research Inc. (Dr. M. Porter).

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