Planning Systems Incorporated

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December 8, 2005

Michael Wardlaw
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Mr. Wardlaw:

Enclosed you will find the first year summary report for the Phase II STTR "Advanced Physics-Based Modeling of Discrete Clutter and Diffuse Reverberation in the Littoral Environment" under ONR Contract Number N00014-04-C-0399. This summary report covers the time period from 2 December 2004 through 1 December 2005. Per the contract instructions, only a copy of the cover letter is being sent to the ACO (DCM Manassas).

Sincerely,

Peter Neumann
Planning Systems Inc.

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Advanced Physics- Based Modeling of Discrete Clutter and Diffuse Reverberation in the Littoral Environment
STTR Phase II - Topic N03-T011

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Phase II STTR First Year Summary Report
Covering December 2, 2004 through December 1, 2005

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Executive Summary

In response to the Navy STTR Topic N03-T011, "Physics-based modeling of Acoustic Reverberation in the Littoral Environment," a team representing PSI (Planning Systems Inc.), ARL-PSU (Applied Research Laboratory – Penn State University) and NRL-DC (Naval Research Laboratory – District of Columbia) was assembled to develop a broadband time series simulation capability for both discrete clutter and diffuse reverberation. This simulation capability is based upon the work by Kevin LePage (NRL-DC), who is participating on this STTR as an outside funded resource, and uses the coherent summation of narrow band results using normal mode methods to generate the broadband time series simulations. This high level of simulation fidelity is proposed for use in the LAMP (Littoral ASW Multistatics Program) and AEER (Advanced Extended Echo Ranging) programs as a tool for active, coherent sonar system development.

The product of the Phase II STTR will not replace an existing modeling capability within the proposed programs but rather will provide these programs with an entirely new simulation capability. Current modeling tools at low and mid-frequencies (up to 5 kHz), including the Navy standard ASPM (Acoustic System Performance Model) and CASS (Comprehensive Acoustic System Simulation) models, cannot produce a simulated time series including the effect of discrete clutter at the receiver. The simulation tool being developed under this Phase II STTR is intended to augment the in-water testing done on active, coherent sonar systems and will allow more sophisticated in-water testing through the use of simulation during the early design process.

Phase II Objectives and Technical Approach

The Phase II base program has two primary objectives.

1. Develop a more complete understanding of the physical mechanisms responsible for observed clutter (primary geo-clutter) in available acoustic data sets and develop an approach to model those physical mechanisms within the simulation code framework.

2. Develop a MATLAB based simulation product based upon the prior and current work of Kevin LePage which uses a coherent summation of narrowband normal mode results which will simulate broadband time series from both discrete clutter and diffuse reverberation in a littoral environment. This simulation will be validated against in-water acoustic data sets and will include both documentation of the validation and simulation suitable for use by the targeted transition programs (LAMP and AEER).

The technical approach for the first objective is the analysis of acoustic data with clutter events to provide a more complete representation of the physical mechanisms responsible for the observed clutter features. The use of measure acoustic data to produce a physical representation of the clutter mechanisms will produce modeling approaches that can be extrapolated to other environments and source/receiver characteristics with a much higher degree of confidence than modeling approaches that utilize empirical descriptions of the clutter mechanisms.

The technical approach for the second objective described above utilizes the modeling approach being developed by Kevin LePage that uses the coherent summation of narrowband normal mode results to generate a simulated broadband time series. The modeling approaches developed for the identified clutter mechanisms will be integrated into this simulation in addition to currently developed modeling for the diffuse reverberation component of the simulated broadband time series. Model-to-data comparisons will be performed as the simulation is developed to confirm the correct implementation of the various clutter mechanisms within the simulation.

Phase II Work Completed

The technical objectives described in this report are part of a 24 month Phase II STTR base program. The work completed at the time this report was written include the Phase I base and option tasks (described in the FY 04 summary report) and the first 12 months of the Phase II STTR base program tasks (to be described in this summary report).

Charles Holland of ARL/PSU has focused his work on the processing and analysis of acoustic data sets from the Boundary 2004 experiment and the observed clutter features that are the results of submarine mud volcanoes in the experiment area (see Figure 1). The analysis of the acoustic data received on the vertical line array (see Figure 2) used a direct path measurement technique which significantly reduced the assumptions[1] present in long-range reverberation observation.

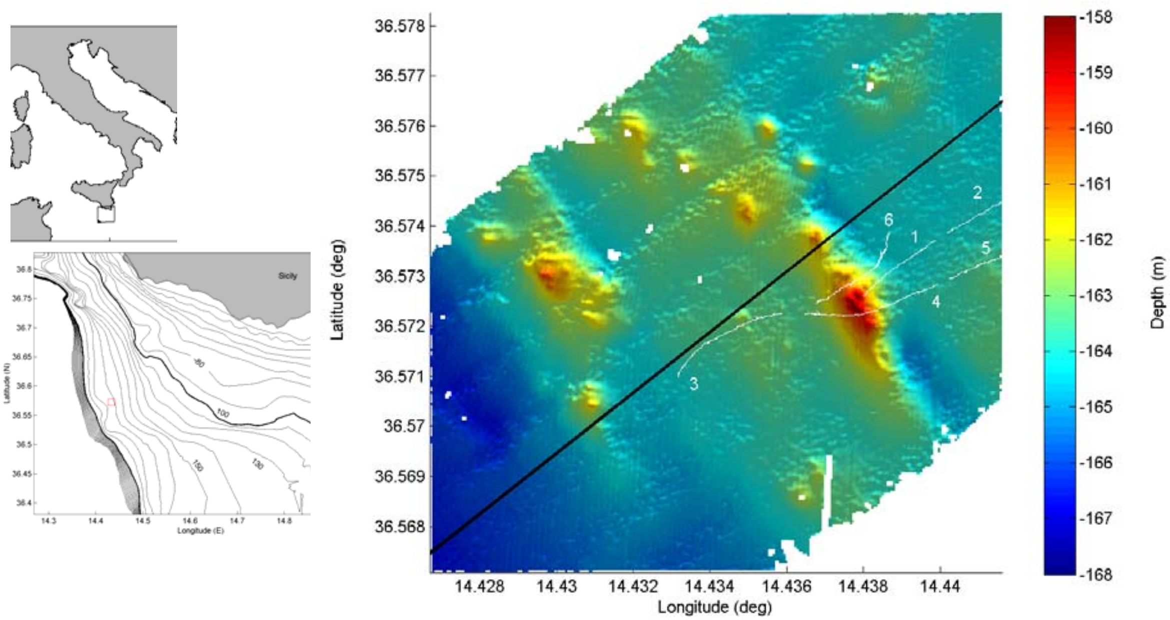

Figure 1: Boundary 2004 Experiment (May 2004) showing the experiment area with the side-scan sonar track line (solid black line) and experiment track lines (white lines) overlying the bathymetry showing the submarine volcano of interest.

[1] Long-range reverberation observations require an extremely accurate estimate of the bottom loss in order to estimate accurately the target strength of an observed clutter feature.

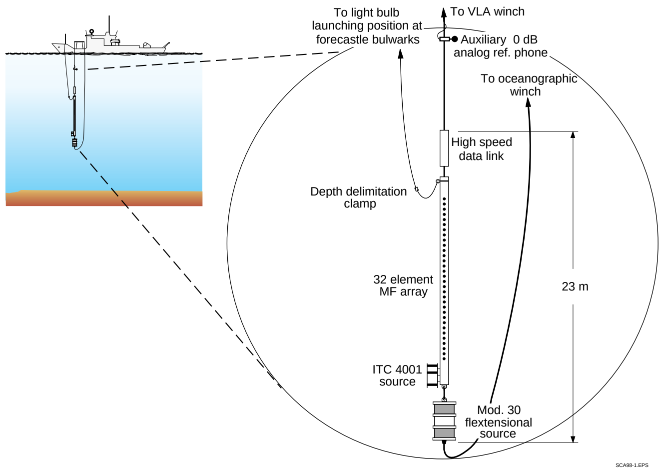

Figure 2: Transmit and receive system used for the Boundary 2004 experiment data collection.

This technique (shown in Figure 3) has the potential for direct observation of the clutter feature of interest and can study small scale spatial variability and isolated features, due to the small distances between the source, receiver and the clutter features. This measurement technique requires both a short transmit pulse and a vertical receive array to mitigate the problems of multipath (as shown in Figure 3) and care must be taken to avoid contamination by sub-bottom reflections at normal incidence.

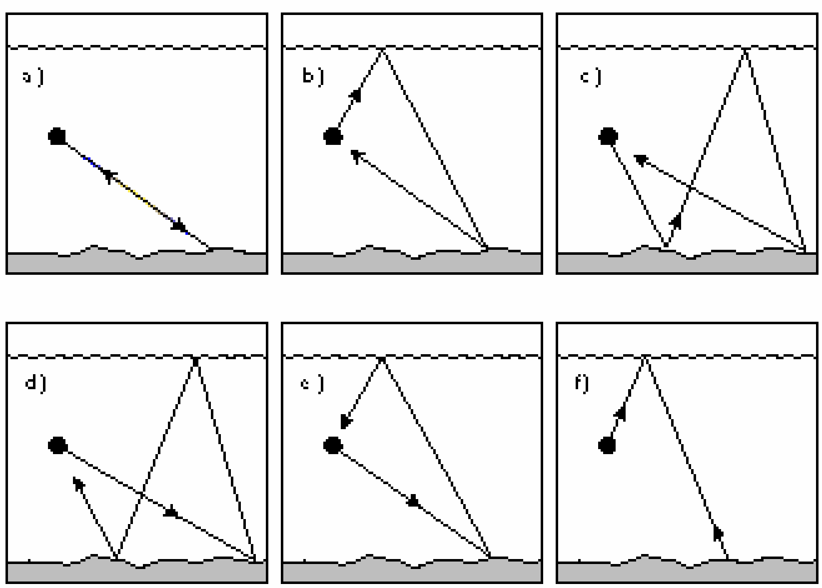

Figure 3: Diagram showing the direct path measurement technique and the various paths for acoustic energy (path a – direct path source to bottom and back to receiver, path b – path from source to surface, bottom and receiver, etc.).

An example of the acoustic data from this experiment is shown in Figure 4. The results show the vertical line array data (vertical receive angle versus time) paired with a diagram showing the various ray path combinations with the black arrows highlighting the clutter feature for each ray path combination in the processed acoustic data. The analysis of this data uses the sonar equation to compute the target strength of the clutter feature. This requires estimates of the transmission loss along each of the paths (shown in Figure 3) as well as estimates of the reflection loss at the bottom and surface. Unlike long-range reverberation measurements where small errors in the boundary reflection loss are magnified due to the large number of boundary interactions, reflection loss errors have significantly less effect on the direct path measurements used in this data analysis due to the limited number of boundary interactions.

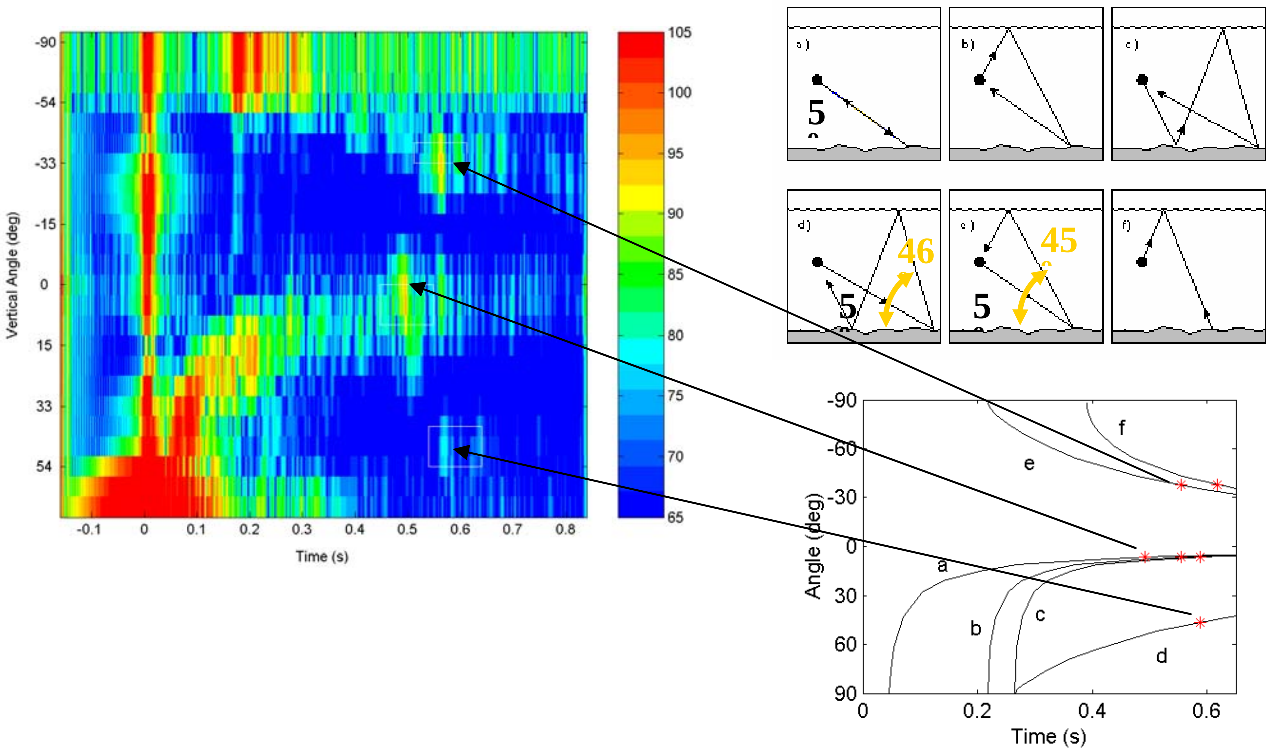

Figure 4: Scattering at 1800 Hz (vertical receive angle versus time) showing the submarine mud volcano clutter feature (marked by the black arrows).

This work has produced estimates of the target strength for the submarine volcanoes as a function of frequency in both monostatic and a vertically bistatic geometry. The information gained from this analysis is presented in the "Phase II Results" section beginning on page 9 of this summary report.

Kevin LePage of NRL-DC has been working on providing a more rigorous understanding of the physical mechanisms responsible for long-tailed (non-Rayleigh, clutter-like) reverberation in littoral environments. This work was initially presented the ASA meeting in Vancouver, B.C. in May 2005. The goal of this work is to estimate the non-Rayleighness of littoral reverberation as a function of the active sonar system (frequency, bandwidth and beam pattern), the environment (sound speed profile and bottom properties) and the scatterers (amplitude and spatial distribution). The approach developed by Kevin LePage has been to use a X_1^2 (Chi squared with one degree of freedom) distribution for the two and four point correlation function to compute the second moment of the reverberation intensity. The mathematical derivation of his work requires considerably more space than is available in this summary report. Interested readers are invited contact Kevin LePage directly using the contact information on the first page of this report.

A simulation result for 75 and 750 Hz shown in Figure 5 illustrate several of the capabilities of this work. For correlation lengths less than a wavelength, the reverberation intensity (top row in Figure 5) is not a function of correlation length. The standard deviation (middle row in Figure 5) increases with increasing correlation lengths due to fewer scatterers in the illuminated bottom patch and decreases as time increases due to a larger number of bottom patches being illuminated due to waveguide dispersion. The ratio of the standard deviation of the reverberation to the reverberation intensity (bottom row in Figure 5) increases as the correlation length increases due to the number of scatterers in the bottom patch decreasing.

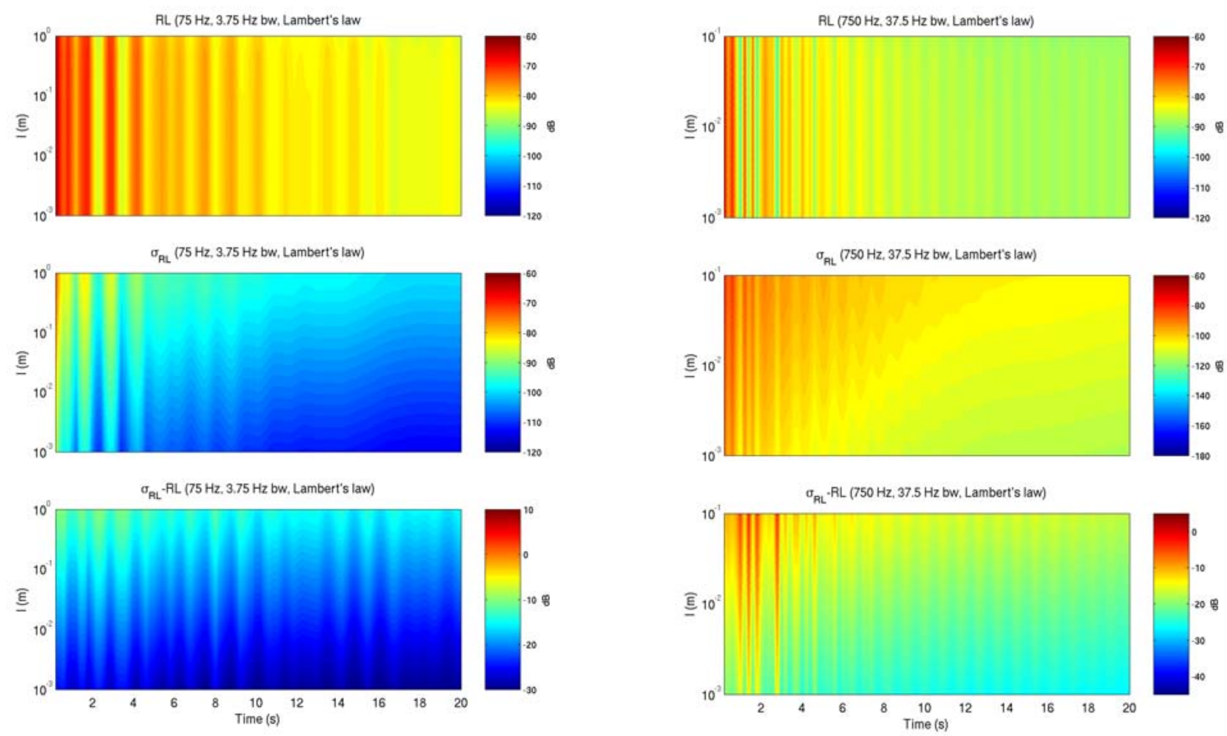

Figure 5: Simulation results for 75 Hz (left) and 750 Hz (right) showing the reverberation intensity (top row), reverberation standard deviation (middle row) and ratio of the two (bottom row) as a function of correlation length (y-axis) and time (x-axis).

This result is shown in more detail in Figure 6 where the ratio of the standard deviation to the intensity at 10 seconds is plotted versus the correlation length. The ratio of the standard deviation to the reverberation intensity becomes very large as the number of scatterers in the bottom patch approaches one (correlation length scales of 10 m for 3.75 Hz of bandwidth at 75 Hz, or patch size of 200 m; and correlation length scales of 1 m for 37.5 Hz of bandwidth at 750 Hz, or patch size of 20 m).

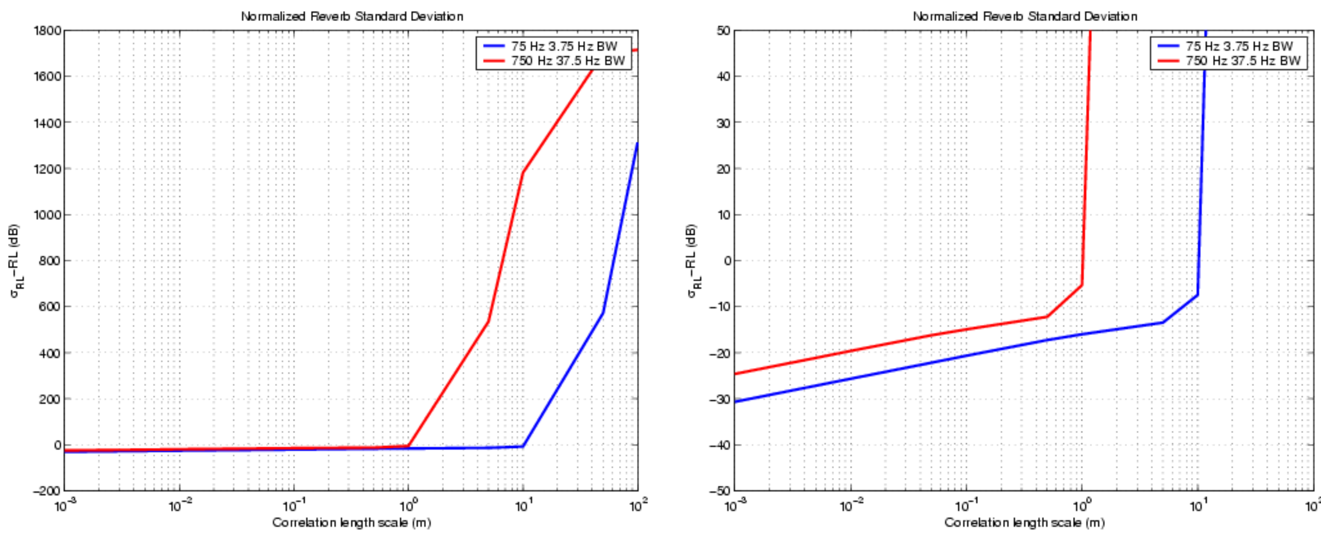

Figure 6: Normalized reverberation standard deviation at 10 seconds plotted versus frequency (75 and 750 Hz) and correlation length.

Phase II Results

The analysis of the Boundary 2004 experiment data by Charles Holland produced both estimates of the target strength from single mud volcanoes and a clearer understanding of the scattering mechanism responsible for the observed clutter features in the acoustic data. The target strength estimates shown in Figure 7 are for 800, 1800, 2400 and 3600 Hz for path a (solid blue line), path e (solid red line) and path d (dashed green line). These are target strength measurements from a single mud volcano and they provide several insights into the physical scattering mechanism responsible and the most plausible modeling approach. The target strength estimates for 1800 and 3600 Hz for path a and path e show a target strength of 6 to 12 dB that does not appear to be a facet scattering mechanism as there is little difference between the different scattered angles at these frequencies. The noticeable difference between the target strength estimates at 2400 Hz is not currently understood and will be investigate further in the second year.

The acoustic data and the analysis peformed to date does not indicate any evidence of mud volcanoe induced scattering from within the water column, either from methane ebullition or from effluent particulates in the water column. The observed target strengths could be fit using a bubble size distribution (within the sediment) to the frequency dependent target strength. However, Charles Holland believes that the simplest, and most plausible, explanation for the observed scattering is that it is the result of scattering from inhomogeneities within or at the interface of the mud volcano itself which is composed of mud breccia or carbonate. Regardless of the modeling approach adopted for mud volcano features of this type, it is clear that their measured target strength of 6 to 12 dB indicates that they can be a significant source of clutter for an active sonar system operating in littoral environments with gassy sediments.

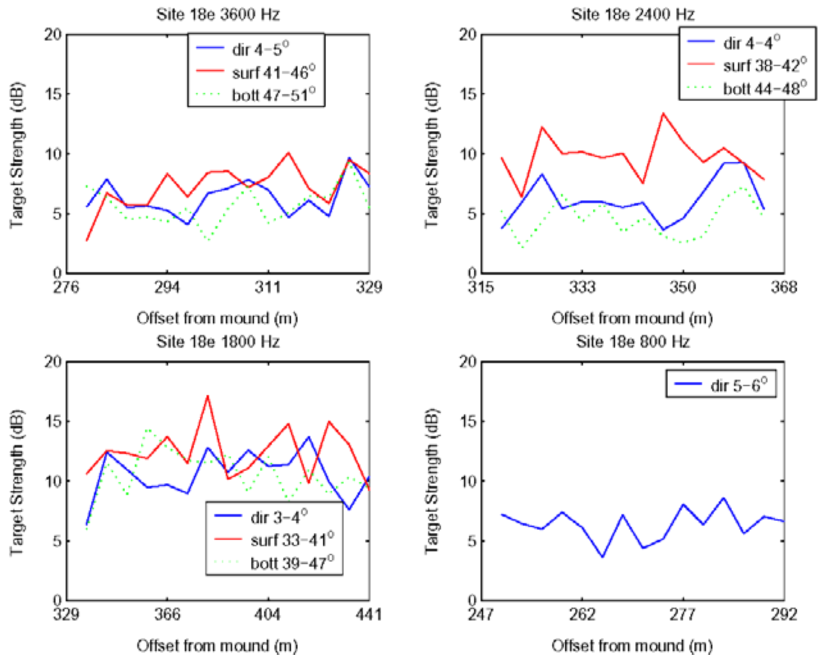

Figure 7: Estimated target strength at 800, 1800, 2400 and 3600 Hz using path a (see Figure 3) shown by the solid blue line, using path e shown by the solid red line and path d shown by the dashed green line.

The model-to-data comparison described in the objectives section of this report began with a data set (shown in Figure 8) from the SCARAB 98 experiment that used a SUS source and a towed line array receiver. A model-to-data comparison for beam 36 (77.26 deg) from forward end-fire (heading 19.5 degrees NNE) is shown in Figure 9 (time series) over the band 100 to 1150 Hz compared to the data over the 0 to 1800 Hz band. As we move forward we will refine this model data comparison using Holland's estimates of the frequency dependent sediment scattering coefficient, Ragusa ridge scattering coefficient and ship target strength. The lack of registration between the ship position in the simulation and the data is due to an error in estimating the ship range. The lack of registration between the Ragusa ridge returns in the data and the simulation may be due to an error in the estimate of the ridge in the simulation inputs or in the assumed position of the ship.

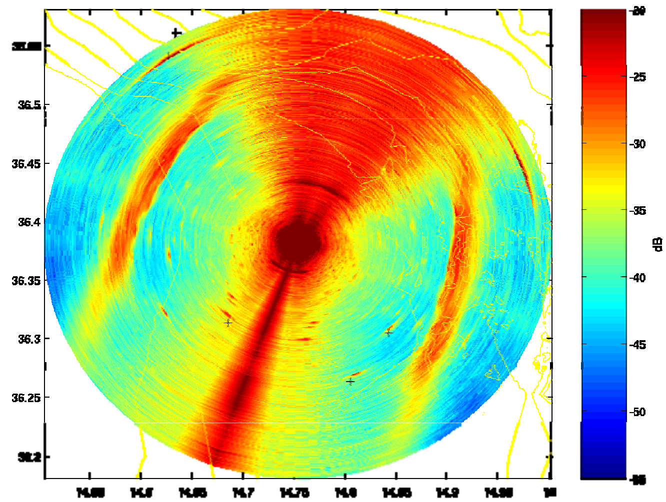

Figure 8: **The beam time series of the smoothed SUS response from SCARAB 98, including the Campo Vega rig (late time, NNW), and the three wreck sites (the three other black crosses to the SE, SSE and SW).**

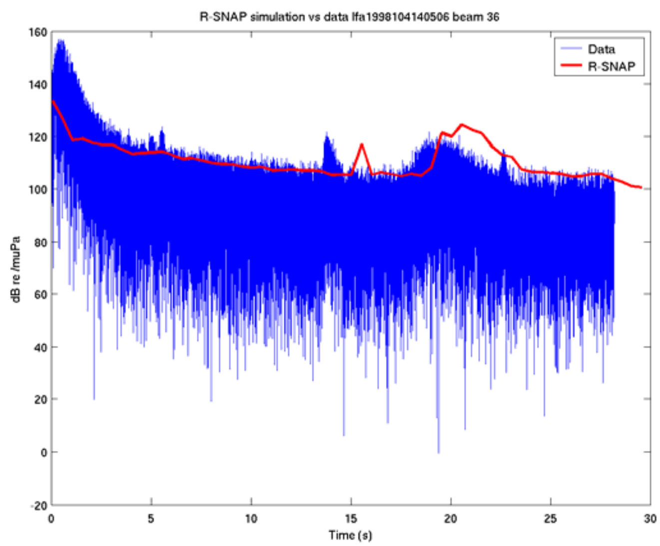

Figure 9: **SCARAB 98 model-to-data time series comparison for beam 36 (100 to 1150 Hz for the model and 0 to 1800 Hz for the data).**

The time-frequency of the data and the simulation are shown side by side in Figure 10. The simulation was run every 500 ms for a frequency spacing of $f/20$ Hz (i.e. at 100 Hz, the frequency spacing of the simulation is 5 Hz, while at 1000 Hz it is 50 Hz.). The striation pattern of the data is visible in the simulation, although at much lower resolution due to the large time steps, also, the frequency independent basement scattering mechanism for the Ragusa ridge seems to under-estimate the scattering from this feature at higher frequencies. Finally, the simulations do not accurately model the high levels at early time where normal mode propagation ignores the high angle early time returns above the critical angle, and the levels seem too high at late time and higher frequencies.

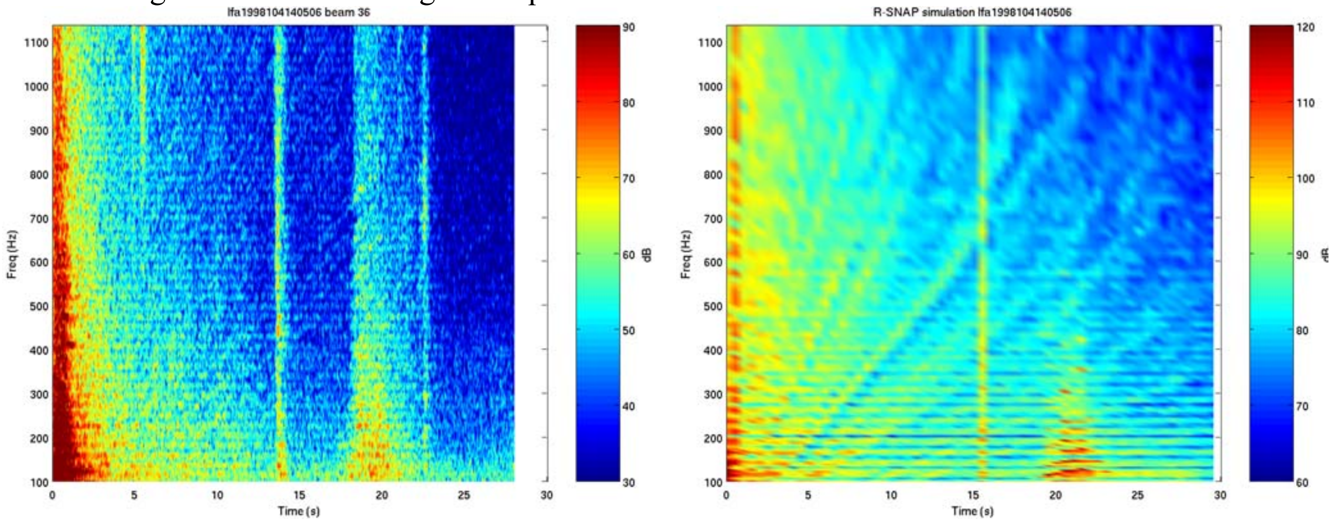

Figure 10: SCARAB 98 model-to-data comparison for beam 36 for 100 to 1150 Hz.

Tasking for First Quarter of Second Year of Phase II

The plans for the coming months (first 2-4 months of the second 12 months of the Phase II STTR) were discussed and clarified at the meeting held at ARL/PSU on November 22nd and are summarized below for each performer on this Phase II STTR.

Charles Holland (ARL/PSU)

- Develop the geo-parameters for the rim and ridge in the SCARAB 98 data site (a working draft of a JASA paper with this work is already in progress)
- Develop the parameters for a simple sphere model for a carbonate mound scattering feature and explore the potential for a statistical description for the distribution of mounds in the environment.

Kevin LePage (NRL-DC)

- Convert the Matlab scripts for the monostatic, range-independent simulation of the received level into a set of Matlab subroutines/functions. This will allow the function of the code to be more easily read and allow such elements as the diagnostic plotting to be easily included or excluded from the code.
- Implement the time series simulation with R-SNAP for range dependent environments for diffuse reverberation.
- Verify the reflection component in R-SNAP (need to determine if benchmark solutions are available).

- Implement boss scattering in R-SNAP to simulate discrete scatterers.
- Conduct the model-to-data comparison for the SCARAB 98 data using the scattering coefficient (μ), Weston parameter (α) and scattering law (m) provided by Charles Holland.[2]

Peter Neumann (PSI)

- Compile the C-SNAP Fortran code using Compaq Visual Fortran and modify Matlab scripts to run on a Windows PC (originally developed on Linux).
- Format Matlab scripts with appropriate comments and begin draft documentation describing input parameters, input files, output files, etc.
- Contact Rick Fillhart (NAWC-AD) to discuss current interest within the EER source development program in the simulation being developed under this Phase II STTR. An email to Ricky Fillhart was sent on November 30th.

Applications of Phase II Work and Products

The ability to simulate broadband time series at the receiver (monostatic or bistatic) in an active sonar system including the effects of both discrete clutter and diffuse reverberation will be a new capability for the sonar system designer. The simulation package being developed under this Phase II STTR will not replace in-water testing but should allow the sonar designer to test early designs with the simulation, instead of in-water, with the result being a reduction in the development costs (simulation costs are expected to be less than in-water testing costs). The simulation will also allow sonar designer to test hypothetical sonars in environments against particular types of discrete clutter with a degree of control that cannot be achieved through in-water testing.

Related Projects

Charles Holland of ARL/PSU is currently participating in the ONR GeoClutter Program which is providing measurements and analyses results from a May 2004 experiment in the Straits of Sicily that are being leveraged into this Phase II STTR to enhance the development of the broadband simulation product. Dr. Holland is also working on the Boundary Characterization Joint Research Project (ONR and NURC) providing acoustic, geoacoustic, geologic and geophysical data for the Straits of Sicily.

[2] C. Holland, "On errors in estimating seabed scattering strength from long-range reverberation," *Journal of the Acoustical Society of America*, **118**, 2787-2790 (2005).

Publications, Briefs, Reports and Travel

The following is a summary of the publications (both published and submitted) during the first 12 months of this Phase II STTR by the key personnel.

- LePage, K. D., "Environmental effects of waveguide uncertainty on coherent aspects of propagation, scattering and reverberation," *IEEE Journal of Oceanic Engineering* [refereed, submitted].
- Holland, C. W., "Mapping seabed variability: Rapid surveying of coastal regions," *Journal of the Acoustical Society of America* [refereed, in review].
- Holland, C. W., "On errors in estimating seabed scattering strength from long-range reverberation," *Journal of the Acoustical Society of America*, **118**, 2787-2790 (2005).
- LePage, K. D., "Modeled and measured characteristics of non-Rayleigh reverberation," BOUNDARY JRP meeting, NATO Undersea Research Centre (12-14 September 2005).
- LePage, K. D., "Higher moment estimation in physics-based reverberation modeling," Joint ONR 321US and NRL Active Sonar ASW D&I Program Review, Naval Research Laboratory, Washington DC (30-31 August 2005).

The following is a summary of the briefs and reports by key personnel during the first 12 months of this Phase II STTR.

- Kevin LePage presented his paper "Effect of multipath propagation on reverberation statistics in shallow water" at the ASA meeting in San Diego, CA on November 16th, 2004.
- Tom Weber in collaboration with Charles Holland and Giuseppe Etiope presented his paper "Observations of a geoclutter feature in the Straits of Sicily" at the ASA meeting in Vancouver, B.C. on May 17th, 2005.
- Charles Holland in collaboration with Tom Weber and Giuseppe Etiope presented his paper "Close-range acoustic scattering from mud volcanoes" at the ASA meeting in Vancouver, B.C. on May 17th, 2005.
- Kevin LePage presented his paper "Higher moment estimation for shallow water reverberation" at the ASA meeting in Vancouver, B.C. on May 20th, 2005.
- Peter Neumann presented a brief on this STTR at the ONR Code 321MS annual program review in Newport, RI on August 16th, 2005.
- The fiscal year 2005 report for ONR Code 321MS was submitted by email to Jim Holt and Todd Brunori on September 30th.
- Kevin LePage presented "Non-Rayleigh Reverberation Prediction for Shallow Water Waveguides" at the ASA meeting in Minneapolis, MN on October 21st, 2005.

In addition to this report, a CDR disk is being sent to the TPOC for this Phase II STTR, Michael Wardlaw, This CDR includes the monthly summary reports as well as the publications and presentations generated during the first 12 months of this effort. Any reader of this report who would like a copy of this CDR disk should contact Peter Neumann using the contact information listed in the next section of this report.

The following is a summary of the travel by key personnel during the first 12 months of this Phase II STTR.

- Peter Neumann traveled to the ONR Code 321MS annual program in Newport, RI (August 16^{th} – 18^{th}).
- Peter Neumann and Kevin LePage traveled to ARL/PSU (State College, PA) to meet with Charles Holland on November 22^{nd} to plan the goals and tasking for the second year of this Phase II STTR.

Summary of Funding Expended during First 12 Months

The following is a summary of the funding expended by month during the first 12 months of this Phase II STTR.

- December 2004 - $2,192
- January 2005 - $2,042
- February 2005 - $13,761
- March 2005 - $9,403
- April 2005 - $7,254
- May 2005 - $23,246
- June 2005 - $14,527
- July 2005 - $18,220
- August 2005 - $18,596
- September 2005 - $28,472
- October 2005 - $22,634
- November 2005 - $18,909

The total funding expended through November 30^{th}, 2005 is $179,253 with $317,913 in funding remaining for the second 12 months of this Phase II STTR. The current level of effort shown for the last three months (September through November 2005) will result in this Phase II STTR being completed on time and within the budget allocated.

Report Preparation

This report was prepared and submitted by the following individuals:

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