TREX13 data analysis/modeling

Dajun (DJ) Tang
Applied Physics Laboratory, University of Washington
1013 NE 40th Street, Seattle, WA 98105
phone: (206) 543-1290 fax: (206) 543-6785 email: djtang@apl.washington.edu

Award Number: N00014-14-1-0239

CO-PI's: Jie Yang (jieyang@apl.washington.edu)
Frank Henyey (frank@apl.washington.edu)

LONG-TERM GOALS:

To understand mid-frequency (1-10 kHz) acoustics in shallow water through measurements and modeling, including propagation, reflection, and forward- and backscatter, as well as reverberation. The top-level goals of this effort are to understand the important environmental processes that impact mid-frequency sonar performance in shallow waters.

OBJECTIVES:

TREX13 (Target and REverberation eXperiment) was conducted during April-June, 2013 off the coast of Panama City, Florida where the water depth is approximately 20 m. Figure 1 provides a concise schematic of the TREX13 experiment lay out. The frequency range covered is 1-10 kHz, emphasizing 3-4 kHz. The Navy relevance is reflected in the fact that detection using mid-frequency sonar is in most cases reverberation limited. This project addresses a clear need in basic research for a 6.1 level measurement program, using well-controlled geometries and high resolution environmental measurements, designed (1) to test models predicting reverberation and (2) to quantify the most important environmental measurements to make in order to maintain accuracy in those predictions. With extensive TREX13 data in hand, the objective now shifts to realizing the long-term goals using data analysis and modeling.

APPROACH

While the TREX13 data sets are extensive and cover almost all aspects of shallow water acoustics, a central theme based on a simplifying SONAR equation

$$RL = SL - 2x\ TL + ISS,$$

integrates all aspects of them. In this equation, RL is reverberation level, SL is the source level, 2xTL the two-way transmission loss, and ISS the scattering strength integrated over the scattering patch for given sonar beam.

Two unique features of TREX13 are that 1) all components of the SONAR equation were individually measured in the same frequency band over the same environment, 2) an extensive environmental measurements at the appropriate temporal and spatial resolutions were made such basic research questions concerning predictability and uncertainty of shallow water reverberation can be quantitatively addressed. The approach to analysis can be summarized into the following steps:

1. Based on measurements, assess to what degree the measured reverberation, transmission, and scattering quantities satisfy the SONAR equation? This first step establishes a complete data set that enables detailed follow-up analysis. It also bounds the predictability and uncertainty of reverberation.
2. Incorporating environmental data, assess the predictability and uncertainty of the individual terms in the SONAR equation. Identify key environmental parameters that contribute to the variability.
3. Review available reverberation predictive models, and if necessary, develop new models to incorporate environmental knowledge in order to improve accuracy and/or speed.
4. With both acoustics and environment measured, divide model environmental parameters into categories, e. g., those that can be inferred from acoustic data and those where databases are necessary.
5. Given prediction requirements and uncertainty tolerance, provide a set of key environmental parameters necessary as input to models.

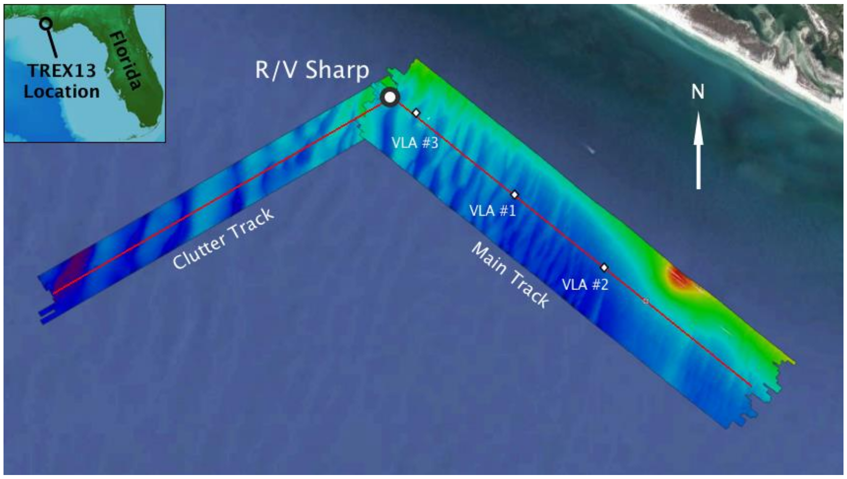


Figure 1. Schematic of TREX13. The 400 kHz bathymetry from the multibeam survey (de Moustier) is shown in color. The reverberation sources and receiving arrays are deployed from the R/V Sharp. The three vertical line arrays fielded by Scripps Institution of Oceanography are also shown.

WORK COMPLETED AND RESULTS

This year’s effort is a continuation from the previous, hence the Long-term Goals, Objectives, and Approach remain unchanged. In addition to co-PI’s, Drs. Hefner and Williams contributed in an essential way to the accomplishment reported here. Dr. Hefner is primarily responsible for analyzing the environment data and coordinating efforts from those who are involved in the TRX13 research. Dr. Williams is involved in discussions of all aspect of the work. While it is difficult to cover all aspects of TREX13 research, which is extensive, reported here are progress made in the study of reverberation and its relation to the SONAR equation. Scientific results will be documented in a special collection to be published in the IEEE Journal of Oceanic Engineering. Progress in the creation of a dedicated website to TREX13 will also be covered.

The discussion on acoustic results will be divided into each term of the SONAR equation, i.e., the reverberation level (RL), transmission loss (TL), and the integrated scattering strength (ISS).

Reverberation Level (RL)

To address different physics issues in reverberation, we have divided the data sets into four categories: (1) Reverberation under calm sea surface conditions with low ambient noise and low biological activity. Data in this category are especially suited for studying reverberation dominated by bottom scattering. (2) Reverberation under different sea surface conditions, including calm condition and rough sea surface waves moving in different directions. Data in this category are meant for detailed study of wind impact on reverberation (See report by Throsos). (3) Reverberation under the influence of high bio-clutter and ambient noise. Fish are frequently present in the TREX13 scene and often a major reverberation source. Fish effect is especially notable after dusk and before sunrise. (4) Target detection under varying environmental condition.

Among the category (1) data, a strong correlation of RL to bathymetry is found, which is one of the manifestations of RL-dependence on the environment. For the correlation analysis, RL data were compared among multiple sets spanning over multiple days. Only those part of data which show consistent RL are used for the correlation study. To demonstrate the correlation, a wedge plot of RL fluctuations, i.e. with the general trend removed, is shown in Figure 2. Data correspond to look angles of ±20° from the main reverberation track (129°), which is centered in the middle. Overlaid on the figure are bathymetry fluctuation contours to assist visually identifying the correlation between RL and bathymetry fluctuations. As seen in the figure, when bathymetry goes deeper, RL increases. To show quantitative results, cross-correlation coefficients between RL and bathymetry fluctuations are computed at each look angle and the results are shown in Figure 3. For look angles between 109°-135°, the correlation coefficient is 70-80%; but it drops off to 50-60% as look angles go beyond 135°. This sharp drop-off in correlation corresponds to diminishing bottom features.

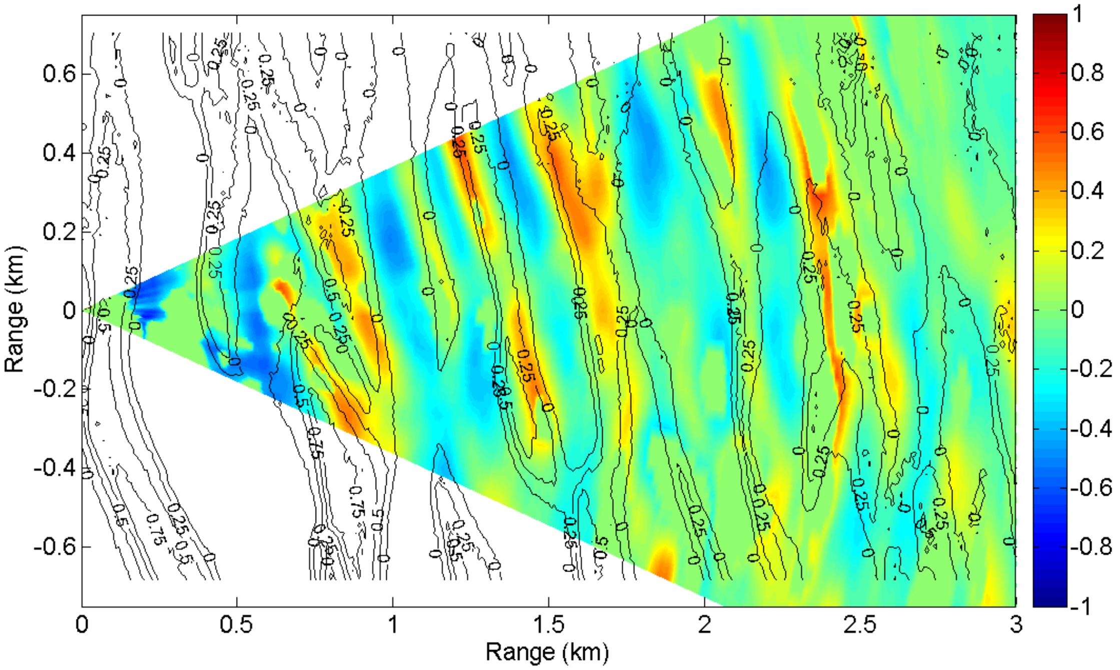


Figure 2. Correlation between RL and bathymetry fluctuations using 2.7-3.6 kHz LFM signal during TREX13. The color wedge shows beamed RL fluctuations with look angles in the range of 109° – 149° re North. Note, wedge was rotated with the main acoustic track, 129°, lined up horizontally. Bathymetry fluctuation contour is shown as the black line. The colorbar: normalized fluctuation level for both RL and bathymetry fluctuations.

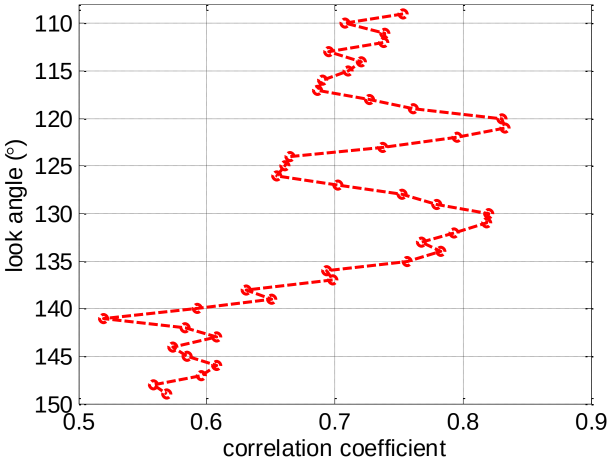


Figure 3. Cross-correlation coefficients between RL and bathymetry as a function of look angles using data in Figure 2.

Transmission Loss (TL)

The relevant quantity of propagation (TL) in the context of reverberation is acoustic field distribution as a function of range and grazing angle. For a given frequency and source level, TL determines how much sound energy is available to be scattered. However, the response of a scattering process depends on the incident grazing angle of the incoming sound. For example, sound incident at high grazing angles generally scatters more from the seafloor than sound incident at shallow grazing angles. Therefore, the TL data analyzed are as a function of frequency, range, and grazing angle.

TL data analyzed here were collected by Scripps Institution of Oceanography led by Dr. Hodgkiss. Reported here is a set of source-tow data recorded on stationary vertical line arrays (VLA's). The source waveforms are simultaneous single frequency tones centered at the following six frequencies: 1503, 2003, 2503, 3003, 3503, 4003 Hz. These tones were transmitted continuously for 15 s with a 15 s interval between subsequent transmissions. The GPS locations of the transmissions during the source tow were also recorded. Since each transmission follows a 30-s cycle with the signal on for 15 s and then off for 15 s, it is natural to segment the continuous time series into pings with each ping consisting of one cycle. Given the tow speed (2 m/s) and the 15 second transmission, the ship moved approximately 30 meters over the duration of transmission. The GPS location of the center of each transmission is designated as the source position for that ping. The overall mean transmission loss is shown in Figure 4. The TL vs. range shows similar trend for all frequencies.

The angular distribution of TL vs. range is achieved by analyzing the frequency-dependent Doppler shifts. In shallow water, only sound energy at low grazing angles can propagate effectively. Energy at grazing angles higher than the critical angle, which is present when the sediment sound speed is greater than that in the water column, would be lost to the bottom. From the normal mode point of view, the trapped modes all have eigenvalues corresponding to grazing angles smaller than the critical angle. The attenuation of the trapped modes depends on the grazing angle with lower order modes attenuating less than higher order modes. Therefore with increasing range, the number of modes will decrease due to this selective attenuation, or mode stripping.

If the sound source is moving, different modes will have different Doppler shifts: lower order modes with lower grazing angles, hence higher phase velocity, have higher shift than high order modes. As a result, at a given range, the received tonal signal will be spread over to a finite frequency bandwidth, which is determined by the number of modes present at the range. With increasing range, mode stripping will reduce the number of modes, hence the frequency spread will decrease. Therefore, measuring the range-dependent angular frequency spread provides a quantitative method of assessing sound angular distribution as a function of range. Figure 5 shows the measured Doppler spread vs range over all frequencies. These curves constrain the models which will predict both TL and RL.

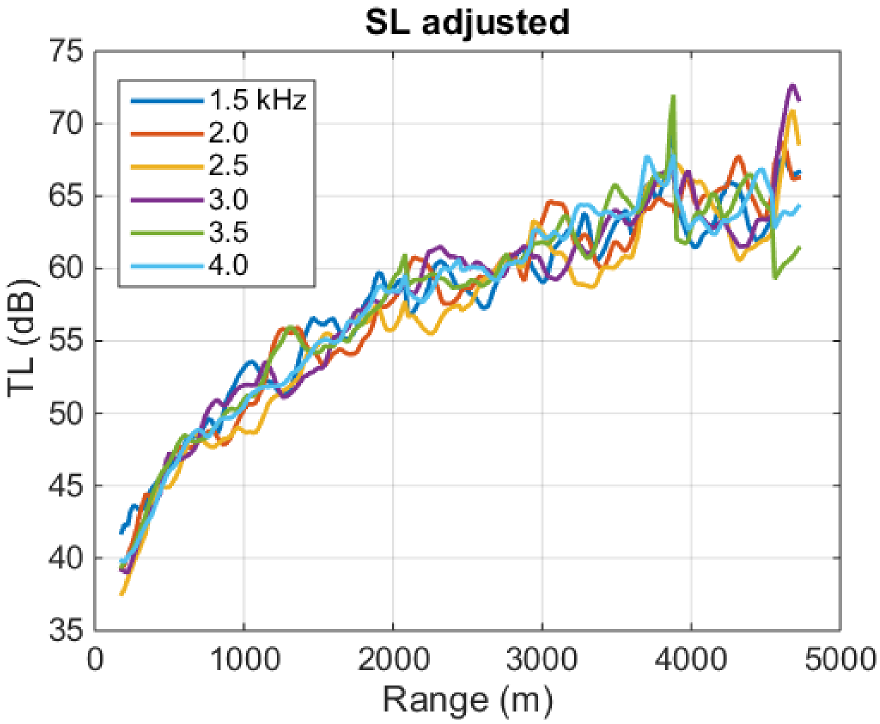


Figure 4. Overall mean TL vs. range for different frequencies. Source level for each frequency is adjusted against the data at 2.5 kHz to minimize the difference over all ranges.

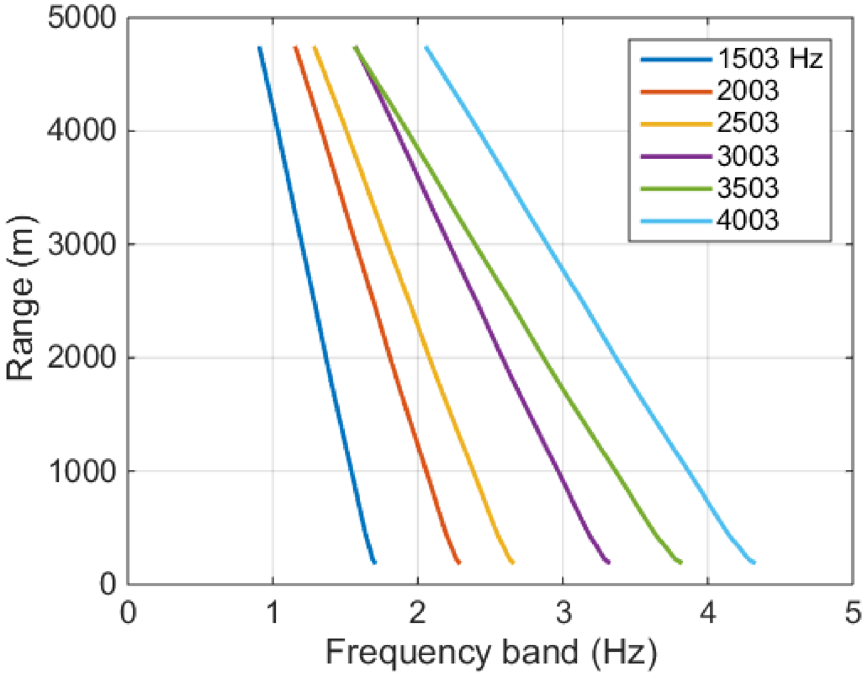


Figure 5. Doppler spread bandwidth vs. range for all six frequencies.

The Integrated Backscattering Strength (ISS)

Taking the SONAR equation viewpoint, reverberation consists of two-way propagation (transmission loss) and a single backscatter. In order to understand reverberation as a function of range and bearing, local acoustic properties as a function of space need to be measured and understood. TREX13 included measurements of normal incident reflectivity of the seafloor and backscattering strength as a function of space along the *main reverberation track* to a range of 5 km. Extensive environmental measurements are conducted along this track.

All measurements reported here were made on a hired 30-ft-long dive boat. The measurement strategy is to target the transition regions observed in the multibeam data, which are the low regions in Fig. 1. To that end, the dive boat was steamed to a position near a transition region where the prevailing current would make the boat drift across the transition region. When a pre-selected starting location was arrived at, the engine of the boat was turned off and the boat was free drifting. The course of the boat was tracked by a GPS receiver as a function of time, and acoustic transmission time was also recorded, hence the locations of each transmission could be derived. The uncertainty of the locations is on the order of 10 m.

While in drift mode, the sensor bracket of the BSS was lowered by a line from the stern of the boat to a depth roughly 2-5 m above the bottom, taking data. This operation covered several of the transition regions along the main reverberation track, and also included a track toward the southwest at a range of ~ 5 km where the sediment appeared uniform in the multibeam data.

Examples of normal incident refection measured at 3 kHz are shown in Figure 6. It is found that the reflectivity is a constant at ~ -10 dB for most of the areas, as shown in the left panel of the figure. However, at the transitions regions where mud is present, the reflectivity is highly variable, as shown in the right panel. These observations are consistent with the variability observed in the RL data: RL fluctuates across the muddy transition region.

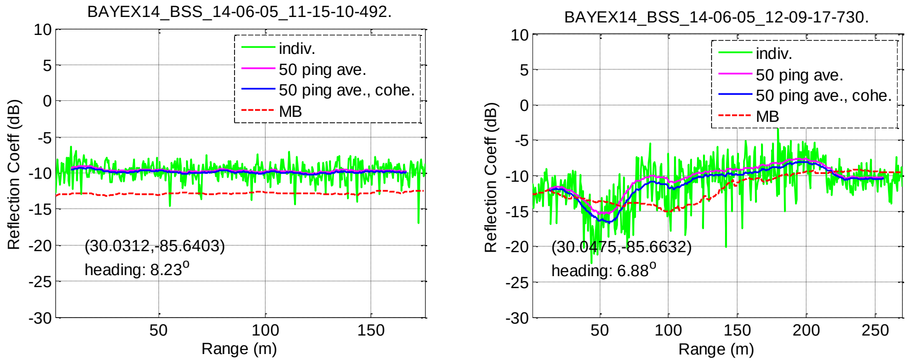


Figure 6. Measured normal incident reflectivity. The green curve is individual measurements, the solid red curve is incoherent average over 50 pings, and the blue solid curve is coherent average of the 50 pings. The red dash curve is intensity from the 400 kHz multibeam data. The left panel is from a sandy area and the right panel goes across a transition region. Based on the same data sets, the mean backscatter strength, a direct input to any reverberation model, can be derived, as shown in Figure 7.

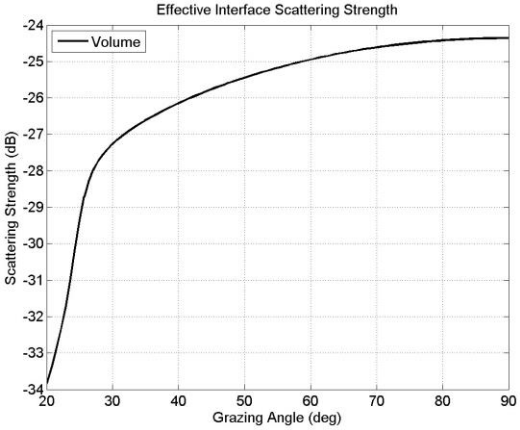
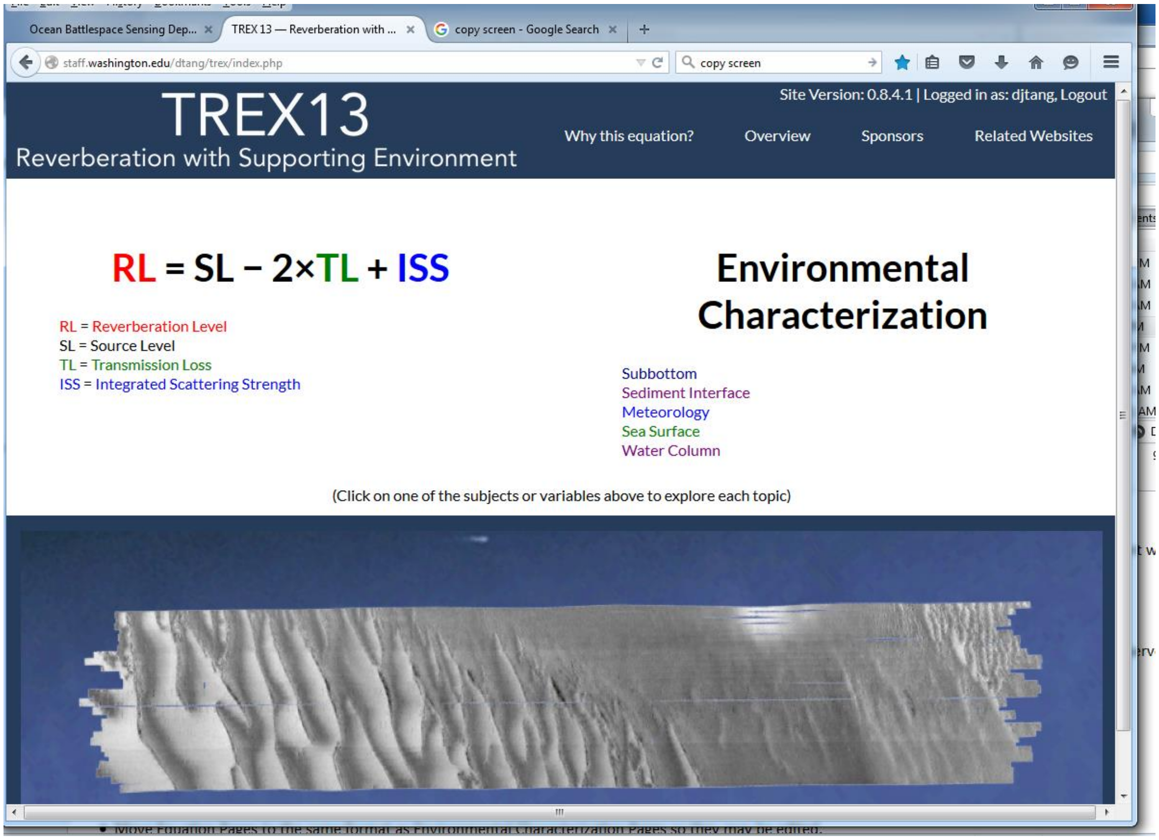


Figure 7. Mean scattering strength estimated based on data away from the transition region.

Now, data from each individual terms of the SONAR equation are measured and analyzed. Put together, along with environmental data, these data constrains modeling effort, which is the next step.

<u>TREX13 website developed</u>

TREX13 is a major field effort where extensive acoustic and environmental data sets were taken. These data sets will be valuable for basic research, teaching, as well as applications. In the past two years, we have devoted substantial resources and effort to develop a dedicated website which will serve the TREX13 community initially to facilitate exchange of ideas and encouraging collaboration and publication. Later the site will also be made available to ONR sponsors and to a wider research community for teaching and as resources for long-term research. Figure 8 is the front page of the site.



TREX13

Reverberation with Supporting Environment

$RL = SL - 2 \times TL + ISS$

RL = Reverberation Level
SL = Source Level
TL = Transmission Loss
ISS = Integrated Scattering Strength

Environmental Characterization

Subbottom
Sediment Interface
Meteorology
Sea Surface
Water Column

(Click on one of the subjects or variables above to explore each topic)

Figure 8. Front page of the TREX13 website.

IMPACT/APPLICATIONS

Naval active sonar detection is often reverberation limited. Understanding the main mechanisms that cause the diffuse reverberation will lead to better sonar performance.Theoretical and numerical progress inspired by the field work will find applications toward detection in shallow water areas including operational recommendations of the most important environmental measurements to make in order to maintain accuracy in predictions of reverberation.

RELATED PROJECTS

NAVOCEANO data bases

STTR Topic N13A-T026
Improving the Physics of Applied Reverberation Models
Contractor’s Reference Number: A99326
Title: Enhancement of the Navy’s Propagation/Reverberation model ASTRAL/ASPM: Increasing fidelity in handling realistic physical phenomena while maintaining speed

“High Fidelity Finite Element Modeling for the Identification of Low- to Mid-Frequency Proud and Buried Object Elastic Responses and SAS Image Features,” ONR Grant #: N62909-10-1-7153, PI: M. Zampolli

“Reverberation, sediment acoustics, and targets-in-the-environment,” ONR Grant #: N00014-11-1-0428, PI: K. L. Williams.

“Full Scale Measurement and Modeling of the Acoustic Response of Proud and Buried Munitions at Frequencies from 1-30 kHz,” SERDP Contract #: W912HQ-09-C-0027, PI: S. G. Kargl

PUBLICATIONS

1. A group of publications will appear in a special collection dedicated to TREX13 in the IEEE Journal of Oceanic Engineering in 2016.
2. Henyey, F. S., and D. Tang, “Reverberation clutter induced by nonlinear internal waves in shallow water,” *J. Acoust. Soc. Am.* **131**, EL302-308 (2013).
3. Tang, D., and D. R. Jackson, “Application of Small-Roughness Perturbation Theory to Range-Dependent Waveguides,” J. Acoust. Soc. Am., **134 (4)**, 289- 293 (2013).
4. Jie Yang, Darrell R. Jackson, and Dajun Tang, “Mid-frequency geoacoustic inversion using bottom loss data from the Shallow Water 2006 Experiment”, J. Acoust. Soc. Am. **131 (2)**, 1711- 1721 (2012).
5. Tang, D., and B. T. Hefner, “Modeling backscatter from a series of sediment rough interfaces by a normal incident chirp sonar,”J. Acoust. Soc. Am., **131**, EL302-308 (2012)
6. Tang, D., F.S. Henyey, D. Rouseff, and J. Yang, “Single-path mid-frequency acoustic intensity fluctuations in shallow water, ”J. Acoust. Soc. Am., (In preparation).
7. Henyey F., K Williams, J. Yang,and D. Tang, “Simultaneous nearby measurements of acoustic propagation and high-resolution sound speed structure containing internal waves,” *IEEE J. of Oceanic Engineering*, Vol. 35, 684-694 (2010).
8. Yang, J., D. Rouseff, D. Tang, and F. S. Henyey, “Effect of the internal tide on acoustic transmission loss at mid-frequencies”, *IEEE J. Oceanic Engineering,* Vol. 35, 3-11 (2010).