Measurements and analysis of phenomenology and statistics of sound propagation over sand dunes on upper slope of the Northeastern South China Sea

Ching-Sang Chiu
Department of Oceanography
Naval Postgraduate School
Monterey, CA 93943-5001
Phone: (831) 656-3239 Fax: (831) 656-2712 E-mail: chiu@nps.edu

Award #: N0001413WX20392

LONG-TERM GOALS

My long-term research goals are: (1) The characterization, understanding, and prediction of the statistics (mean, variance and coherence) of low-frequency acoustic signals and ambient noise in the littoral zone. The signal statistics are primarily influenced by the ocean variability and bottom properties. The noise statistics are influenced by atmospheric forcing and shipping in addition to the ocean and bottom variability. (2) The development and improvement of inverse techniques for measuring the dynamics and kinematics of meso and finer-scale sound speed structure and ocean currents in coastal regions. (3) The understanding of three-dimensional sound propagation physics including horizontal refraction and azimuthal coupling and the quantification of the importance of these complex physics in the prediction of sound signals transmitted over highly variable littoral regions.

OBJECTIVES

The primary objectives of this three-year (FY12-14) research project are:

In collaboration with Taiwanese Scientists (Drs. Yang, Jan, Chen and Song of the National Taiwan University, Dr. Lou of the Taiwan Naval Academy, Dr. Chang of the National Taiwan Ocean University, and Drs. Chiu and Wei of the National Sun Yet-sen University) and U.S. Scientists (Dr. Reeder of the Naval Postgraduate School and Dr. Ramp of the SOLITON Ocean Services, Inc.), an ONR-sponsored, multiyear field program was launched to characterize the large sand dunes discovered on the upper slope of the northeastern (NE) South China Sea (SCS), associated physical processes and their impact on acoustic signal propagation and reverberation. Specifically, the joint field study has the following overall scientific goals:

- To characterize the time and space scales and the distribution of large submarine sand dunes on the upper slope.
- To study the impact of the sand dunes, and the combined impact of sand dunes and nonlinear internal waves, on sound propagation, in terms of phenomenology, including anisotropic propagation characteristics, and two-dimensional (2D) and three-dimensional (3D) focusing/defocusing scattering phenomena.

- To study the associated statistics (mean, variance and coherence) of sound signal propagation over the sand dunes and their dependence on range, frequency and orientation.
- To examine the hypothesis that the internal tide and large trans-basin NLIWs are the generation mechanism of the dunes.
- To study how enhanced bottom roughness in the dune field affects transformation and energy dissipation of the NLIWs and tides as they shoal over the upper continental slope.

A secondary research objective is to quantify the physics and magnitude of the fluctuations of a low-frequency acoustic signal propagating through the NE SCS basin using a combination of numerical modeling and actual measurements.

APPROACH

Upper slope sand dunes acoustics study: All fieldworks for this project are being carried out in collaboration and coordination with our long-time Taiwan colleagues listed above, and utilizes their Research Vessels (RVs), Ocean Research 1 (OR1), Ocean Research 2 (OR2), Ocean Research 3 (OR3) and their newest vessel Ocean Research 5 (OR5). Pilot cruises have been successfully carried out in the first two years of this project with OR2 in 2012 and with both OR2 and OR5 in 2013 that are instrumented with multibeam systems to survey the spatial distribution and scales of the sand dunes over a 60 km by 60 km area spanning the upper slope. The survey data are used to design the main acoustic propagation experiment for 2014, including choosing the mooring locations and source-receiver geometries.

The main acoustic propagation experiment will be performed in spring of 2014. We envision a two-week cruise with three vessels, OR1, 3 and 5, operating together. One of the two weeks will span a spring cycle of the tides and the other an adjacent neap cycle, during which the internal waves will have maximum and minimum amplitudes, respectively. During the two weeks, OR5 will be dedicated to perform multibeam survey, operate lowered sound sources and deploy and recover moored acoustic receiver arrays, while OR3 will operate a towed source. Concurrently, OR1 will be used to deploy and recover oceanographic moorings, follow transbasin internal waves and measure their physical characteristics in situ with a lowered package of oceanographic sensors. The multiship operations will allow us to capture the changes in spatial scales and distribution of the sand dunes between the two cycles, and examine and contrast the associated impacts on the sound fields. It is our hypothesis that, the sound field and its statistics are primary controlled by the spatial scale and distribution of the sand dunes during the neap cycle, whereas during the spring cycle, they are controlled by a combination of the sand dunes and internal waves. One of the moorings, instrumented by our Taiwan colleagues, will have high-resolution pressure, current and turbidity sensors to characterize the sediment resuspension process and capture the associated intra-cycle time and space scales that are expected to be short, on the order of 30 mins and a few hundred meters.

The acoustic receivers to be fielded during the main experiment will include three vertical line arrays (VLAs). A limitation of these VLAs is their short apertures relative to the full water depth of the upper slope (100 m versus 400 m). Therefore, we plan to moor them at different depths such that the combined aperture will span most of the water column. The VLAs will be moored on a single mooring to allow for measurement and quantification of the resultant scattering of sound in the vertical direction.

Two newly acquired sound sources from the DURIP program, transmitting 500-1,200-Hz frequency modulation signals, will be lowered from OR5 at pre-assigned stations spanning a straight-line path down slope and cross slope from the VLAs. Each station will be occupied with enough time to repeat a signal to allow for proper measurement of the received signal statistics. A towed source transmitting at the 3.5-5 kHz band, provided by Taiwan, will be used to investigate anisotropy and 3D phenomena.

The analysis of the acoustic data would begin in summer of FY14 after the main experiment. It would entail time series analysis and modeling to characterize and elucidate the anticipated nonstationary statistics as well as anisotropic, 2D and 3D focusing/defocusing phenomena in the measured sound field. The focus of the analysis would be to relate the observed statistics and phenomena to the scales and distribution of the sand dunes, with and without the coexistence of the nonlinear internal waves.

<u>Basin transmission modeling analysis</u>: Investigation into the physics and extent of the signal fluctuations in a SCS basin transmission in the presence of transbasin nonlinear internal waves entails the development a ray theory model in Matlab, simulation of fluctuations in the multipath arrival structure, analysis of model results and comparison to observed data.

WORK COMPLETED

<u>Upper slope sand dunes acoustics study</u>: To enable optimal design and planning for the main experiment (scheduled for spring of 2014), a pilot experiment was carried out during May 8-14, 2013 to collect the preliminary and necessary environmental and acoustic data, test mooring designs and resolve logistics concerns. All cruise objectives of the pilot experiment were successfully accomplished. These include:

- Remapped the bathymetry of the experimental area with Multibeam Echosounder (MBES) on both vessels to permit an assessment of the spatial and temporal variability of the sand dune field. Note that the same area was first mapped with MBES using OR2 last year. Comparisons between this year's and last year's MBES data will provide valuable initial information on spatial and temporal changes.
- Sampled the sediment properties at peaks and troughs of the sand dunes using box cores to measure and contrast the corresponding sediment properties.
- Collected preliminary acoustic transmission and ambient noise data that are crucial to the proper design and placement of acoustic sensors and sources relative to the orientation of the sand dunes during the main experiment.
- Evaluated the capabilities of a brand new research vessel, OR5, for MBES, mooring deployment and lowered instrument package operations.
- Assessed possible mooring design and sampling technologies for a challenging environment that has a high relief and potential temporally evolving bottom.
- Tested circular-track towed-source operation using OR2.
- Examined the physical oceanographic and acoustic conditions during May 2013.

<u>Basin transmission modeling analysis</u>: For this separate research, a ray theory model in Matlab was successfully developed and tested. The new model reliably reproduced the previous model results obtained by Bernotavicius et al. (2010) for a 400-Hz pulsed signal transmission in an unperturbed SCS basin. The raytracing part of the pervious model employed the Hamiltonian Acoustic Raytracing Program for the Ocean (HARPO), which is an obsolete Fortran program that no longer compiles with

today's Fortran compilers. The new model was all coded in MATLAB. It was built by interfacing the raytracing code developed by Y.T. Lin at the Woods Hole Oceanographic Institution and the eigenray search and arrival structure synthesis code developed by C.-S. Chiu, PI of this study. Input with perturbed sound speed fields simulating the perturbations caused by a transbasin nonlinear internal wave moving along the transmission path, the resultant changes in the multipath arrival structure were calculated and studied.

RESULTS

Upper slope sand dunes acoustics study: The execution of the pilot experiment involved two research vessels, OR5 and OR2 (Chiu et al., 2013). Equipped with capable A-frames and winches, OR5 was used to deploy moorings, occupy stations where a package of sensors was lowered, collect sediment samples using a box core, and perform a high-resolution MBES survey focusing on the area in the vicinity of the two moorings. The smaller OR2 was dedicated to towing a sound source transmitting acoustic signals along circular and radial tracks and performing a high-resolution MBES survey over a larger area planned for the main experiment. Drs. Y. J. Yang and L. Chiu served as Chief Scientists of OR5 and OR2, respectively. After towing the source, OR2 went on to carry out a MBES survey of a larger area planned for the main experiment.

Two moorings were deployed, one of which was designed to test a new system to place a recoverable package on the sea floor to obtain observations in the bottom boundary layer. This mooring, referred to as M (Fig. 1, right), used a rope canister to deploy a line to the surface that could then be used to haul back the entire package. A backup release was also deployed in the event that the system failed or the bottom portion became buried in the sand by dune migration. Both moorings supported a four-element Simple Hydrophone Receiving Unit (SHRU), as well as Acousonde and/or Data Logger receivers. Both moorings were deployed at the beginning of the OR5 cruise and recovered as designed at the end.

OR2 towed a sound source in a circle of 5-km radius around each of the two moorings to provide acoustic signal propagation in different orientations with respect to the dune crests/troughs. Signals were recorded by the two four-element SHRUs, Acousondes and Data Logger receivers mounted on the two moorings, the data from which are being analyzed for transmission loss and its anisotropy. The new Atlas MBES on OR5 worked extremely well, producing bottom maps with phenomenal detail. These maps will be essential for the placement of observational assets in the main experiment during spring of 2014.

The towed-source transmissions alternated between low frequency (LF) and mid-frequency (MF) linear frequency modulated (LFM) and pseudo-random noise (m-sequence) signals in the 900-2000 Hz and 4000-6000 Hz bands, respectively. Each one-minute-long transmission period consisted of 5 LFM's, one short m-sequence, and one long 45 sec m-sequence. From the acoustics perspective, the big scientific bonus during the pilot experiment was that the ocean was still in a winter condition with weak stratification and no high-frequency internal waves; thus, the data allow for an initial examination of the acoustical effects of the sand dunes alone, without the complication of NLIWs.

An initial result is illustrated in Figure 2. The top panel shows the processed and calibrated OR5 MBES bathymetric data as well as the circular ship track of OR2 as she towed the sound source around mooring M. Note that while the OR5 MBES survey did not cover the entire transmission area, the

OR2 MBES survey did. The latter dataset, however, is not displayed here because our NTU colleagues are still calibrating it. However, both MBES datasets clearly reveal that the NE, NW and SW quadrants inside the towed-source circle were populated with sand dunes with approximately SW-to-NE orientations. The MBES datasets also clearly reveal that the SE quadrant was a smooth area containing little to no sand dunes. The bottom panel of Fig. 2 displays the processed MF signal energy level versus bearing angle, showing a depleted level for signals arriving from the SE relative to the levels in the other quadrants. This is an expected and intuitive result owing to that the source was towed at a shallow depth (~10 m). A shallow source would excite only high modes. The sand dunes in the NE, NW and SW quadrants would then cause the a portion the energy initially contained in the high modes to scatter to the low modes, which could then propagate to the receiver more efficiently with relatively less loss to the bottom. The SE quadrant, however, had a smooth bathymetry that would cause no scattering, and thus all the energy would remain in the high modes that would suffer appreciably more bottom losses in reaching the receiver.

Briefly, to obtain the signal energy displayed in the bottom panel of Fig. 2, the raw data was first processed with a signal-energy-conserving matched filter to significantly improve the SNR. A short integration spanning the duration of the observed multipath arrival structure was then applied to calculate the energy of the matched-filter output for each transmission. The energy of the processed noise, estimated using the same integration time applying to the noise immediately following each transmission, was then subtracted out from the energy of the matched-filter output to yield the signal energy. The towed track was not a perfect circle. The signal level of each transmission was compensated for the distance deviation from the mean distance to the receiver. These corrections were based on a linear regression curve that was fitted to all the signal energy level versus distance data.

<u>Basin transmission modeling analysis</u>: The FY13 research work in this topic was to model and study the effects of transbasin nonlinear internal waves on low-frequency signal transmission through the NE SCS basin. Specifically, the fluctuations in the multipath arrival structure of a 400-Hz acoustic pulse transmitted through a distance of 167-km in the presence of an internal ocean soliton were modeled. The modeling entailed the integration of a raytracing program with an eigenray search and arrival-structure calculation program, and the use of measured bathymetry and inferred bottom-loss characteristics from previous research. A range-dependent perturbation was added to a range-independent background sound-speed profile to model the varying sound-speed field as the nonlinear ocean internal soliton propagates along the transmission path.

The modeled sound speed field perturbed by a nonlinear ocean internal soliton centered at 40 km from the source along the transmission path is shown in Figure 3. This placement of the soliton at the 40-km range from the source is denoted as Case 1. Cases 2, 3, 4 and 5 denote soliton at increasing ranges (40, 60, 80, 120 and 160 km, respectively). Both the source and receiver were placed at a depth of approximately 800 m. All cases modeled, each simulating a soliton at a different location, had six distinct acoustic arrivals that suffered large-amplitude fluctuations (up to ~ 10 dB). The factors that affect the amplitude of the arrivals are changes in the number of bottom interactions, in ray tube convergence/divergence, in multipath phase interferences and in the number of eigenrays making up an arrival. The results also show that the closer the soliton to the receiver, the less impact the soliton has on the arrival structure. This is because an eigenray interacts with the bottom with a changed angle and at a changed location for each bottom bounce downrange from the soliton. The closer the soliton to the receiver, the lesser number of bottom interactions can produce cumulative bottom-loss changes.

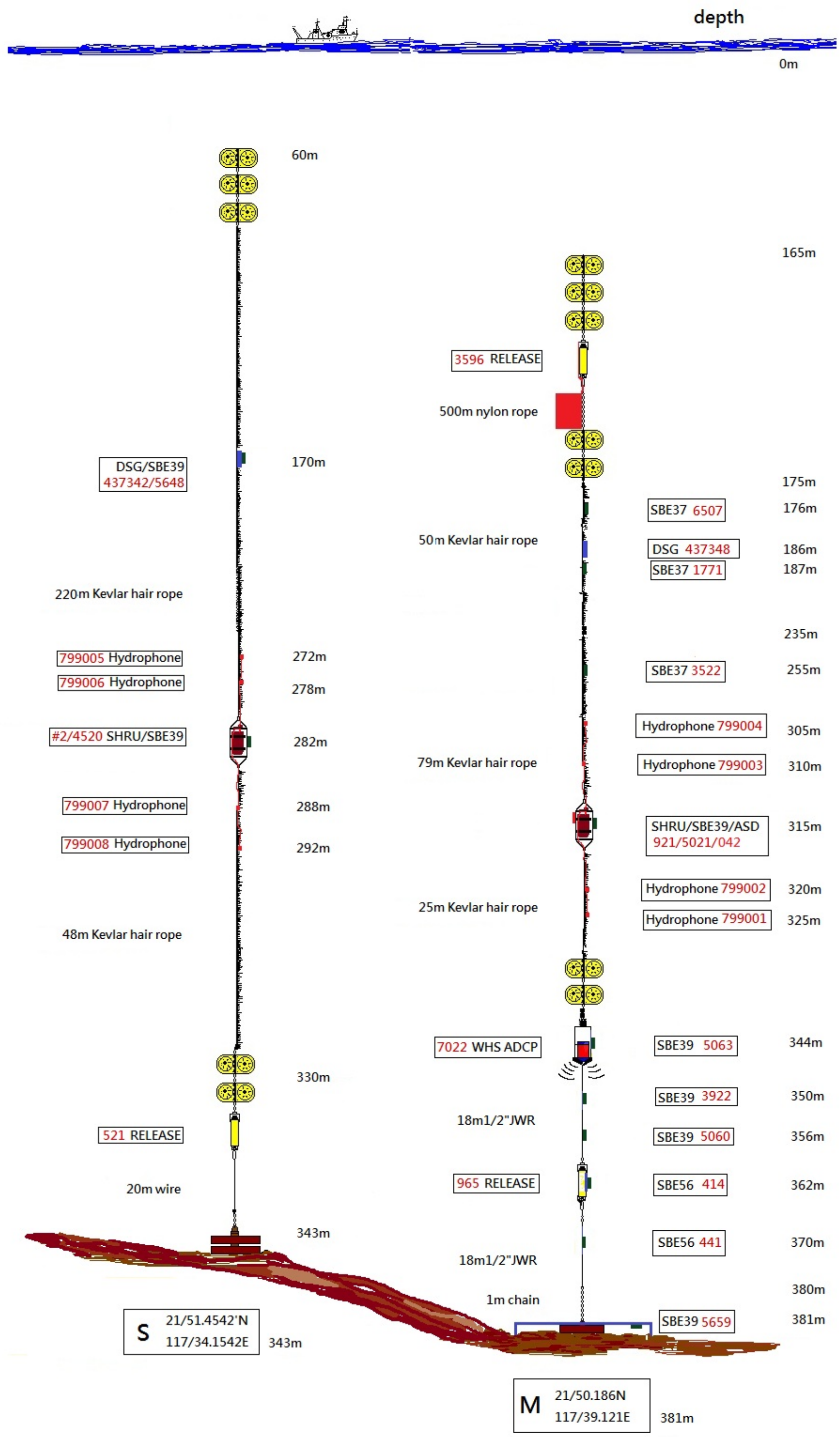

Figure 1. Schematic diagrams for the two moorings deployed during the Sand Dunes pilot study, May 8-14, 2013. (Diagrams drawn by Wen-Hua Ho, NTU.)

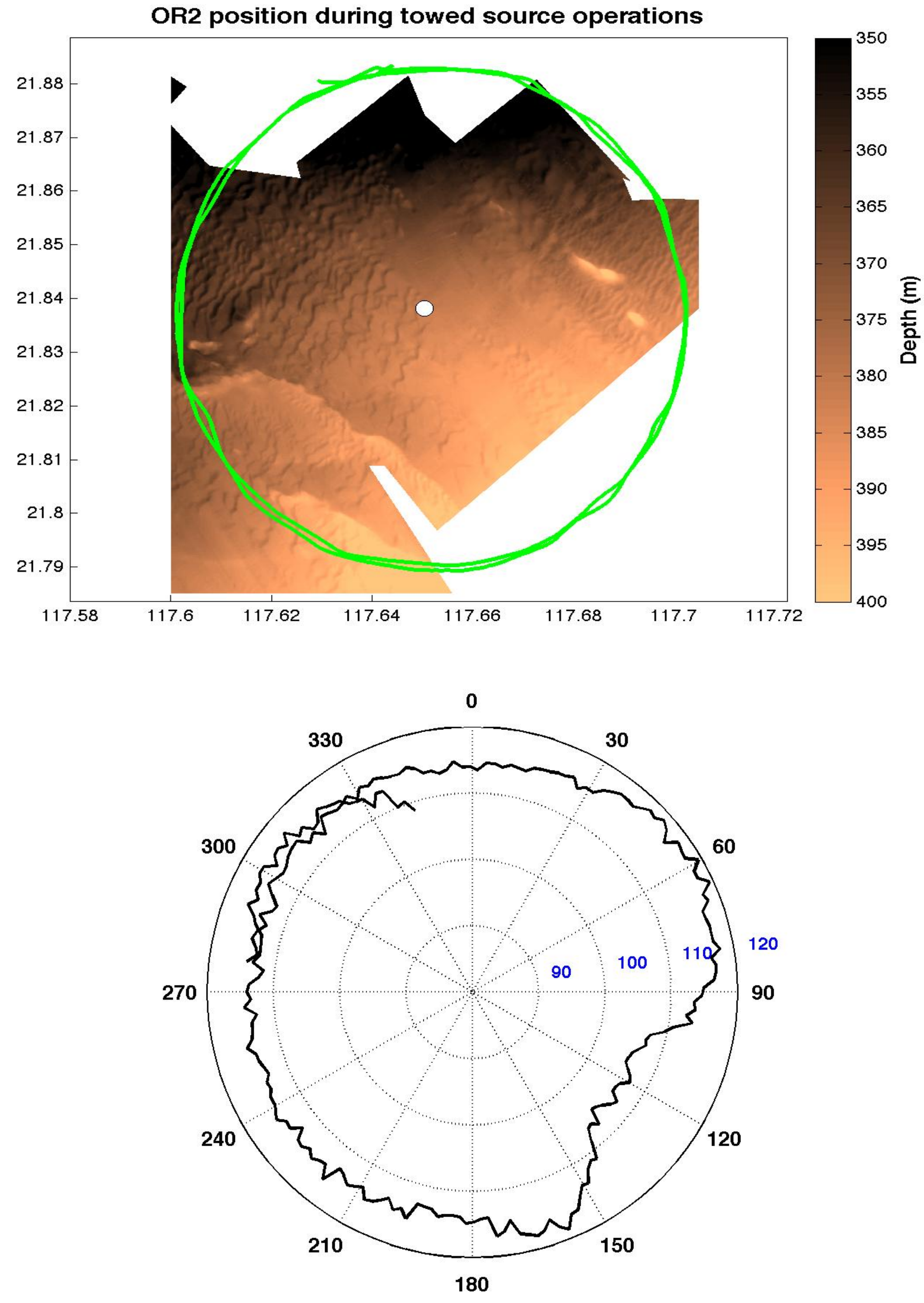

Figure 2. Towed-source track (green circle) around mooring M location (white dot) superimposed on the processed OR5 MBES bathymetric data (top panel), and the corresponding processed MF signal energy level (in dB re 1 μPa^2 s) as a function of bearing angle (bottom panel). The source was towed at a shallow depth (~10 m).

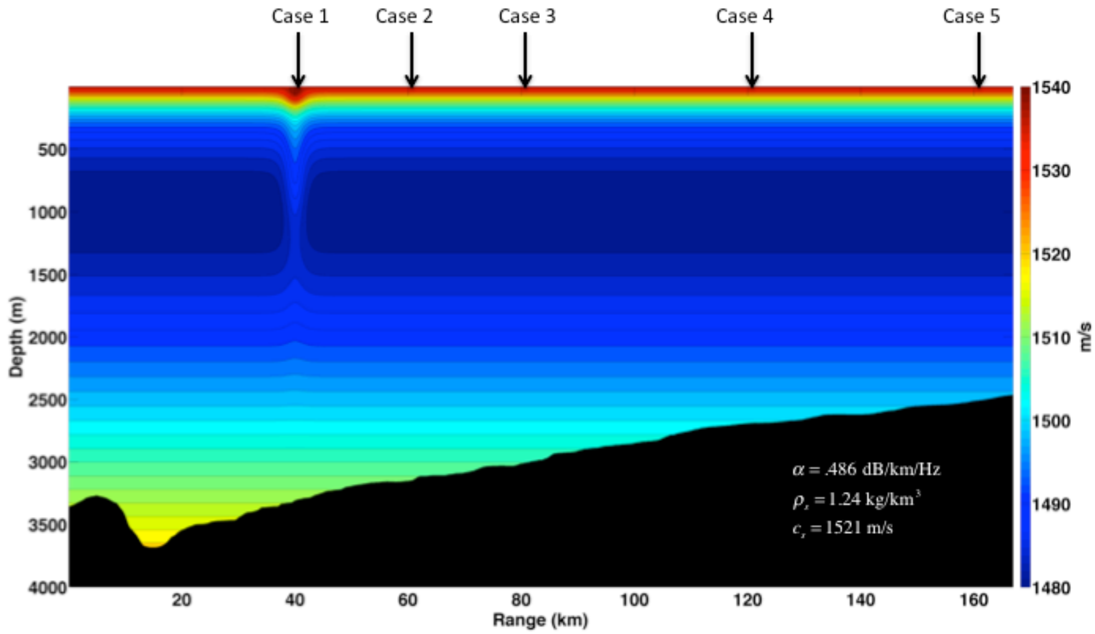

Figure 3. A modeled sound speed field, containing perturbation induced by an ocean internal soliton located at 40 km from the source, overlaid with bathymetry. The modeled bottom attenuation rate, bottom density and bottom sound speed are listed. The arrows/Case numbers point to where the same perturbation was added to the background sound speed field to simulate changes as the internal soliton moved along the transmission path toward the receiver.

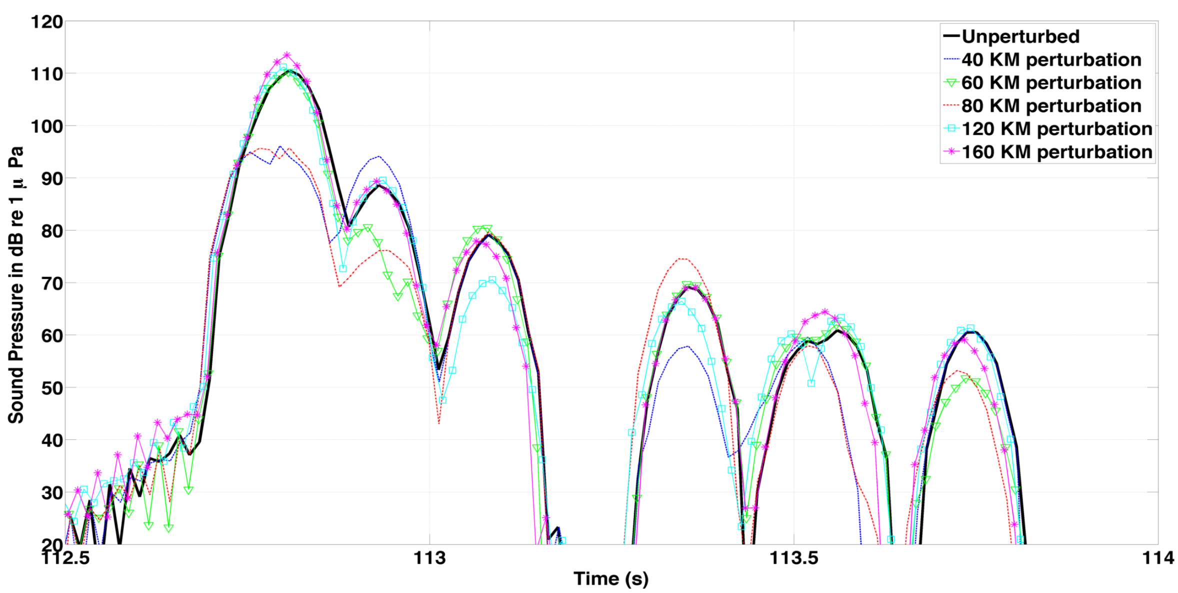

Figure 4. Modeled, demodulated acoustic multipath arrival structure (receive level versus travel time) for each ocean internal soliton location simulated as well as for the unperturbed background ocean. Both source and receiver were placed at a depth of ~800 m.

IMPACT/APPLICATIONS

The oceanographic, bottom and acoustic data gathered in this field study will be valuable in helping to create models of shelfbreak regions suitable for assessing present and future Navy systems, acoustic as well as non-acoustic.

RELATED PROJECT

This integrated acoustics, oceanography and geology experiment should extend the findings and data from SWARM, Shelfbreak PRIMER, ASIAEX, SW06 and NLIWI, thus improving our knowledge of the physics, variability, geographical dependence and predictability of sound propagation in a shelf-slope environment.

REFERENCES

Bernotavicius, C.S., Chiu, C.-S. (corresponding author), Miller, C.W., Reeder, D.B., Wei, R.-C., Yang, Y.-J., and Chiu, L., "Modeling a 400-Hz signal transmission through the South China Sea Basin," *J. Comput. Acoust.*, **18**(2), 193-208, 2010.

PUBLICATIONS

Chiu, L., Chen, Y.-Y., Chen, C.-F., Reeder, D.B., Chiu, C.-S., Lin, Y.-T. and Lynch, J.F., "Enhanced nonlinear acoustic mode coupling resulting from an internal solitary wave approaching a shelf break," *J. Acoust. Soc. Am*., **133**(3), 1306-1319, 2013.

Chiu, C.-S., Reeder, D.B., and Ramp, S.R., "Cruise Report: South China Sea Upper Slope Sand Dunes Project Research Vessels OCEAN RESEARCHER 5 and 2, May 8-14, 2013," Naval Postgraduate School Technical Report (in press).

Ceschini, J.J., "Modeling the effects of transbasin nonlinear internal waves through the South China Sea basin," Naval Postgraduate School M.S. Thesis, June 2013.