

## Shallow Water Propagation and Surface Reverberation Modeling

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### LONG-TERM GOALS

The primary long term goals are to measure and model high frequency acoustic propagation and scattering near the sea surface. Processes of particular interest are scattering from surface gravity waves and the effect of whitecaps and bubble clouds on underwater acoustic communications. A secondary long term goal is to exploit measurements of breaking wave noise to infer bubble cloud populations at the sea surface. These original goals have been augmented in 2013 to study ambient noise from glaciers in high latitude regions.

### OBJECTIVES

#### *Objectives for 2013*

The overall program objectives are reproduced below for completeness. Program objectives specific to work in 2013 were to: (1) continue the work of Berry (1972) to deduce the form of surfaces from scattered sound and (2) to measure and analyze the underwater ambient noise marine terminating glaciers in high latitude regions.

Berry's research focused on determining the structure of sea ice from scattered sound. He determined some of the basic physical constraints that would limit an inversion method based on reflected pulses interacting with a rough ice surface, but did not present any actual inversions for surface shape. Our objective has been to extend this work to actually determine surface shape from scattered acoustic pulses, and compare the results with experiment.

The study of undersea ambient noise in the Arctic is extensive and extends back to the 1960's, with early results focusing on noise associated with processes in the ice margin. Much of the work on Arctic noise since has been concerned with the generation, propagation and statistical properties of noise generated by sea ice, consistent with the observation that the interaction of the ice cover with the air and water boundary layer is the primary source of noise. More recently, there has been a growing interest in the underwater noise in Arctic fjords, particularly those that contain the terminus of one or more glaciers. The program objective was to measure the directionality of underwater ambient noise in a glacial fjord in Spitzbergen and characterize the noise directional properties in terms of frequency band and generating mechanisms.

### *Original Program Objectives*

The primary goals of this 3-year program of research are to: (1) measure the amplitude, time delay and Doppler shifts associated with high-frequency, forward scattering from surface gravity waves and (2) continue the development of the Wavefronts time-domain propagation code to model surface scattering.

The standard approach to modeling high-frequency, forward scatter from the ocean surface is to use statistical methods. Surface arrival intensities, for example, are often characterized in terms of probability density distributions. This approach has the advantage that deterministic details about the physical properties of the surface wave field do not need to be known. We have taken an alternative approach and have the objective of measuring and modeling surface reverberation deterministically. Our objectives are to build computationally efficient, deterministic models of scatter from surface gravity waves and to measure the second order statistics relating sound focusing by gravity waves and wave-induced Doppler shift.

## **APPROACH**

The technical approach for 2013 is divided between the analysis of an existing oceanic dataset, a scale model laboratory experiment, and two field deployments; 1) as part of the TREX13 campaign, and 2) a field deployment in Brepollen fjord, Spitzbergen.

### *Dataset analysis*

As part of the deterministic analysis of the forward-scattering of acoustic energy from surface gravity waves, data from the SPACE08 campaign is being analyzed to study the connection between sound intensification and wave shape. The analysis is based on a time domain form of the Helmholtz-Kerchoff integral for scattering and an iterative, perturbation technique that systematically alters wave shape until agreement between observed and modelled reflected pulses is found.

### *Scale model laboratory experiment*

A scale model laboratory experiment was conducted to test the code and computer algorithms used in the dataset analysis described above. The project report in 2012 described a scale model experiment whereby 300 kHz pulses were transmitted between a source receiver pair and scattered from surface gravity waves generated along the transmission path. One of the outcomes of that study was an expectation that the use of multiple receivers would improve the ability to reconstruct surface shape from scattered sound, and this experiment was designed to test that hypothesis.

### *TREX13*

Our task in the TREX13 campaign was to characterize surface reverberation conditions during wind-driven seas using remote observations of whitecaps. Whitecaps are a visible consequence of bubble entrainment by wave breaking and are expected to be a robust indicator of the importance of bubbles in modifying forward-scattered sound from the sea surface. Our observing system consisted of a high-frame rate, high-resolution camera mounted on the mast of the R/V Hugh R. Sharp looking down at the ocean surface. Images from the system were collected with a high storage capacity computer system. Two GPS receivers were mounted midship to provide ship heading and speed.

### *Arctic ambient noise*

A month long field campaign was undertaken in Brepollen fjord, Spitzbergen. The work was based out of the Polish polar station located approximately 1 mile from Hans glacier. The measurement system

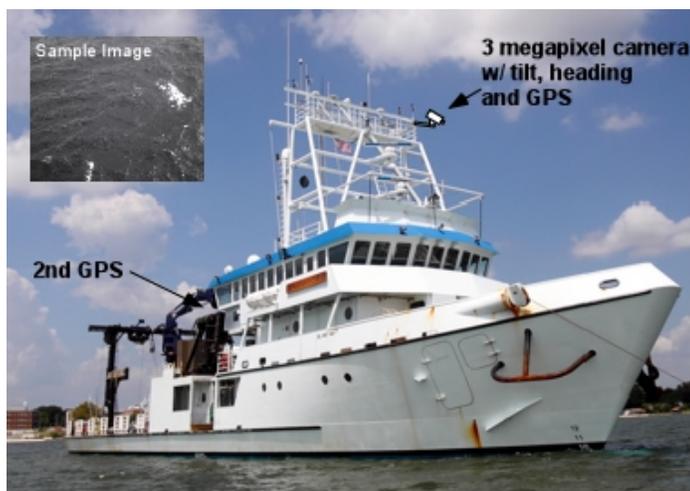
(the directional acoustic buoy or DAB) consisted of two broad-band hydrophones mounted on a vertical mast that was deployable from a small boat. The mast topside included a GPS receiver, a magnetic compass, and roll and tilt sensors. Signals from the hydrophones were recorded on digital audio tape along with data from the orientation and navigational systems. DAB was used to map the frequency dependent directivity of ambient noise in the fjord at 8 locations throughout the fjord and on 4 separate days.

## WORK COMPLETED

This report concludes the third year of the three year period of investigation. Four significant objectives have been completed during this period: 1) the acquisition of whitecap data during the TREX13 deployment to support the interpretation and analysis of shallow water, surface scattered acoustic signals, 2) the collection and initial analysis of ambient noise data in a high latitude fjord containing a marine terminating glacier, 3) a laboratory study of sound reflected from surface waves to study sea surface shape through reflected acoustic pulses using multiple receivers has been completed and 4) data from the SPACE08 campaign has been analyzed and modeled to study the role of wave-induced surface bubbles on absorbing and scattering underwater acoustic signals reflected from the sea surface.

### *Acquisition of whitecap data during TREX13 deployment*

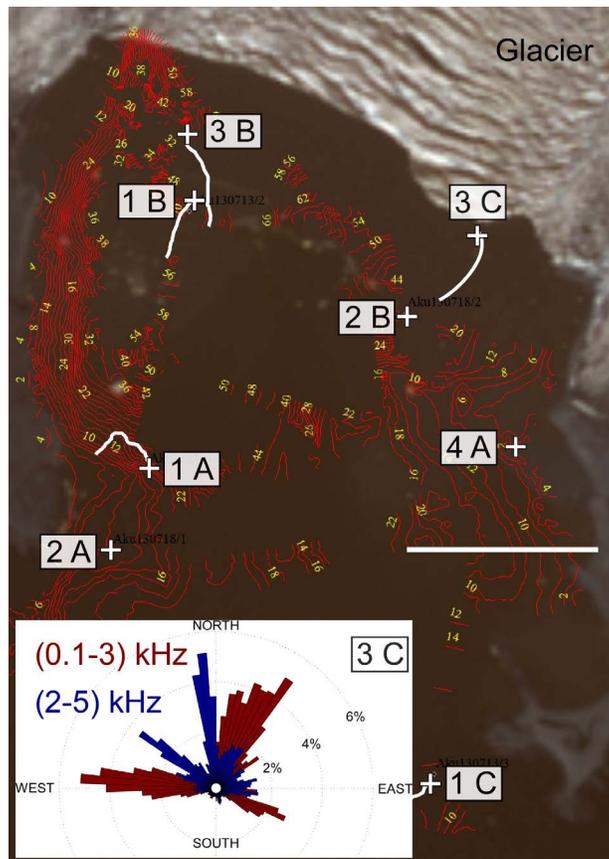
The data acquisition system described in the approach section was successfully deployed on the R/V Sharp and used to acquire roughly 1 TByte of image data documenting sea surface state during a variety of meteorological conditions. The camera and GPS locations are shown in Figure 1 along with an inset sample image taken during the experiment. Data products from this system, such as wave breaking rate and whitecap coverage, will be processed and offered to any interested participants in the TREX13 experiment. The integration of this dataset with acoustic transmissions and other environmental measurements will be discussed at the TREX13 workshop to be held Dec 7-8, 2013 in San Francisco.



***Figure 1. Image acquisition system for monitoring surface conditions during the TREX13 campaign on the R/V Hugh R. Sharp. A sample image from the experiment is inset in the top right of the figure. This data will help interpret the characteristics of sound scattered from the surface during different meteorological conditions.***

### Glacial ambient noise

This experimental campaign was undertaken and successfully completed in August 2013. An overview of the sites at which recordings were made in Brepollen fjord are overlaid on a picture of the terminus of Hans glacier in Fig. 2. Note that the satellite image of the glacier was taken in 2010 and the 2013 terminus is actually located further north, thus measurement location 3C was actually considerably further from the terminus than appears in the image. The inset at the bottom of the figure shows a rose plot of the ambient noise directionality measured at location 3C in 2 frequency bands: (0.1-3 kHz) in red and (2-5 kHz) in blue. The rose plot shows that the underwater ambient noise field is both highly directional, and the directionality is a function of frequency. Our working hypothesis for this result is that different physical mechanisms generating the noise are associated with distinct spectral bands and are distributed non-uniformly in space.



**Figure 2.** A summary of deployment locations during the Arctic ambient noise survey campaign in August, 2013. Approximately 30-60 minutes of data were collected at each deployment site labeled 1A through 4A using the Directional Acoustic Buoy described in the text. The white tracks indicate the boat path during recording, and the horizontal, white scale bar marks 500 m. The sites are placed on a satellite image of Hans Glacier taken in 2010. The red lines annotated with yellow numbers are depth contours in the fjord in m. The inset at the bottom left of the figure shows a sample of ambient noise data taken at site 3C close to the glacier front. The noise has been divided into two frequency bands (blue and red) and processed into arrival angle.

### Laboratory study of surface scattered sound and analysis of SPACE08 data

The 2012 project report describes the creation of an inversion algorithm to determine the shape of the ocean surface from the interference structure of reflected acoustic pulses and the successful application

of that algorithm to a high frequency scale model tank experiment. The additional work completed during this reporting period is the successful completion of a second scale model experiment to study the benefits of using multiple receivers in the inversion algorithm. In addition surface reflected data from the SPACE08 field campaign has been analyzed using the surface scattering model and inversion algorithm. The inversion of field data is considerably more challenging than data from scale model tank experiments, but is expected to yield unique insights into surface scattering. For example, we are hoping to separate the effects of coherent gravity wave focusing, scattering from small scale surface roughness, and the scattering and absorption due to sub-surface bubble clouds under wind-driven seas. This data analysis is in an early phase but is yielding promising results for relatively benign conditions with low winds and moderate swell.

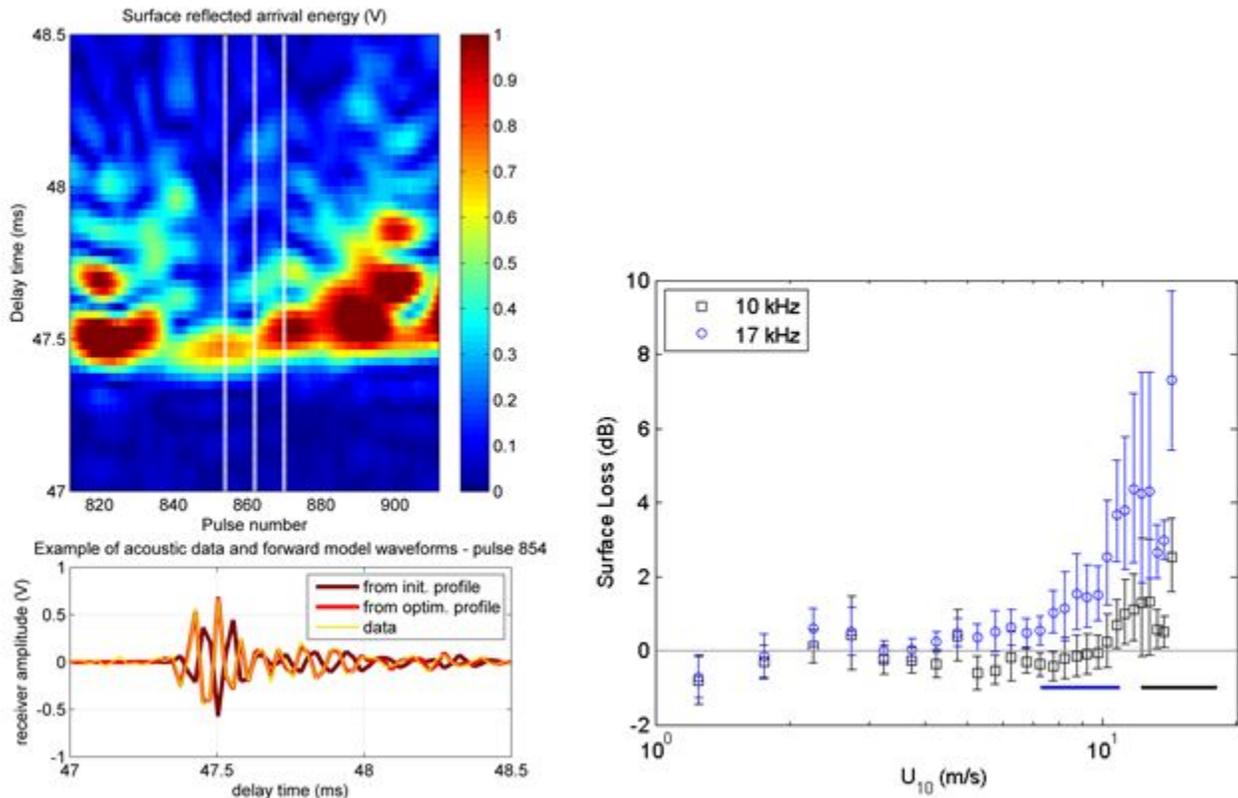
#### *SPACE08 data analysis*

Anecdotal data on the performance of mid-frequency underwater communication systems suggest that the underwater communications channel under wind driven seas is more benign than calm seas. One hypothesis to explain this observation is that bubbles entrained by wind-driven wavesbreaking scatter and absorb acoustic signals incident on the surface, thereby reducing surface reverberation. Since surface reflected energy is both scattered and Doppler shifted by gravity waves, its removal can improve the performance of communications systems. Motivated by this process, a model of bubble entrainment by near surface turbulence has been formulated and compared with SPACE08 transmission data. The results of this model and comparison with observation are presented in the Results section.

## **RESULTS**

#### *Deterministic study of surface scattered sound*

Figure 3 shows a key result from the analysis of SPACE08 data. The top, left plot shows amplitude of surface-reflected pulses as a function of delay (vertical axis) and pulse number (horizontal axis). The red regions indicate the arrival of wave-focused energy. The 3 vertical, white lines are times for which the surface shape was inverted. The three graphics to the right show the inversion for surface shape. The brown line shows surface elevation versus horizontal range estimated using the pulse arrival time and pseudo-harmonic analysis. The red line shows the optimized surface elevation determined from the shape of the surface-scattered pulse and the gray line shows the confidence interval for the inversion – a narrow gray band indicates high confidence. The blue line shows the region of a Fresnel zone, which is where the inversion is expected to be accurate. Away from the Fresnel zone, the confidence in the inversions is low, and the red line is unlikely to accurately represent the actual shape of the surface. The pattern of surface curvature in the three inversions around the Fresnel zones agrees well with the curvature expected from the pattern of arrivals in the color contour plot (2 focal regions separated by a trough). This result demonstrates that the surface inversion technique can be applied to ocean data, despite the complications of 3D wave fields and sub-surface bubble clouds. This new technique will provide a powerful tool for studying the connection between surface shape and the amplitude and Doppler statistics of surface reverberation, with application to underwater acoustic communications.



**Figure 3. Inversion of ocean acoustic data for wave shape. See preceding text for details of graphics.**

#### *Screening of the surface by wave-induced bubbles*

Figure 4 shows observations of surface screening by wave-induced bubbles using data taken through the SPACE08 campaign. Each symbol shows average surface bounce loss as a function of wind speed at 10 kHz (black squares) and 17 kHz (blue circles). The data show a rapid increase in surface bounce loss for wind speeds above roughly  $8 \text{ m s}^{-1}$ , with losses at 17 kHz rising more rapidly and earlier than losses at 10 kHz. The increase in surface bounce loss with increasing frequency is partly due to the scattering and absorption of sound by bubbles trapped directly beneath the surface by fluid turbulence. When present in sufficient concentration, absorption and scattering by bubbles has the effect of screening the surface from incident sound. The horizontal blue and black lines show model calculations of the range of wind speeds over which the screening effect is expected to take place. The reasonably good agreement between data and model indicates that the model is suitable for use as a tool for underwater communications performance prediction.

Figure 3. A summary of surface bounce loss data taken during the SPACE08 campaign. Surface loss in dB is plotted as a function of wind speed for 10 kHz (black squares) and 17 kHz (blue circles) pulses. A transition from low loss to high loss can be seen at around approximately  $8 \text{ m s}^{-1}$  at 10 kHz and  $10 \text{ m s}^{-1}$  at 17 kHz. The blue and black horizontal lines show model calculations of the expected range of winds speeds for the transitional behavior.

## IMPACT/APPLICATIONS

The analysis and modeling of the SPACE08 data has application to the development of a predictive capability for underwater acoustics performance and improved algorithms for acoustic communications systems. The scale model experiments further our understanding of focussing and Doppler shifts induced in scattered sound by surface waves and will be used to study the second-order statistics relating these two effects. The bubble model predicts ‘regime shifts’ in the underwater acoustic environment, and has practical application to determining optimal source-receiver geometries in different meteorological conditions.

## RELATED PROJECTS

A100530: Underwater acoustic propagation and communications: a coupled research program.

## PUBLICATIONS

- Callaghan, A. H., G. B. Deane, M. D. Stokes and B. Ward, “Observed variation in the decay time of oceanic whitecap foam,” *J. Geophys. Res.* **117** C09015 doi:10.1029/2012JC008147, 2012 [published, refereed].
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- Walstead, S. P. and G. B. Deane, “Reconstructing surface wave profiles from reflected acoustic pulses,” *J. Acoust. Soc. Am.*, **133**, 2597-2611, 2013 [published, refereed].
- Deane, G. B., J. C. Preisig and A. C. Lavery, “The suspension of large bubbles near the sea surface by turbulence and their role in absorbing forward-scattered sound,” *IEEE J. Ocean Eng.*, 10pp, 2013 [In press, refereed].