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Experimentally-Based Ocean Acoustic Propagation and Coherence Studies

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LONG TERM GOALS

The long term goal is to better understand fluctuating sound propagation conditions in two distinct ocean acoustic environment types. The first type is stratified shallow water where sound is highly bottom interacting. The second type is the mostly non bottom-interacting temperate deep-ocean sound channel. Reliable predictions of temporal and spatial variability of received underwater sound can improve processing and handling of signals of interest, including remediation of signal degradation and exploitation of available sonic information. Acoustic field fluctuations have time scales from less than a minute to hours, and horizontal spatial scales from tens of meters (as short as a few wavelengths at our lowest frequencies) to kilometers, and thus impact exploitation of underwater sound.

OBJECTIVES

An overarching objective is to explain observed sound fluctuation behavior in environments with three-dimensional structure at all significant scales. For the shallow-water ocean environment, the objective is to develop knowledge of factors controlling acoustic field mean and variability (both transmission loss and phase) at frequencies from 50 to 3000 Hz. For the deep-ocean sound channel, the objective is to better characterize coupled-mode propagation at 50 to 100 Hz, which may have some behavior in common with shallow-water coupled-mode propagation.

APPROACH

The planned approach includes analysis of existing data, modeling, theory, and planning of future experiments. The majority of the work will be development of theoretical and computational results, and direct comparison of these results with data collected in recent field experiments. For shallow water studies, data are mainly from the recent ONR Shallow-Water 2006 experiment (SW06) [Tang *et al.,* 2007], with lesser amounts from the ASIAEX study [Chiu *et al.,* 2004; Duda *et al.,* 2004], the northeastern South China Sea spring 2007 ONR/Taiwan NLIWI acoustics experiment [Reeder *et al*., 2010], and the Shelfbreak PRIMER study. For deep-water studies, data are from the ONR Long-range Ocean Acoustic Propagation Experiment (LOAPEX) [Mercer *et al.,* 2009]. Planned activities are: (1) Continue analysis of the existing data sets, improve the modeling capability, and update theories, with

a focus on 3D effects (i.e. azimuthal variations not correctly handled by N×2D models); (2) Begin planning for a year 2016 shallow-water experiment, possibly in a shelf-edge and canyon area.

Fluctuation properties from the data sets will be compared with predictions from theory and numerical simulation to identify and characterize the major causes of the fluctuations. Because three-dimensional (3D) acoustic effects arising from 3D aspects of the environment are an important class of effects that we focus on for shallow water, our computational methods include fully-3D acoustic propagation simulations through realistic environments. The shallow-water effort is aimed primarily at summer conditions in the temperate ocean (an approximate two-layer system), but also includes conditions found just inshore of shelfbreak fronts.

For shallow water work we have focused this year on data from the Mid-Atlantic Bight Littoral Environmental Acoustics Research (LEAR) portion of SW06, and on NLIWI 2007 data set. The SW06 area has warm water offshore and winter-cooled water on the shelf. In this area there is often a thin deep warm salty layer, capped by an inverted thermocline. The NLIWI area has multiple types of large nonlinear internal waves. Internal tides and nonlinear mode-one internal gravity waves are known to often dominate acoustic variability in these (and other) regimes. In each field study moored acoustic sources transmitted signals to moored acoustic receivers, and larger numbers of other sensors measured environmental variations. Temporal variations of the acoustic propagation conditions were examined and compared directly with local conditions and with data-driven predictions.

WORK COMPLETED

A large number of LEAR/SW06 pulses transmitted from moored sources to the WHOI L-array (co-located HLA/VLA) have been analyzed. A manuscript has been submitted to the Journal of the Acoustical Society of America this year, and accepted for publication. The manuscript describes spatial coherence of 100 to 400 Hz acoustic signals measured with the horizontal portion of the L-array resting on the seafloor at 80 m depth. Figure 1 shows the experimental arrangement. Figure 2 shows some coherence length estimates, obtained with a broadband method. The coherence lengths are e-folding scales of spatially lagged covariance functions of complex demodulated signals. Figure 3 shows horizontal array gain variations between two 2.4-hour windows of the experiment. The array gain is defined as the signal to noise ratio for coherently added (beam steered) acoustic receptions with an array, divided by the signal to noise ratio for a single array element.

Also this year, a paper modeling sound propagation through the environmental conditions conditions measured during NLIWI has been finalized and published [Duda, Lin and Reeder, 2011]. Our Cartesian coordinate 3-D parabolic equation (PE) code was used for this study. The paper included 3-D modeling of sound through realistic curved internal waves. Simulated acoustic fields, strongly refracted in the waves, showed good agreement with measurements. The simulations fully mimic the propagation along the measured curved wave crests. The simulations provide results at many angles besides those measured in the field, so other effects may be discovered. The good data/model comparisons imply that insight taken from the model results can be trusted.

A study of LOAPEX low-mode arrivals at 50 to 3200 km distance in the North Pacific (Figure 4) has yielded a manuscript for journal submission. Dr. Ilya Udovydchenkov leads the LOAPEX work. The statistics of modal arrivals have been analyzed and compared with theoretical estimates and numerical model predictions. The spreading in time of mode-filtered sound arrivals (intended to quantify arrivals of energy contained in individual acoustic normal modes) agrees with predictions for a sound source

near the depth of the sound speed minimum. The degree of agreement is sensitive to details used in the prediction, such as environmental mismatch.

RESULTS

SW06/LEAR: Continuing analysis of the SW06 L-array fluctuation data set that was partially analyzed and published earlier [Collis *et al.,* 2008] was completed, leading to an accepted publication. Highly variable SW06 horizontal array gains and coherence lengths for along-internal wave duct propagation and for across-internal wave duct propagation have been analyzed for the entire experiment. The results show rapid variability of these quantities along with slow trends of these quantities.

Two additional papers headed by colleague Professor John Colosi have also been produced and accepted for publication. One describes the nature of sound-speed variability in SW06 from density compensated temperature and salinity fluctuations along isopycnals (so-called spiciness), and quantifies internal wave normal modal bandwidth (mode spectrum). The other paper investigates cross coherence of acoustic normal modes in low-frequency shallow-water propagation, yielding apparently robust estimates of mean acoustic fields in fluctuating conditions and range evolution of the scintillation index. One paper headed by Kara McMahon and Prof. William Siegmann of Rennselaer Polytechnic Inst. was also produced and accepted for publication. The paper describes sound propagation in somewhat randomized shallow-water internal waves, as appearing in Figure 1.

SCS/NLIWI: Sound refraction effects measured at the South China Sea site were found to be consistent with model results. A published paper reports modal refractive indices and critical angles of the internal waves present during the experiment. The 3D acoustic effects measured in the field were replicated with simulated 3D propagation through curved internal waves, aloe reported in the paper. The study of sound within high-amplitude curved internal waves showed a new effect: surface ducting at different azimuth angles than low-mode deep ducting. In the curved-wave situation, critical mode refraction effects evolve as the sound moves along the curved duct, rather than being constant.

LOAPEX: The temporal structure of measured modal group arrivals (modal pulse width) was compared to theoretical predictions and numerical simulations. Theory, simulations, and observations generally agree. For situations having poor agreement, reasons for the disagreement have been analyzed in terms of the underlying physical processes and data limitations. A manuscript describing the work is complete. New work on bottom-interacting sound recorded at 50-km range shows some promise for separation of bottom-reflecting and direct energy and for seafloor geoacoustic property inversion.

IMPACT/APPLICATIONS

The results may be useful in the signal processing domain, particularly of horizontal array data. Algorithms may be developed by others that are robust to signal fluctuations, or which may exploit them.

RELATED PROJECTS

The PI collaborates with Dr. Y.-T. Lin of WHOI on computational efforts. The PI is working with other ONR PI's analyzing data from the SW06, 2007 South China Sea, and ONR QPE experiment sites. An ONR-funded 3D sound modeling study joint with the Scripps Institution of Oceanography is

in place this year. Also, a large project was initiated this year, the Integrated Ocean Dynamics and Acoustics (IODA) DoD MURI project, intended to improve acoustic modeling and prediction by coupling improved acoustic models to improved high-resolution ocean environmental models.

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HONORS/AWARDS/PRIZES

Dr. Duda received the award "Fellow of the Acoustical Society of America".

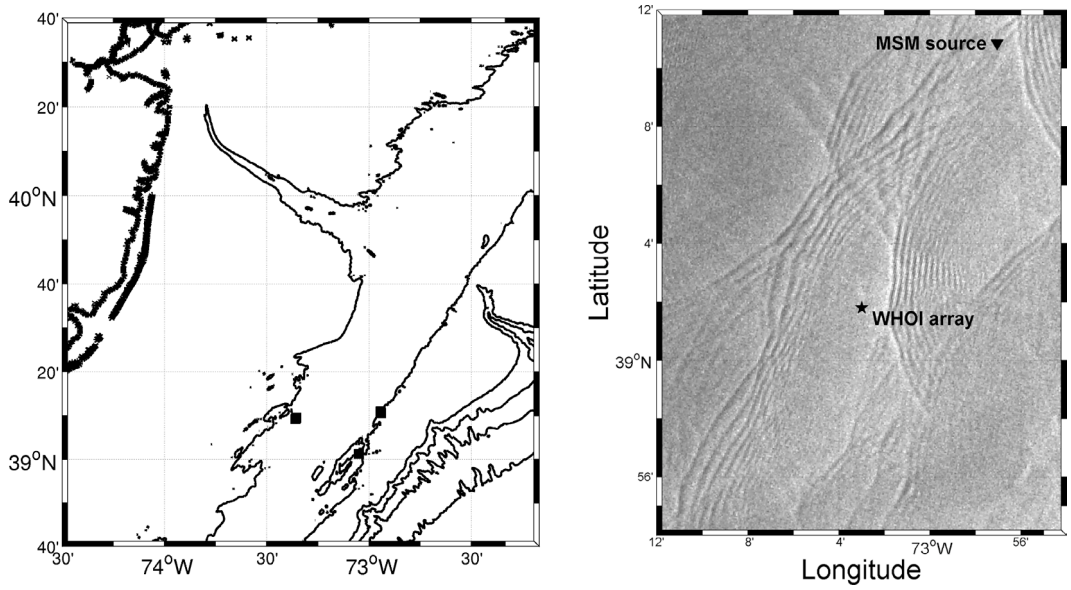

FIG. 1. (left) The SW06 site is shown. New York harbor is at the extreme upper left corner. Contours at 0 m (coastline, thick line), 50, 80, 200, 500, 1000 and 2000 m are shown, with the 80-m isobath crossing Hudson Canyon in a nearly straight line at 39-40 N, 72-30 W. Three squares show the WHOI L-array receiver (southernmost) at approximately 39-1 N, 73-3 W, the 'NE' acoustic source mooring position 19 km to the northeast, and the 'NW' source mooring position 32 km to the northwest. (right) A satellite SAR image showing internal wave surface signatures from the University of Miami (CSTARS) is shown, with two mooring positions repeated from the other frame.

[(left) The chart shows receiver and NE positions at 80-m contour, NW near the 50-m contour. Hudson Canyon is north and northeast of these. (right) Many internal wave packets traveling westward are seen in the image, with one to three waves per km and three to eight waves per packet.]

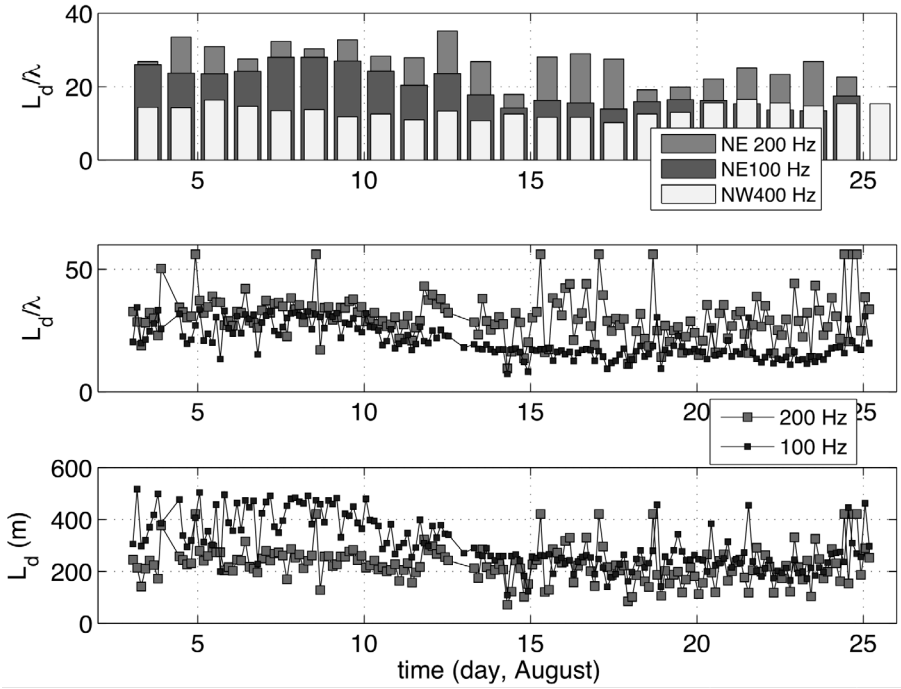

FIG. 2. (top) One-day average horizontal coherence scale, normalized using acoustic wavelength, measured at the HLA receiver, is plotted for three SW06 acoustic sources: NE 200 Hz, NE 100 Hz, and NW 400 Hz. (See Fig. 1 for positions.) (middle) Normalized horizontal coherence scales are shown for the two NE sources, with three-hr averaging in place of 24-hr averaging. (bottom) The results of the middle panel are shown again without normalization with respect to wavelength.

[(top) NW 400 Hz coherence for a transmission path across internal-wave crests is shorter and steadier than the others, at 15 wavelengths. The others are 25 to 30 wavelengths for about ten days, then drop to 15-20 wavelengths for about ten days. (middle) The three-hour average results are near 30 wavelengths for ten days, then diverge for ten days to a steady value of 15 wavelengths for 100 Hz and a fluctuating higher value for 200 Hz. (bottom) The dimensional correlation lengths differ for the two frequencies over the first ten days, being greater for 100 Hz, and are similar for the two frequencies over the final ten days.]

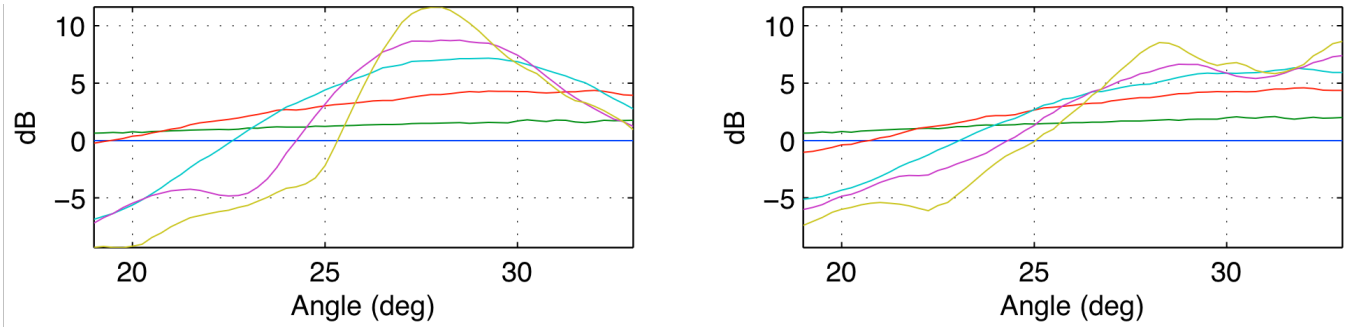

FIG. 3. 200-Hz (NE) array gain is shown in dB units. Results are from two 2.4-hour long windows on 14 August, hours 0-2.4 (left) and hours 4.8-7.2 (right). The panels show window-mean gain as a function of HLA beam steering angle, converted to dB after averaging. Subarray lengths are one element (flat line, no gain), 2, 4, 8, 16 and 32 elements. The gain increases montonically with subarray length near 28° from north for each window, showing the line coloration order. The first period (left) has weak internal waves and one strong peak of high gain. The later period (right) has two lower gain peaks, suggesting horizontal acoustic multipath and interference.

[The left panel shows higher gain than the right panel, and also shows maximum gain in the steering direction toward the source. The other has lower gain and two peaks for 16 and 32 elements, at 28 and 32 degrees from north.]

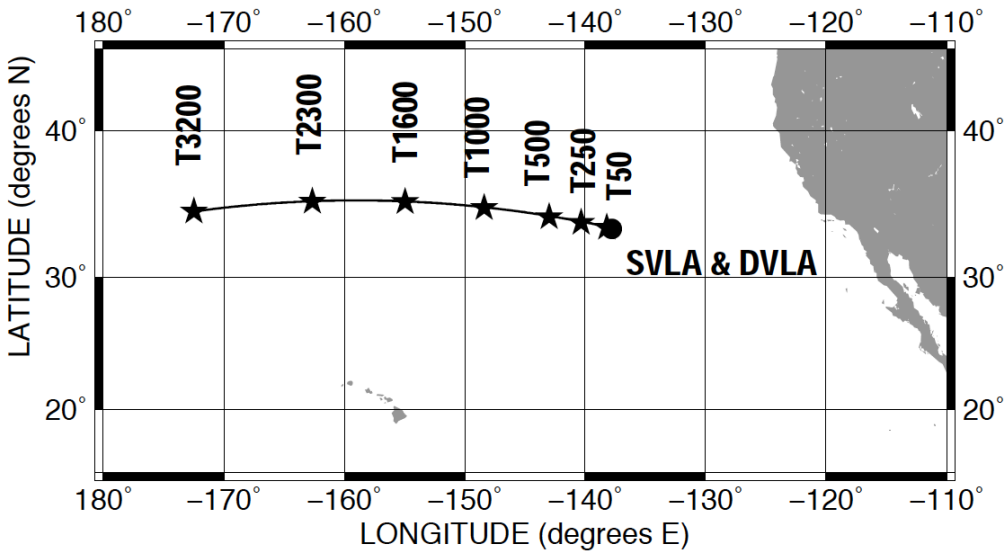

FIG. 4. The geometry of the LOAPEX experiment in the eastern North Pacific Ocean is shown. Two vertical line arrays of hydrophones were deployed at the location denoted by SVLA and DVLA. The source was suspended from the ship at seven stations labeled T50, T250, ...,T3200 at one or more of these depths: 350 m, 500 m, and 800 m.

[The receivers were near 33.4 N, 137.7 W, approximately 1500 km west of Los Angeles. The source stations were to the west along a geodesic, at distances of 50, 250, 500, 1000, 1600, 2300 and 3200 km. Station T3200 was near 34.6 N, 172.5 W.]

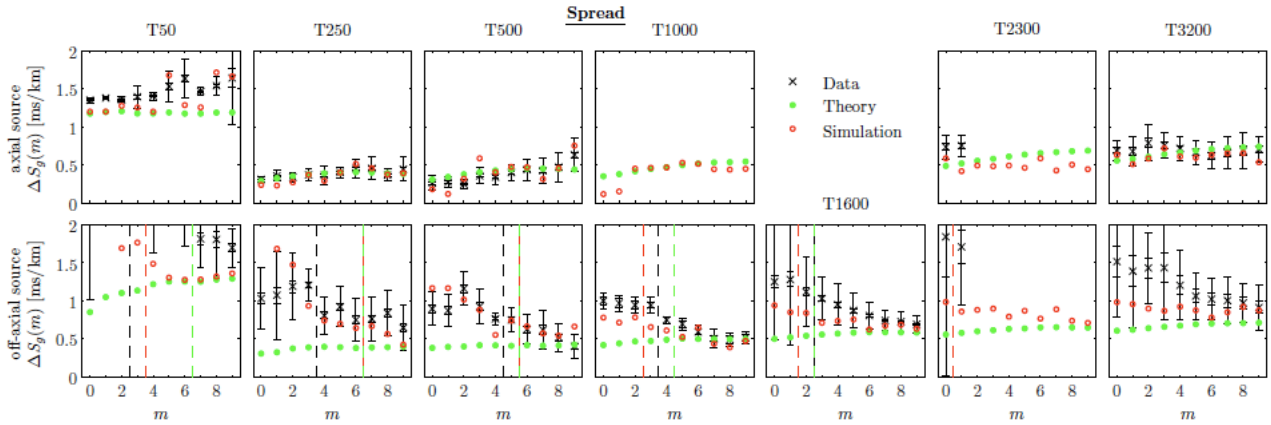

FIG. 5. Modal group time spreads (widths of arriving energy pulses for each mode) are shown for each source station with black x's. Results for the sound source at 800 m depth (near the sound speed minimum) are shown at the top. Results for the source at 350 m depth are shown at the bottom. Also shown are theoretical and computational predictions.

[The modal group time spreads for the axial source agree with theory and numerical predictions for the lowest 10 modes. The shallow-source spreads generally exceed the predictions for these modes. The agreement between theory, numerical model and data is best for higher mode numbers at intermediate ranges.]