

## **Experimentally-Based Ocean Acoustic Propagation and Coherence Studies**

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### **LONG TERM GOALS**

The goal is to better understand fluctuating sound propagation in two distinct ocean acoustic regimes: Stratified shallow water, where sound is highly bottom interacting, and the temperate deep-ocean sound channel. Acoustic field fluctuations have time scales varying from less than a minute to hours, and horizontal spatial scales from tens of meters to kilometers, comparable to processing time scales and system spatial scales, and thus impact exploitation of underwater sound. With proper understanding, reliable predictions of temporal and spatial variability of received underwater sound may be possible, thus improving processing and handling of signals of interest. Processing could include remediation of signal degradation and/or exploitation of available sonic information.

### **OBJECTIVES**

An objective is to quantify and explain underwater sound fluctuation behavior that has been observed in both shallow and deep regimes, for the purpose of meeting the stated goals. For shallow water, transmission loss and phase data are available at frequencies from 50 to 3000 Hz. For the deep-ocean sound channel, data are in hand for propagation at 50 to 100 Hz over 100's to 1000's of kilometers. Propagation and forward scattering models, both theoretical and computational, will be used to test hypotheses regarding the origin of signal variations. Therefore, making better models is a second (enabling) objective.

### **APPROACH**

The approach toward understanding the fundamentals of ocean sound propagation variability in numerous environmental regimes is to study the propagation together with the local environmental conditions. First, acoustically important features, such as nonlinear internal waves in the shallow seas and quasi-homogeneous internal waves in the deep seas, must be identified in the coupled studies. Next, the acoustic phenomena caused by those features are studied in detail, to identify the feature properties that are relevant to acoustics. Next, those properties are investigated, with a purpose of extrapolating (predicting) acoustic behavior in parameter regimes that may not have been encountered. The investigations of physical ocean phenomena that are critical to this approach are likely to differ from studies of the features motivated by other branches of ocean science, such as studies of biogeochemical/physical cycling, fisheries, or climate.

# Report Documentation Page

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The major efforts this year have involved preexisting data sets and computational modeling. Specifically, field data are from the 2009 ONR Quantifying, Predicting and Exploiting Uncertainty study near Taiwan (QPE, Figure 1) (Gawarkiewicz *et al.*, 2011, Gawarkiewicz and Jan, 2013), the ONR Shallow-Water 2006 experiment in the Middle Atlantic Bight (SW06) (Tang *et al.*, 2007), and the 2004 North Pacific Ocean deep-water ONR Long-range Ocean Acoustic Propagation Experiment (LOAPEX, Figure 2) (Mercer *et al.*, 2009). In prior years, data from the ONR South China Sea ASIAEX study (Chiu *et al.*, 2004; Duda *et al.*, 2004), and the northeastern South China Sea spring 2007 ONR/Taiwan NLIWI acoustics experiment (Reeder *et al.*, 2010) were analyzed. Most of the acoustic modeling has been three-dimensional (3D) modeling of sound propagation through simulated time-dependent ocean conditions offshore of San Diego and New Jersey, the second of these being the SW06 site.

All of the shallow-water data sets are from stratified areas that support short-wavelength, high-frequency nonlinear internal waves and wave packets. We have quantified many first-order acoustic effects from these waves over the last decade or so. Because many of these effects are not described by two-dimensional (2D) environmental models or by 2D acoustic models, our methods include fully 3D theories and fully 3D acoustic propagation simulations.

In each shallow-water field study, moored acoustic sources transmitted signals to moored acoustic receivers, and large 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.

In the deep-water LOAPEX study, sound was transmitted from ship-lowered sources to vertical line arrays moored north of Hawaii in the North Pacific. The source-to-receiver distances were 50 to 3200 km (Figure 2). Environmental data were collected in the area, but the data coverage is by necessity less than for the shallow-water studies. These deep-water studies are led by Dr. Ilya Udovydchenkov.

## **WORK COMPLETED**

*Shallow Water Effort:* The shallow-water effort this year resulted in an article on the QPE internal-wave conditions in the southern East China Sea just northeast of Taiwan (Duda *et al.*, 2013a), a conference proceedings paper on modeling sound at slopes and canyons (Duda, *et al.* 2013b), and a conference paper on SW06 fluctuation properties (Colin *et al.*, 2013). Prior year's work involving the ASIAEX, NLIWI, and SW06 data sets is discussed in last year's report, with those papers listed here in the Publications section. Subsequent to the publications for this year, the shallow-water work has included studies of 3D acoustic phenomena under a variety of simulated environmental conditions motivated by the observations.

The publication of the internal tide and internal wave conditions in the East China Sea (Duda *et al.*, 2013a) utilized data collected by many QPE PI's. Figure 1 shows the work area. The nonlinear internal waves of the area were characterized using sub-optimal new methods because of logistical constraints. The methods were developed in order to quantify the wave amplitude and energy, and are based on matching computationally generated waveforms with remote-sensing measurements of the waves. The computed waveforms were made with Long's Equation; the remote sensing systems were an EK500 scientific echo sounder and a ship-mounted radar. Sequential radar images were used with ship navigation information to compute the wave speed and direction. These, with the echo sounder images of scattering layer displacement (Figure 3), yield wavelength and wave amplitude, with some

uncertainty. Comparing the results with strongly nonlinear waves modeled with Long's Equation further constrains these results, to the degree that wave energy and energy flux can be computed. The figure also demonstrates (again) the value of remote sensing systems for this type of work. One caveat is that the buoyancy frequency profile must be known (not measurable remotely), although the tolerance for relaxation of this requirement has not been determined. On the other hand, it may be that the fitting of Long's model wave profiles to the data constrains this profile, although a blind global search would likely not be effective and some apriori information would probably be needed. Moored sensor data was also analyzed to determine internal tide energy for direct comparison to other regions.

Two additional papers covering QPE acoustic conditions were submitted in 2013. One paper covered acoustic signals transmitted from an OASIS Inc. Mobile Acoustic Source (OMAS) to three receivers located near the west branch of North Mien Hua Canyon (Lin *et al.*, 2013). The frequency range is 800-1000 Hz. 3D acoustic modeling was done, showing that strong bathymetric focusing was occurring, but the focusing did not entirely match the data because of terrain uncertainty. The paper further notes that a rapid drop-off of received sound level from the moving source for a path length of a few kilometers coincides with arrival of nonlinear internal waves, but is not consistent with expectations for the OMAS moving through the predicted 3D spatial beam/shadowing patterns. The other paper covered mean transmission loss (TL) versus range curves and TL fluctuation probability distributions for a set of OMAS transmission experiments on the shelf (Emerson *et al.*, 2013). Ambient noise and signal excess are also examined. The paper concludes that signal excess in the region will have a standard deviation of 6 dB under the conditions of propagation and noise variability that were encountered in the field studies.

*Shallow-Water Effort, Modeling:* Work has continued on time-stepped 3D parabolic equation (PE) model development and applications. One conference paper (Duda *et al.*, 2013b) describes some interesting localized time-dependent effects for 100-Hz sound obliquely reflecting from slopes. We are now moving to higher frequency, and calculating things like sound field correlation length and time in a variety of places and conditions using environmental inputs from ocean models. This project aims at describing shallow-water acoustic effects, whereas a companion MURI project has goals of improving the ocean models and the acoustic models. Figure 4 shows a snapshot of time-dependent 700-Hz sound simulated to move down a canyon near San Diego, in a horizontal slice, and the scintillation index for the slice computed for a two-day period. The time-dependent environment was computed with an ocean model having boundary forcing (Ponte and Cornuelle, 2013). Also shown are the horizontal correlation length estimated for this time period, incoherent power on simulated arrays, and the coherence-length scaled power, which yields a map of estimated array performance in the canyon region.

*Deep-Water Effort:* The deep-water work this year resulted in a paper on the properties of mode-filtered waveforms received at the LOAPEX VLA (Udovydchenkov *et al.*, 2013), and a paper covering sound arriving at near-seafloor receivers (Stephen *et al.*, 2013). As with the shallow-water research, prior year's results are discussed in last year's report, with papers listed at the end of this report.

The mode-filtered LOAPEX acoustic signals extracted from the VLA data after propagating at ranges from 50 to 500 km distance in the North Pacific (Figure 2) were objectively analyzed and compared with the transmitted waveforms, with results reported in the new paper (Udovydchenkov *et al.*, 2013). The mode-based analysis has been a primary LOAPEX study topic and was reported in last year's comprehensive paper on the subject of deep-ocean low-order mode dispersion (Udovydchenkov *et al.*, 2012a). This year's paper identifies a new class of arrivals called weakly dispersive modal pulses.

Weakly dispersive modal pulses are characterized by small pulse broadening, as a result of weak dispersion and scattering. These pulses experience minimal propagation-induced distortion and may be well suited to communications and surveillance applications. Two groups of weakly dispersive modal pulses were identified in the LOAPEX environment. The first group consists of low order modes. The first three modes resolved by the LOAPEX VLA, among ten resolved modes, were shown to be weakly dispersive. These modal pulses propagated great distances with minimal distortions, such that the binary content of transmitted m-sequence codes was preserved in the pulses and was successfully recovered at ranges up to 500 km without need for channel equalization. A definition of weakly dispersive modal pulses based on signal parameters and environmental properties was also introduced. The second group of weakly dispersive modal pulses corresponds to intermediate mode numbers (around mode number 20 at 75 Hz in the LOAPEX environment). These modes were not resolved by the LOAPEX VLA and were not considered in the paper. However, ongoing analysis with numerical models suggests that the second group may also propagate with minimal distortion up to 500 km. The advantages of using this group of modes for communications and surveillance applications are currently being investigated. Knowledge of the existence and the nature of this category of modes stems from recent basic research into ducted sound-channel propagation and dispersion (Udovydchenkov and Brown, 2008, Virovlyansky *et al.*, 2009).

The LOAPEX data analysis shows that interaction of sound with the seafloor is often an important consideration. At short ranges (one convergence zone, for example) sound reflected from the seafloor interferes with direct water-column-refracted arrivals. It was shown (Udovydchenkov *et al.*, 2012c) that bottom reflections at 50 km range contaminate purely water-column-refracted arrivals making the interpretation of the signal difficult. It was also shown that an adequate knowledge of the bathymetry and seafloor properties is needed to understand even low-order modal arrivals trapped in the sound channel. At longer ranges, bathymetry local to the receiving array was also shown to be important, because the steep angle energy in the propagating wavefield interacts with seamounts in the vicinity of the receiving array (Stephen *et al.*, 2013).

## RESULTS

*Shallow-Water Effort, SW06*: The 2012 publication of the full analysis of the SW06 L-array fluctuation data set (Duda *et al.*, 2012) validates earlier horizontal coherence findings (Collis *et al.*, 2008). Horizontal array gains and coherence lengths  $L_d$  for along-internal wave duct propagation and for across-internal wave duct propagation were highly variable for the entire experiment. An appendix of the paper shows the relationship between the broadband correlation functions that we analyzed, which is useful for pulses, and the traditional narrowband correlation function. The main results show both rapid variability and slow trends of coherence length, array gain, and array gain degradation (AGD), with coherence lengths defined as e-folding scales of spatially lagged covariance functions of complex demodulated signals. The array gain is defined as the signal to noise ratio for coherently added (beam steered) acoustic receptions over an array, divided by the signal to noise ratio for a single array element. AGD, which is departure of array gain from the ideal gain for the situation of fully coherent signals and noise that is independent among the array elements (consistent with summed azimuthally distributed noise sources), is high when internal waves cause signal coherence to fall.

Coherence behavior was strongly anisotropic, measured by transmitting sound along internal-wave (IW) crests and perpendicular to internal-wave crests. Along-IW and across-IW sound propagation differs in temporal variability of  $L_d$  and mean  $L_d$ . Sound from 30-km distant NW sources traveling in the same direction as internal waves (across crest) showed steady short  $L_d$ , approximately 10 to 15

acoustic wavelengths for both 224 and 400 Hz. Sound from 19-km distant NE sources at 100 and 200 Hz (traveling along-IW) had highly variable  $L_d$  for processing windows of 3 hours. As internal waves passed,  $L_d$  dropped from  $\sim 25$  to  $\sim 7$  wavelengths at 100 Hz, and from  $\sim 40$  to  $\sim 7$  wavelengths at 200 Hz.

Continuing with SW06, another paper (Colosi *et al.*, 2012a) describes the nature of sound-speed variability from density compensated temperature and salinity fluctuations along isopycnals (so-called spiciness), and quantifies the internal-wave normal modal bandwidth (mode spectrum). Finally, a paper was published that explores TL variability at less than 10-km range at 600 to 900 Hz (Lynch *et al.*, 2012).

*Shallow-Water Effort, QPE:* Unique new findings were made in the physical oceanographic and acoustic studies. Both studies were performed with a minimum of moored equipment, unlike SW06, and used some new methods, because fishing activity made measurements with moored instruments almost impossible in this area. Only trawl-proof ADCP's on the seabed could survive for extended periods.

The new physical oceanography article (Duda *et al.*, 2013) shows that we were able to gain useful information about larger internal waves in this region using the echo sounder and the radar on the research vessel, not previously done with this particular instrument suite. These remote-sensing data allowed quantitative modeling of the internal waves, to better characterize them, and to show which level of wave-model nonlinearity was needed to describe the wave physics. Internal tides in the region were also quantified in the paper and compared to those of other regions. Primary findings of the paper are: (1) A large nonlinear internal wave was found in deep water, traveling north toward the shelf; this wave was likely formed from internal tides generated 100 km away at Ilan Ridge. (2) Internal waves traveling in many directions were found on the shelf. (3) High-frequency internal waves on the shelf can be strongly nonlinear, as opposed to weakly nonlinear. (4) The diurnal baroclinic (internal) tide was very strong, with the strength not yet explained. (5) Diurnal internal tide vertical beams were detected on the shelf.

The two submitted acoustics articles highlight the propagation variability of the region. The high variability is consistent with the strong currents, barotropic tides, and internal waves. A canyon acoustics paper (Lin *et al.*, 2013) finds weak point-to-point navigated sound transmission in a canyon that does not agree with 3D model predictions. It may be that the bathymetry that governs the spatial TL pattern in the model is not correct, or internal waves cause the sound to be deflected away from the receiver. This follows up an earlier experimentally-based QPE paper on acoustic TL variability in a different canyon (Chiu *et al.*, 2011). The second article (Emerson *et al.*, 2013), shows that 800-1000 Hz acoustic signals traveling up to 10 km were measured to have short-term TL variability of 1.5 to 2 dB, which is perhaps a bit less than measured in SW06 (Lynch *et al.*, 2012). Combined with noise variability in the area of up to 6 dB rms, the signal excess for underwater sound in the area is expected to have a greater than 6 dB rms variability.

*Deep-Water Effort, LOAPEX:* The study of LOAPEX acoustic arrivals at 50 to 3200 km distance in the North Pacific (Figure 2) produced a comprehensive paper on the subject of deep-ocean low-order mode dispersion (Udovydchenkov *et al.*, 2012a). This is a primary LOAPEX study topic, for which one of the VLAs was expressly designed. 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. The LOAPEX work

yielded two other 2012 publications. The first involves unified processing of acoustic data from two VLAs separated by a few km (Udovydchenkov *et al.*, 2012b). The second contains an analysis of seafloor reflecting sound at 50-km range (Udovydchenkov *et al.*, 2012c). At this range, the reflected sound interferes with water-column-refracted sound, and it also contains potentially useful information about seafloor geoacoustic properties.

The ability to reconstruct the binary sequence transmitted during LOAPEX using weakly dispersive modal pulses without performing channel equalization, at ranges up to 500 km, as described above and shown in Figure 5, is an intriguing and newly published result (Udovydchenkov *et al.*, 2013). The maximum range that this operation was successful is perhaps longer than previously thought possible. This result is expected to be worthy of consideration in communications and surveillance applications.

## **IMPACT/APPLICATIONS**

The shallow-water results may be useful for guiding coherent signal processing, particularly of horizontal array data. There is a potential for algorithms that are robust to signal fluctuations, or which may exploit them. The deep-water results imply that bottom-interacting sound can interfere with one-convergence-zone signal processing, and that properly-placed near-seabed receivers can detect energy scattered out of the sound channel by seamounts.

## **RELATED PROJECTS**

The PI collaborates with Dr. Y.-T. Lin of WHOI on computational efforts and works with other ONR PI's analyzing data from the SW06, ASIAEX, 2007 South China Sea, and QPE experiment sites. Also, the PI has another project in its third year, Integrated Ocean Dynamics and Acoustics (IODA), a DoD MURI project, which is administered by ONR Ocean Acoustics, and which is intended to improve acoustic modeling and prediction by coupling improved acoustic models to improved high-resolution ocean environmental models, with model improvements stemming from basic research into the acoustic and ocean phenomena. The deep seafloor interaction studies are done in collaboration with Dr. R. Stephen of WHOI and his colleagues.

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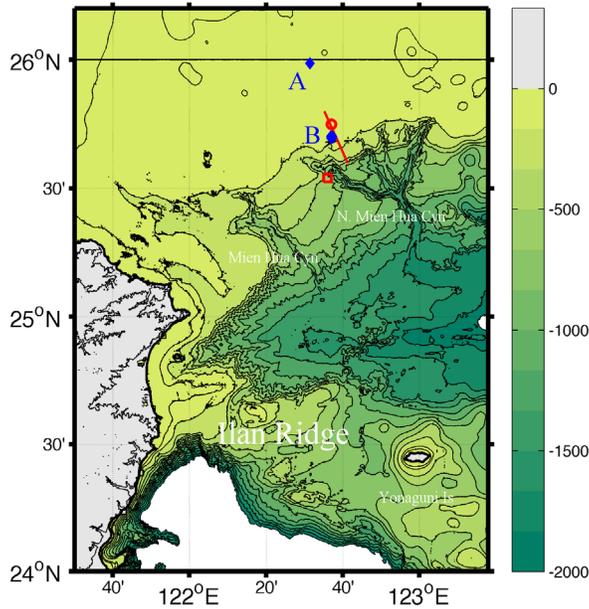
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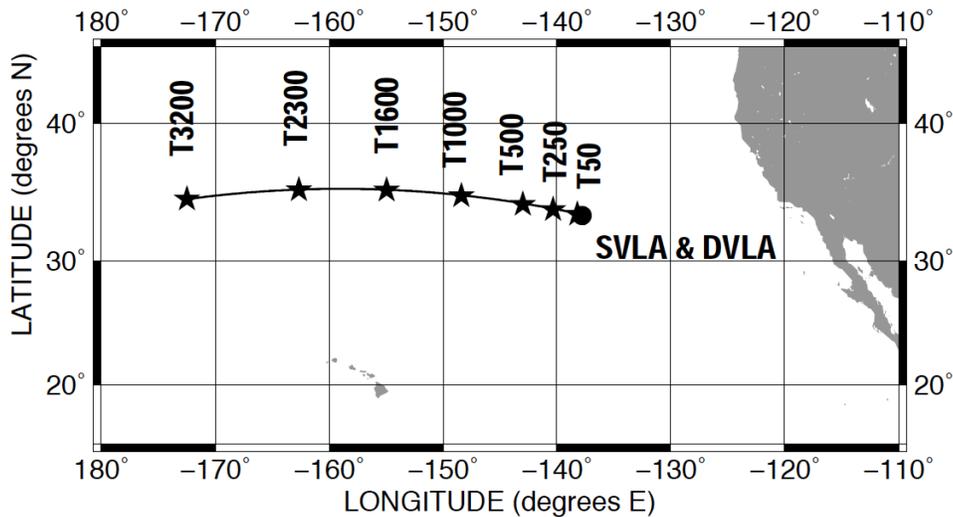
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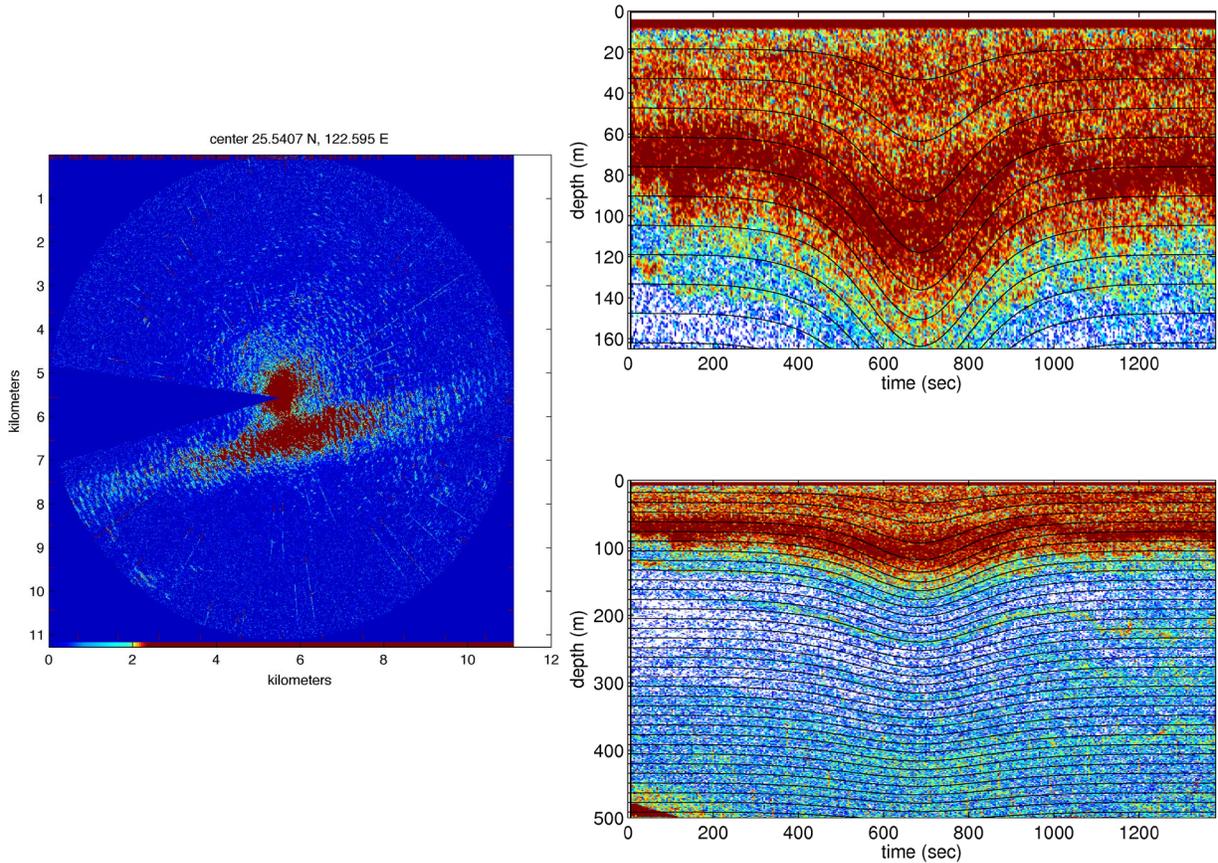
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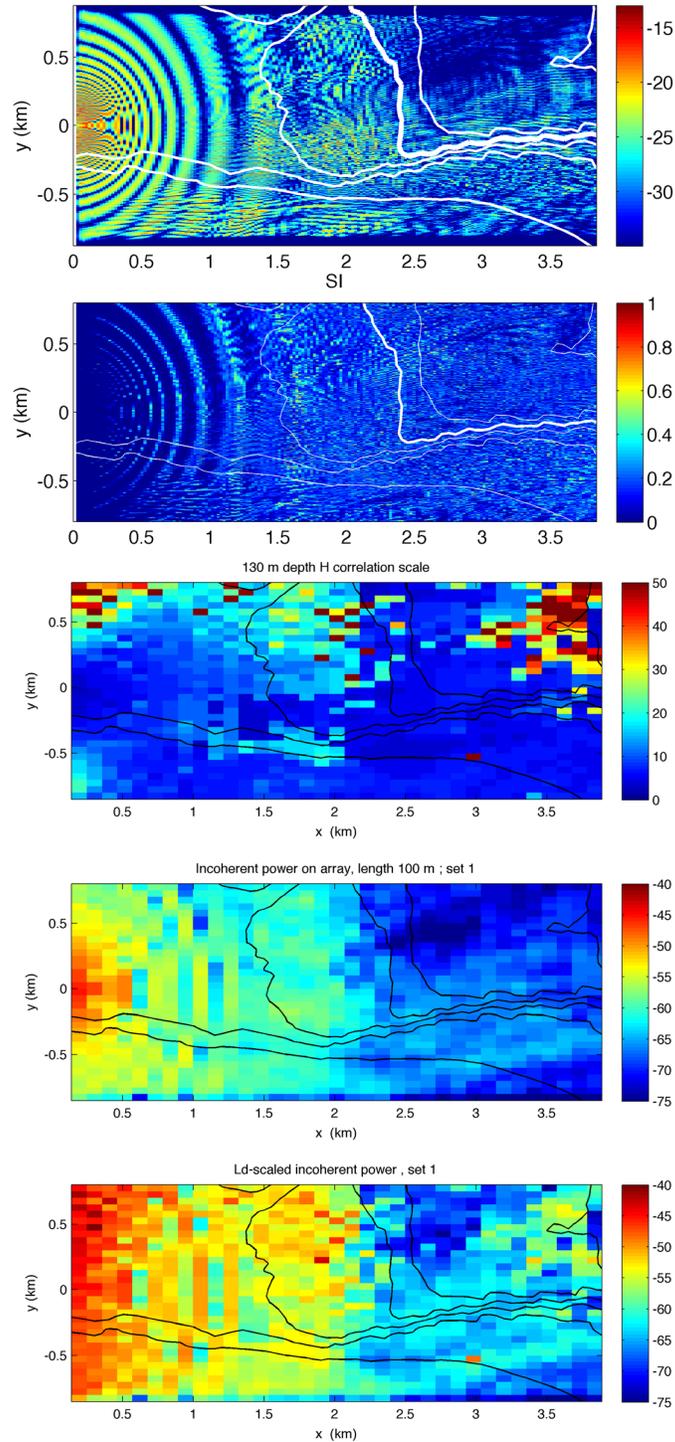
**Figure 1. (left) A chart of the QPE study area is shown. Sites A and B (mooring areas) are marked with blue diamonds. Site B is a short distance north of the west branch of North Mien Hua Canyon. The depth contour interval is three per 500 m, with an additional 100-m contour added with no color change. The white area is deeper than 2000 m. [Sites A and B are ~75 km northeast of the northeast corner of Taiwan, in shallow water at the edge of the shelf, with deep water to the south.]**



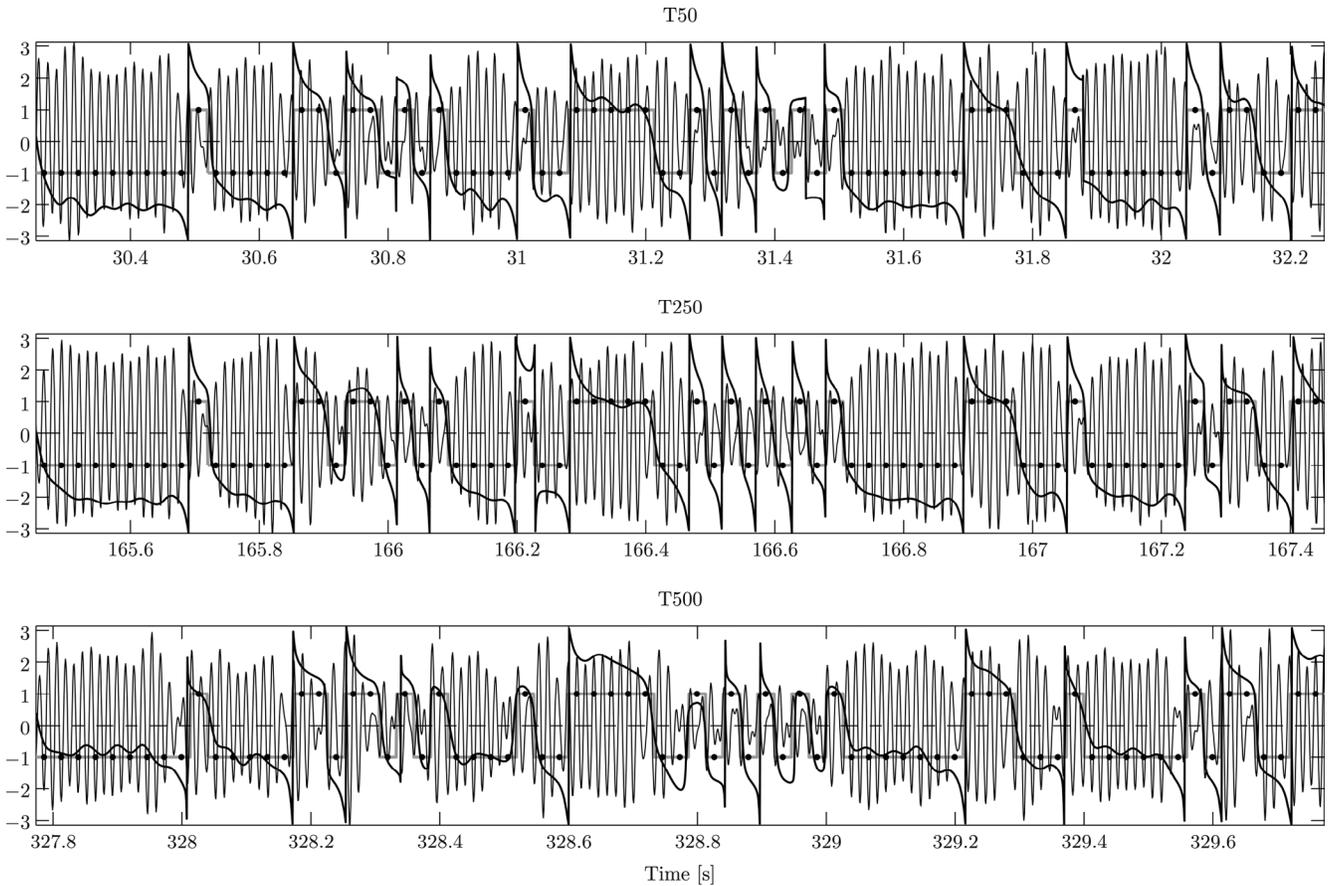
**Figure 2. The geometry of the LOAPEX experiment in the eastern North Pacific Ocean is shown. Two vertical line arrays of hydrophones were deployed at the location denoted by SVLA and DVLA. The source was suspended from the ship at seven stations labeled T50, T250, through T3200 at one or more of these 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.]**



**Figure 3. (left) A single ship’s radar snapshot is shown. North is upward, and the ship is at the center. A stern radar blind spot to the west is evident. The rough patch of sea surface (the leading edge of the internal wave of depression) is traveling basically northward, with a slight westward component, known from a lat./long.-registered image sequence. (right) Scattering layers displaced by an internal wave are seen in the ship’s EK500 echo sounder range-gated intensity time-series plot, with red being highest intensity, white lowest. The black lines show streamlines of a highly nonlinear internal wave modeled to fit the visible layer displacements. The two panels show the same data, with the upper panel being an expanded view. Figures from Duda et al. 2013a. [(left) A stripe of rough water of 1 km-width that crosses the 11-km span of the circular radar backscatter plot is just south of the ship. (right) The figure shows an internal wave of maximum 61-m displacement in 550 m of water (water beginning at 79-m depth moves to 140 m depth). The modeled wave fits the data well.]**



**Figure 4.** For a canyon near San Diego, outputs in a 100-m deep horizontal slice from the Cartesian 3D PE model. Depth contours are 100 m; 500 m is bold in the top frames. Deep water is at the upper right. (top) 700-Hz intensity snapshot, dB, arbitrary reference, corrected for cylindrical spreading loss. (second) Scintillation index in the slice for 24 hourly fields. (third) Acoustic field correlation scale in meters along  $y$ -directed simulated arrays. (fourth) Incoherent power on a 100-m length simulated array, arb. dB. (bottom) Decibel plot of incoherent power times the number of coherent elements, a proxy for coherent signal energy on the array. (Three-meter inter-element spacing).



**Figure 5. Examples of LOAPEX 50, 250, and 500 km mode-one pulse processing output. The thin black line shows mode-1 amplitude (arbitrary scaling). The thick black line shows the phase (radians). The gray line is the square wave code of the transmitted phase-modulated signal. The black dots show the information bits recovered from the phase function, the dots and the code are in agreement in these examples. The horizontal axis is absolute arrival time. From Udovydchenkov et al., 2013. [The measured mode-one amplitude dips at the phase transitions in the code; the measured mode-one phase transitions line up with the code and thus the code can be robustly detected.]**