High Frequency Acoustic Channel Characterization for Propagation and Ambient Noise

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LONG-TERM GOALS

There are two long-term goals for this research: 1) to exploit the ocean ambient noise field in the 0.1-50 kHz frequency band for environmental characterization and for improving sonar system performance and 2) to improve algorithm design for acoustic communications systems and other high frequency sonars by developing propagation and scattering models appropriate in these bands and including important Doppler effects.

OBJECTIVES

The objective of the ambient noise research is to develop new ways for passive remote sensing that takes advantage of ocean noise to gain information about the seabed without using a sound projector or explosives. Progress has been made in coherently processing ocean noise for this purpose [1], but we continue to develop a better understanding and improve processing. The value and impact of these techniques that exploit ocean noise are significant. The passive nature of the measurements is appealing in situations where sound sources are not desired (e.g. due to environmental restrictions). Further, the measurements are relatively simple compared to conventional methods which require one (possibly two) research ship(s) as well as specialized sources and/or sonar systems (e.g. chirp sonar). This may not only result in a better approach to solving some long-standing Navy problems, but possibly at a lower cost.

The objective of the second part of this project is to develop new models to improve our understanding of the physics of high frequency propagation and scattering. For many sonar applications, scattering is treated as an effective loss mechanism and Doppler shifts are often ignored. This may be reasonable for certain types of sonar systems, particularly the low frequency ones. However, new underwater acoustic systems, including those for underwater acoustic communications, are sensitive to both scattering losses and Doppler. In particular, channel equalizers used with bandwidth-efficient, phase-coherent communications methods can be extremely sensitive to Doppler spread. Designing these equalizers to compensate for Doppler often presents a substantial challenge. Significant Doppler spread can be introduced simply from the sound interacting with the moving sea-surface; however, the effects are much greater when the source and receiver are also in motion. Simulating signals using a physics-based model can greatly aid the development of new algorithms and provide valuable performance predictions.

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14. ABSTRACT
There are two long-term goals for this research: 1) to exploit the ocean ambient noise field in the 0.150 kHz frequency band for environmental characterization and for improving sonar system performance and 2) to improve algorithm design for acoustic communications systems and other high frequency sonars by developing propagation and scattering models appropriate in these bands and including important Doppler effects.

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APPROACH

Ocean Ambient Noise Processing

Recently, a technique has been developed to image seabed layers using the ocean ambient noise field as the sound source[1]. This so called passive fathometer exploits the naturally occurring acoustic noise generated on the sea-surface, primarily from breaking waves. This method uses the cross-correlation of noise from the ocean surface with its echo from the seabed to recover travel times to significant seabed reflectors. To make this practical, beamforming is used with a vertical array of hydrophones and this reduces interference from horizontally propagating noise and greatly reduces the required averaging times. The initial development used conventional beamforming but significant improvements have been realized using adaptive techniques.

For adaptive processing we use the Minimum Variance Distortionless Response (MVDR) to suppress the energy coming from directions other than that of interest. In this case there is significant energy coming near horizontal that is of no interest for the passive fathometer processing. To adaptively beamform, the MVDR steering weight vector $\mathbf{w_A}$ at frequency ω are computed according to,

$$\mathbf{w_A} = \frac{\mathbf{K}^{-1}\mathbf{w}}{\mathbf{w}'\mathbf{K}^{-1}\mathbf{w}} \quad , \tag{1}$$

where $\mathbf{K}$ is the data cross-spectral density matrix, the weight $\mathbf{w}$ is the conventional plane-wave steering vector at 90 degrees (for each hydrophone in the array) $\mathbf{w} = [w_1, w_2, \ldots w_M]$, for hydrophone m is, $w_m = e^{im\Delta k}$ and $k = \omega / c$ with Δ being the design half-wavelength spacing and c the sound speed ($\mathbf{w}'$ is the conjugate transpose of the vector). The MVDR correlation at frequency ω is approximated by the expression,

$$\mathrm{C}_{\mathbf{A}} = \mathbf{w}'_{\mathbf{A}}\mathbf{K}\mathbf{w}^{*}_{\mathbf{A}} \tag{2}$$

The conjugation on the second weight vector approximates the weight for -90 degrees or in the direction of the seabed (alternatively, the actual -90 degree weight vector can be computed and conjugated). The time-series passive fathometer response is simply the inverse Fourier Transform of $C_A(\omega)$ or, $c(t) = F^{-1}\{C_A(\omega)\}$. Strictly, this expression is fine if detecting the seabed and layering are all that is of interest. However, if one wants the impulse response of the seabed, then differentiation with time is needed as described in Harrison and Siderius 2008. This adaptive processing was applied with significant improvements on several data sets as shown in the result section. Further, there were cases where a white noise gain constraint provided additional improvements which are also shown in the result section.

Modeling and Validating Acoustic Signals Interacting with a Time-Varying Sea-Surface

We have taken two approaches to develop a model to treat signals interacting with a time varying, rough sea-surface. The first is a ray-based approach to model moving sources/receivers as well as a slowly varying sea-surface (e.g., that from sea swell). To model interactions from finer scale sea-surface roughness, we have developed an implementation of the Kirchhoff approximation which is numerically much less demanding than an exact solution via, for example, the Helmholtz-Kirchhoff integral equation. There are practical limitations to numerically solving the Helmholtz-Kirchhoff integral equation since an inversion of large matrices is required. In practical problems, the sampling of the surface requires approximately 5 points per wavelength. If the objective is to solve a problem with a 1 km surface at 10 kHz (for example for an acoustic communications simulation) the number of discrete points is over 30,000 which requires inversion of a 30,000 by 30,000 matrix for each frequency. This increases to 300,000 by 300,000 for a 10 km simulation. Add to this the requirement that this be done over a broad band of frequencies for many practical problems, and it becomes even more difficult. To make matters worse, if the objective is to determine the time-evolving nature of the scattering this must be done at many time steps. The size of the problem using exact solutions becomes apparent and leads to the approximations such as the Kirchhoff approximation taken here.

WORK COMPLETED

Ocean Ambient Noise Processing

For the ambient noise processing, two existing data sets were analyzed to determine the improvements possible using adaptive beamforming. One was the Boundary2003 data which had been previously shown using conventional beamforming [1]. The second data set was taken near the island of Elba. The Elba data was particularly interesting because the improvements from conventional to adaptive beamforming were dramatic. Further, there were two occasions where a white-noise gain constraint had additional benefit.

This year we also investigated a fixed array scenario to determine how these ambient noise processing methods performed under various sea-state conditions. This work was carried out in collaboration with Steve Means (Naval Research Laboratory) who deployed the array and collected the noise data. There were several unique features of this data set such as the stable platform for the array (mounted on a steel framed tower), the long term deployment and a video camera to capture the surface conditions during the experiment. The site was fairly shallow (25 m) so some of the conclusions may not apply to deeper water deployments but it did provide some interesting results some of which are presented in the next section.

Modeling and Validating Acoustic Signals Interacting with a Time-Varying Sea-Surface

There were two primary tasks completed on the effort to better understand the effects of platform and sea-surface motion on acoustic propagation at communications frequencies. The first was to complete a set of tests on the numerical models and these are published in the Siderius and Porter (2008). The second task involved at-sea validation. The KAM08 sea-test took place in June 2008 near the island of Kauai. This was a test for the ONR MURI on acoustic communications. For this experiment, the group designed a new set of probe signals based on previous work in the acoustic tomography field. These signals included various maximum length sequences (MLS or m-sequences) and non-linear frequency modulated signals. These provided good sidelobe control without sacrificing transmission power. The approach is to analyze these data for both fixed source-fixed receiver geometry (for observing sea-surface effects) and for moving source-fixed receiver geometries (to observe at higher Doppler shifts). In addition to these probe waveforms, numerous communications type waveforms will be used for the analysis such as FSK (Frequency Shift Key) and OFDM (Orthogonal Frequency Division Multiplexed).

RESULTS

Ocean Ambient Noise Processing

The adaptive processing results are shown in Fig. 1. These data were taken during the ElbaEx experiment in collaboration with the NATO Undersea Research Centre. The array was 5.58 m in length with 32 hydrophones allowing processing the noise up to 4 kHz. The array was drifting so the x-axis in the figure is a proxy for range and the y-axis is the bottom or sub-bottom reflection (in dB). The brightest red line is due to the water-sediment interface and the layers below due to sub-bottom layering. The conventional beamforming (upper left panel) has areas that are poorly resolving layers (or not resolving at all). The MVDR adaptive beamforming (upper right panel) improves the results significantly. There are two small areas in the figure where the MVDR also has poor performance and these are removed when including a white-noise gain constraint on the processing (lower panel). The averaging time for each of the vertical lines making up Fig. 1 is about 1 minute.

The second area we investigated used a fixed hydrophone array with measurements taken in 2006 in the shallow waters (25 m) approximately 75 km off the coast of Savannah, Georgia. These data were collected by Steve Means at the Naval Research Laboratory and analyzed jointly. A Navy tower about 100 m from the array was used to measure wind speed and to observe the sea-surface using a video camera. Data were collected in various environmental conditions with wind speeds ranging from 5—21 m/s and wave heights of 1—3.4 m. Figure 2 shows the measurement geometry in the top panel. The unique features included a stable, long term deployment configuration along with wind speed measurements and a video camera to capture sea-surface conditions. The lower panels of Fig. 2 show situations with and without breaking waves in the duration of the averaging time. The left panel is under calm conditions with no visible breaking waves and there is no evidence of the bottom return. In the right panel there is a breaking wave and there is a clear bottom return. Interestingly, there was, in general enough breaking waves even in the lowest wind conditions of around 5 m/s to produce a bottom return from the noise correlation.

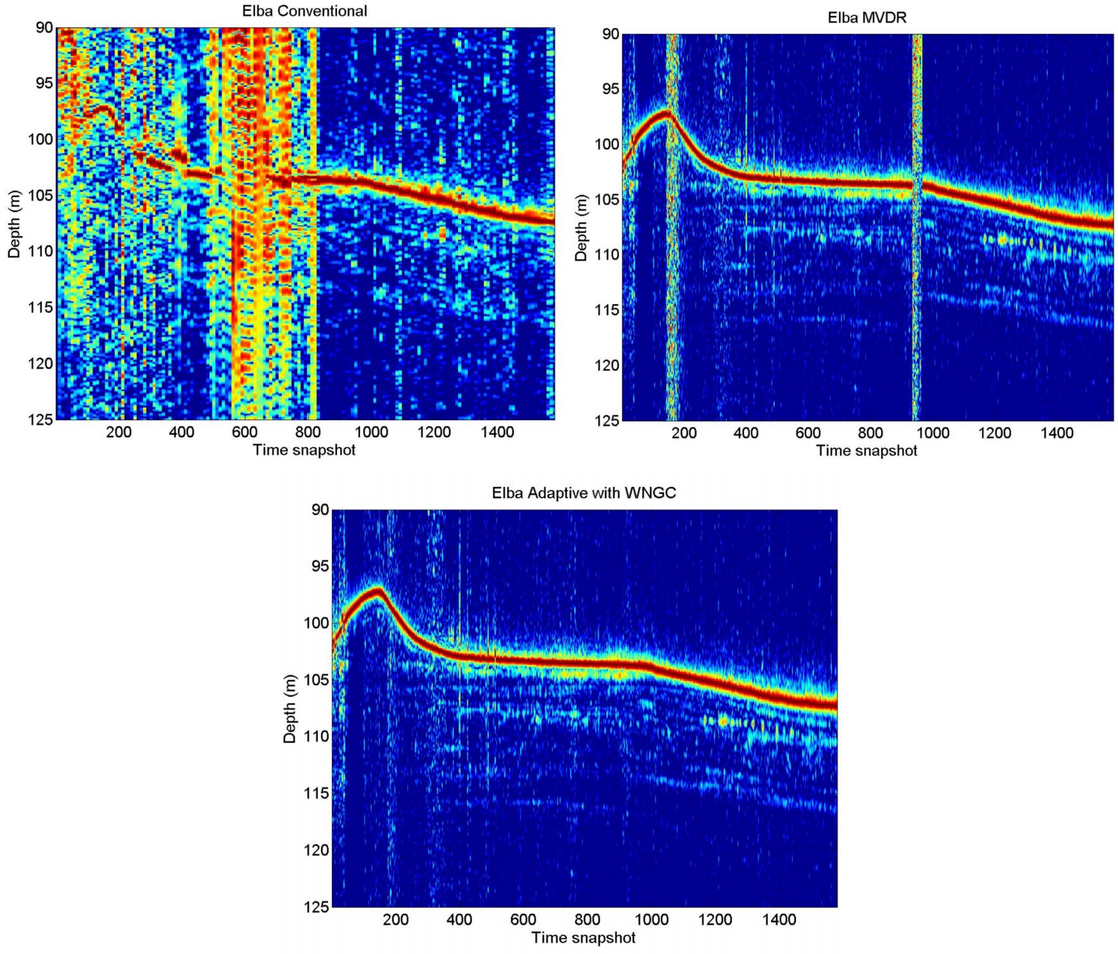

Figure 1: Bottom and sub-bottom layering taken from processed ocean ambient noise measured near Elba Island in the Mediterranean Sea. In each panel the x-axis is time-snapshot which is a proxy for range as the array was drifting. The y-axis shows the bottom return from the bathymetry (strong red return) and the sub-bottom layering (weaker traces below around 105 m). In the top left panel are the results using conventional beamforming. That panel shows significant areas of poor quality. The upper right panel shows the same data processed using MVDR adaptive beamforming and all but two areas are improved. The lower panel uses a white-noise gain constraint and has additional improvements.

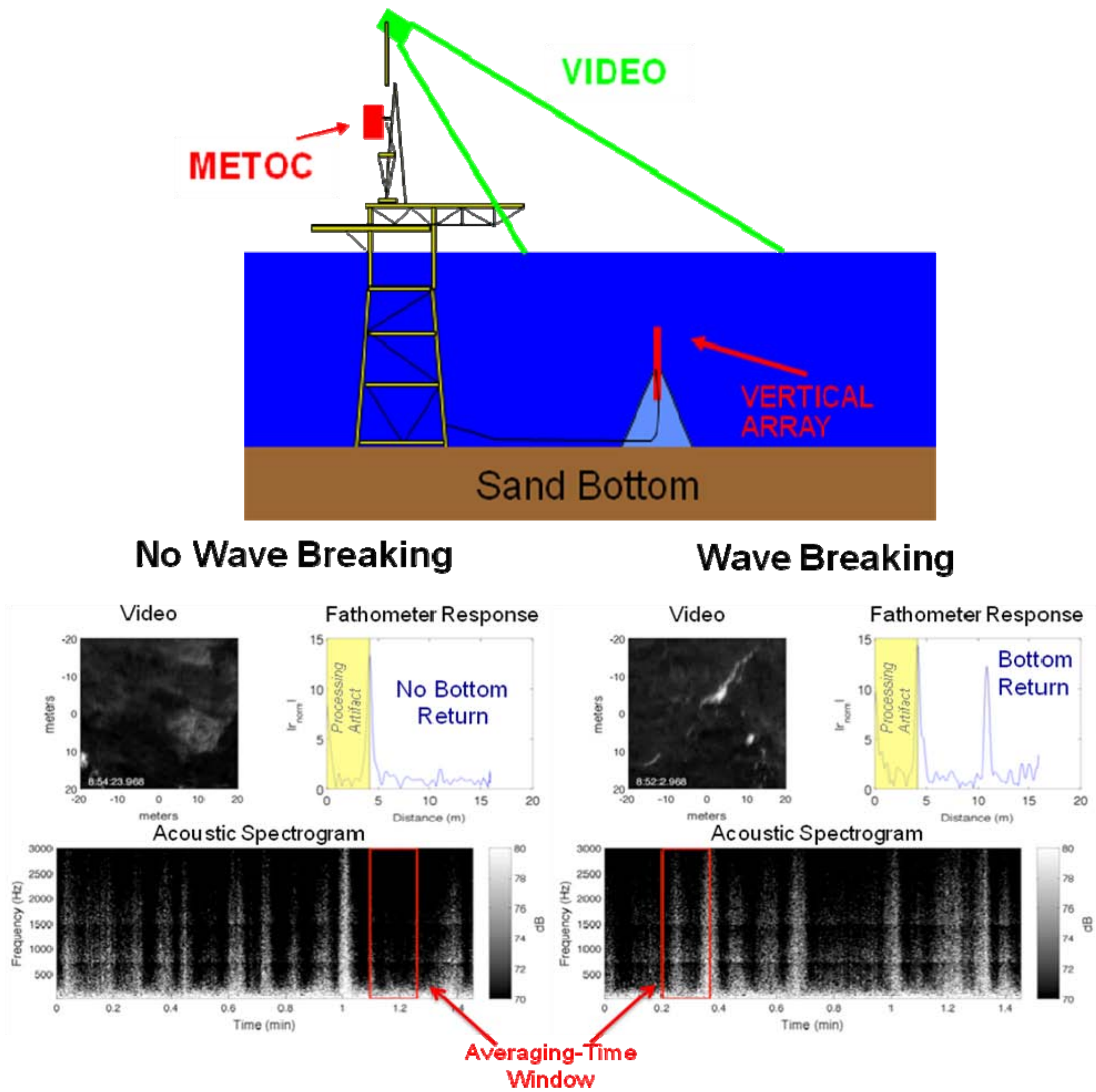

Figure 2: Top panel shows the array and sensor configuration. There were instruments to measure wind speed as well as a video camera to observe the sea surface conditions above the array. The lower panels show the output of the passive fathometer return. On the left is an example where the averaging time does not contain a breaking wave and there is no bottom return. On the right, there is a white-cap breaking and it is captured in the averaging window and there is a clear bottom return.

Modeling and Validating Acoustic Signals Interacting with a Time-Varying Sea-Surface

The details of the modeling effort are presented in Siderius and Porter (2008), however two results from that article are shown here for illustration purposes. The first example uses a rough sea-surface generated using Gaussian filtered white noise. While a Gaussian spectrum isn't the most realistic for the sea-surface it suffices for the purpose of the numerical modeling. In this example, the entire rough sea-surface is moving at 0.25 m/s with an iso-speed water column. The standard deviation of the surface is 1.6 m and the correlation length is 8 m. The source and receiver are separated by 250 m with the source at 30 m depth and the receiver at 40 m. A Doppler sensitive BPSK (binary phase shift key) signal centered at 9.5 kHz is the transmit signal. The surface shape is shown in the top panel of Fig. 3 and the Doppler adjusted, matched-filtered, received waveform in the lower panel. The lower panel of Fig. 3 shows the multipath in time delay (x-axis) and Doppler (y-axis) space. There are indications of Doppler shifts on the multipath as well as various arrivals due to scattering from facets on the surface.

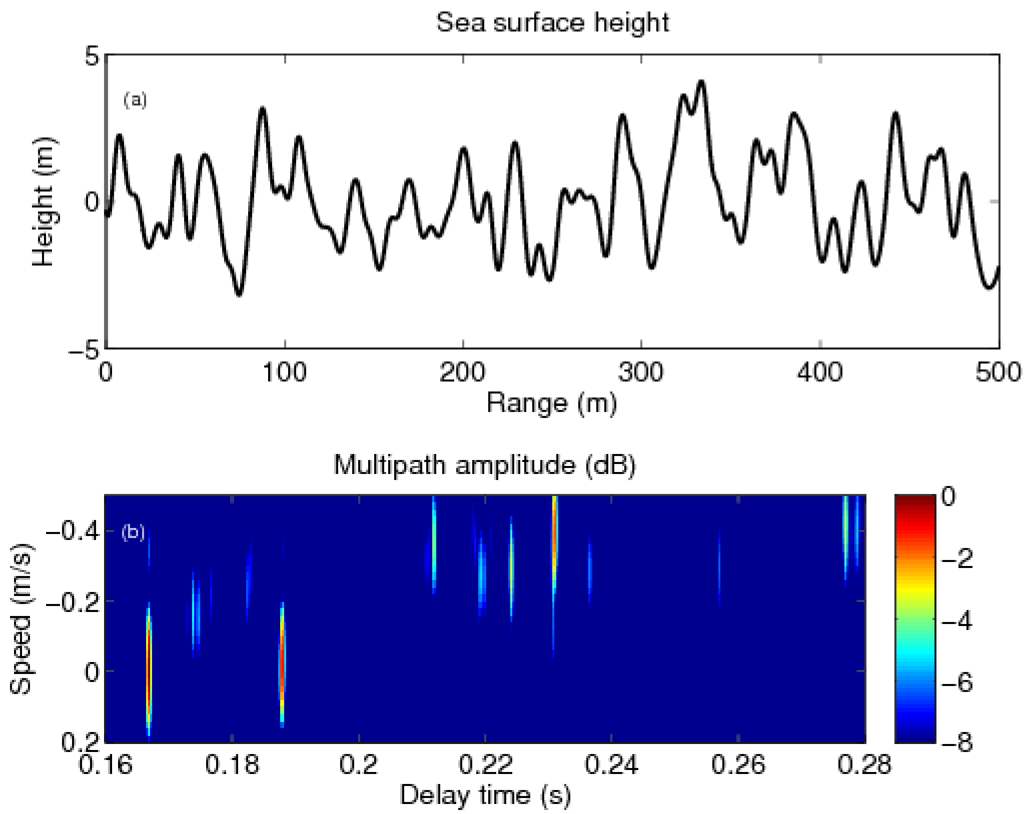

Figure 3: In the top panel (a) the rough surface is shown for the simulation. This surface moves with uniform speed of 0.25 m/s. Shown in the lower panel (b) is the received time-series after applying the Doppler adjusted matched-filter. The spots indicate arrivals with the time-delay along the x-axis and the Doppler speed along the y-axis.

In the second example, a pulse was transmitted from a source at 40 m depth using the band from 50-600 Hz. The time evolution of this pulse is shown in Fig. 4. This example helps illustrate that the model produces the correct pulse shape as well as the reflections from the rough boundary. In this case the surface is rough but not moving.

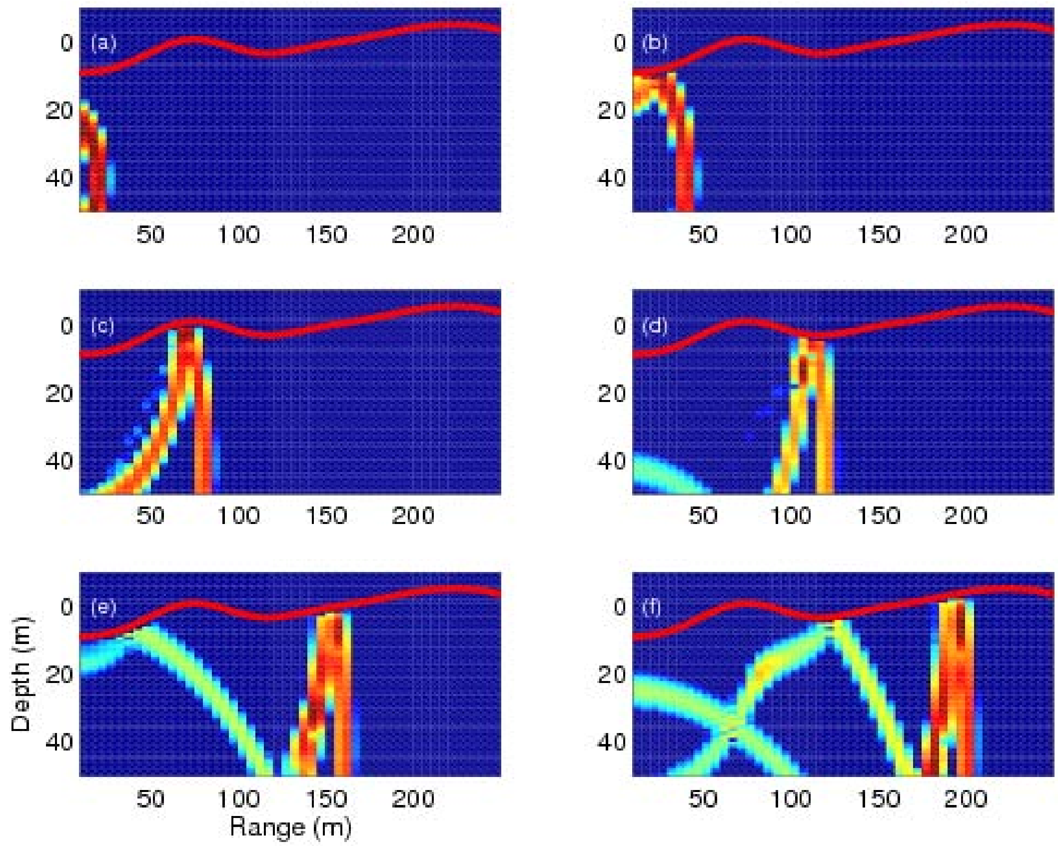

Figure 4: Time evolution of pulse with a rough surface. The x-axis is range and the y-axis is depth. Each panel is a different time as the pulse propagates out in range. The thin line near depth 0 shows the sea-surface shape. Times correspond to the following: (a) 0.013 s, (b) 0.026 s, (c) 0.053 s, (d) 0.079 s, (e) 0.11 s and (f) 0.13 s.

The second part of this work has to do with the validation of our understanding of sound interacting with the rough, time evolving sea-surface. This validation was one of the goals for the KAM08 experiment but results are preliminary since the experiment took place near the end of the 2008 fiscal year. However, the data appear to be of very good quality and the site near Kauai, HI had the expected variations in wind and oceanography to present interesting sets of data to analyze in the coming years. The ray-trace modeling for the site conditions is shown in Fig. 5. The ray trace illustrates the variety of acoustic paths that often occur when there is a downward refracting sound speed profile. Some paths interact with the surface and some do not. Under more mixed water column conditions, the paths tend to all interact with the sea-surface. Figure 6 shows the measured impulse response for a source at 80 m depth, 4 km from the vertical line array that mostly spanned the water column.

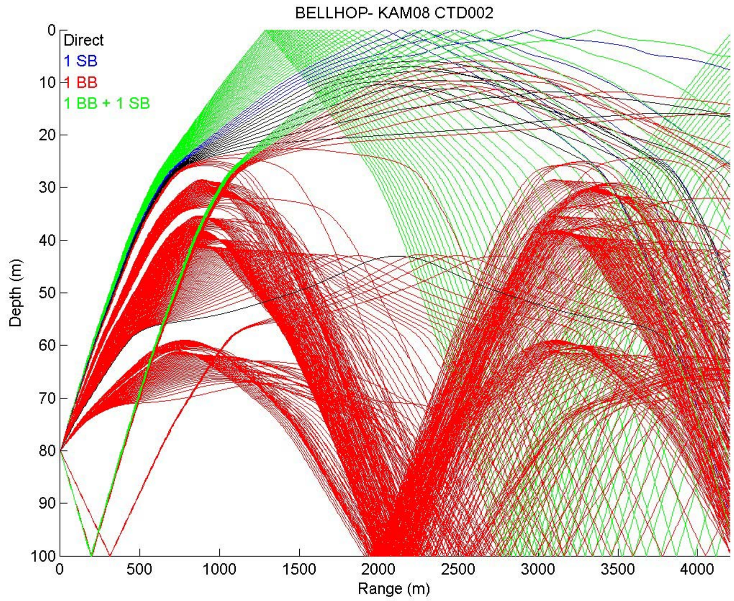

Figure 5: Ray trace modeling for the KAM08 site off the coast of Kauai, HI. The interesting features show that during much of the time there are refracted paths between source and receiver that do not interact with the sea-surface due to the downward refracting sound speed profile. The color coding shows the different path types (black-direct, red-single bottom bounce, blue-single surface bounce and green-one surface and one bottom bounce path).

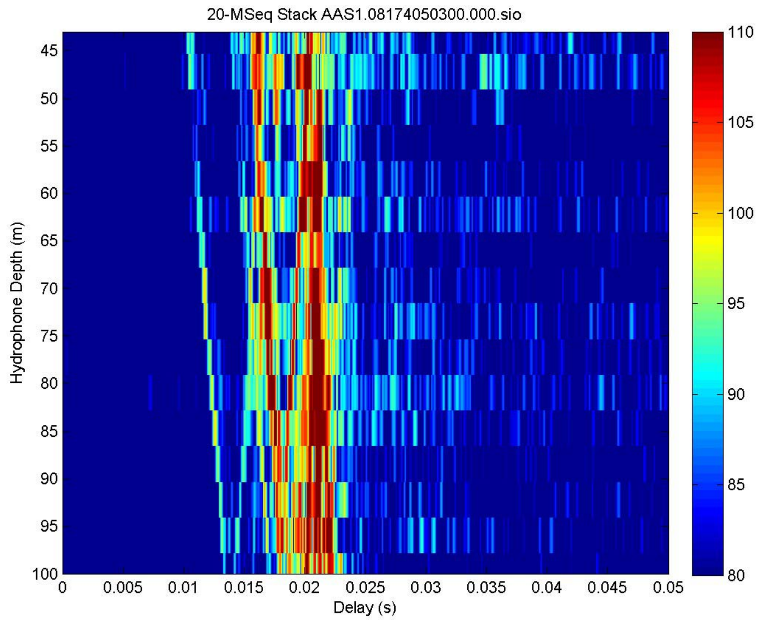

Figure 6: Channel impulse response reception during KAM08 on the vertical line array from a single transducer on the source array (JD 174 050330 UTC). The VLA was at Sta08 4 km from the source array on (transducer #8 at 80 m depth was used here). Coherent integration of 20 MLS transmissions.

IMPACT/APPLICATIONS

This work may have a significant impact on several Navy sonar systems (e.g., ASW, MCM, underwater acoustic communications). Knowing the seabed properties will improve at-sea situational awareness by being able to accurately predict acoustic propagation. And, because this is a passive method it can be designed into a system used for covert activities, low power applications and can be used even in environmentally restricted areas.

TRANSITIONS

Results of this research are being developed under the Ocean Bottom Characterization Initiative (PMW-120). This involves developing an sensor (over the next several years) that is based on techniques described here and will initially be deployed by the Naval Oceanographic Office. These techniques are also being included as part of a Phase II SBIR (Progeny Inc.) to develop a passive seabed characterization sensor.

RELATED PROJECTS

This research has done in close collaboration with Michael Porter and Paul Hursky (HLS Research) also supported by ONR. We have also been collaborating with Steve Means at the Naval Research Laboratory, Chris Harrison at the NATO Undersea Research Centre, La Spezia Italy and William Hodgkiss, Hee Chun Song and Peter Gerstoft at the Marine Physical Laboratory at the University of California, San Diego.

REFERENCES

1. Martin Siderius, Chris Harrison and Michael Porter, "A passive fathometer technique for imaging seabed layering using ambient noise", *J. Acoust. Soc. Am.*, **120**, 1315-1323, (September, 2006).

PUBLICATIONS

1. Martin Siderius, "Analysis of passive seabed imaging techniques" (A), *J. Acoust. Soc. Am.* 123, 3629 (July 2008).

2. Martin Siderius and Michael Porter, "Modeling broadband ocean acoustic transmissions with time-varying sea surfaces", *J. Acoust. Soc. Am.*, **124** (1), 137-150, (July 2008).

3. Chris H. Harrison and Martin Siderius, "Bottom profiling by correlating beam-steered noise sequences" *J. Acoust. Soc. Am.*, **123** (3), 1282-1296, (March 2008).

4. Peter Gerstoft, William S. Hodgkiss, Martin Siderius, Chen-Fen Huang and Chris H. Harrison, "Impact of spatial aliasing on the use of coherent ambient noise processing for estimation of seabed layering", *J. Acoust. Soc. Am.*, **123** (3), 1297-1305, (March 2008).

5. Michael B. Porter, Martin Siderius, and Paul Hursky, "Gaussian beam tracing for high-frequency acoustics" (A), *J. Acoust. Soc. Am.* 123, 3749 (July 2008).