Shallow Water Propagation and Surface Reverberation Modeling

Grant B. Deane
Marine Physical Laboratory, Scripps Institution of Oceanography
UCSD
La Jolla, CA 92093-0238
phone: (858) 534-0536 fax: (858) 534-7641 email: gdeane@ucsd.edu

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http://www.mpl.ucsd.edu/people/gdeane/overview/overview.html

LONG-TERM GOALS

The primary long-term goal is to measure and model high-frequency acoustic propagation in the presence of surface gravity waves and breaking waves to better understand the effects of surface reverberation on shallow water, underwater acoustic communications (ACOMS). Secondary long-term goals are to exploit measurements of breaking wave noise to infer bubble cloud populations at the sea surface and their effect on reverberation, and to model high-frequency, forward scattering from sea ice. These original goals have been augmented in 2012 to study the effects of bubbles on surface reverberation through the analysis of surface video footage of breaking waves.

OBJECTIVES

Objectives for 2012
The overall program objectives are reproduced below for completeness. Program objectives specific to work in 2012 were to: (1) continue the work of Berry (1972) to deduce the form of surfaces from scattered sound and (2) study the physical and (inferred) acoustical properties of sub-surface bubble plumes from remote images of breaking waves.

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. This work will be used to help interpret field data of bistatic scattering from sea ice cover and calibrate approximate analytical and numerical acoustic models used to compute bistatic scattering.

The clouds of bubbles entrained at the sea surface by breaking waves are an important topic in underwater acoustics. Waveguide reverberation (i.e. reverberation in shallow water or through a surface duct) typically includes a significant fraction of energy scattered from the sea surface. Because bubbles have large acoustical scattering cross-sections relative to their geometrical cross-sections, even relatively diffuse clouds of bubbles can have a significant impact on surface-reflected sound. Little data exists on the penetration depth and residence time of the relatively large bubbles (order 0.3 mm radius) resonant at acoustic communications frequencies. Traditional probing techniques, such as high

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frequency backscatter sonar, track smaller bubbles (order 0.03 mm radius), which are less buoyant and resident in the upper ocean for much longer times. An alternative approach is to photograph the bubbles as they rise to the surface and study the persistence of the resulting foam patches. Our objective is to study the physical and acoustical properties of sub-surface bubble plumes active at frequencies in the band 5 - 30 kHz using surface photography.

Original Program Objectives
The primary goals of the 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 (described below).

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. However, this lack of knowledge can also be a disadvantage if propagation models and underwater acoustic communications systems algorithms do not incorporate all the relevant scattering physics. For example, the transient focal regions created by surface swell over short ranges contain micro-paths with regular patterns of significant, time-varying Doppler shifts, which introduce errors into channel equalizers. The result is a decrease in ACOMS performance in what would appear to be a benign environment (short propagation range with swell and low wind speed). These micro-path properties only become obvious when individual wave-focused arrivals are studied.

An alternative approach is to measure and model surface reflections as a deterministic process. This approach allows the properties of surface-reflected arrivals to be studied in detail and ensure that the physics of surface scatter is adequately understood. 'Adequate' in this context means with sufficient insight to predict the performance of ACOMS systems in a variety of shallow-water and surface conditions. Ultimately, detailed information about the ocean surface is discarded, but only after the deterministic physics underlying statistical formulations has been proven. This study is necessary because of the complexity of surface scattering. Surface waves range in scale from centimeters for gravity-capillary waves up to 100's of meters for swell, and break over a range of scales depending on fetch and wind speed. Breaking waves also inject bubbles into the upper ocean boundary layer, which have a spatially-diverse and frequency-dependent impact on surface reverberation. There is no complete physical model describing these processes. Ultimately, the validity of assumptions about surface scattering processes built into propagation models and ACOMS algorithms need to be assessed against the real ocean, and deterministic studies are one means of doing this.

A secondary goal is to use the underwater noise radiated by whitecaps to infer breaking surface wave characteristics, bubble distributions, and their impact on surface reverberation. Whitecap formation is accompanied by broad-band underwater noise that contains information about bubble creation rates at the sea surface. Recent advances in our understanding of noise generation have created the possibility of inverting the noise for bubble creation rates at the sea surface. If this can be accomplished, it would allow communications devices to infer probable surface scattering conditions from the properties of the ambient noise field.

APPROACH

The technical approach for 2012 is divided between the analysis of existing field data sets, two scale-model laboratory experiments and a theoretical analysis.

Data Set Analysis. The photographic investigation of sub-surface bubble plumes is based on data collected during the Surface Processes and Acoustic Communications Experiment in October and November of 2008 (SPACE08). Digital sea surface images were acquired using a 5 mega pixel Arecont Vision digital CCD camera with a 17.5 mm lens, mounted on the Woods Hole Oceanographic Institution Air Sea Interaction Tower (ASIT) at a height of 23 m above the mean sea level and an angle of 59^o from the nadir. The mean image footprint was 339 m^2, which varied by ±5% depending on the water depth at the ASIT, resulting in a mean pixel resolution of less than 1 cm^2. The image sampling frequency varied from 3 - 6 fps. Three days with images suitable for analysis were chosen from the total dataset, covering a range of wind speeds from about 5 - 14 ms^{-1}. Camera images were analyzed using a computer automated whitecap thresholding technique followed by foam patch identification and quantification. Foam area was computed for each selected breaking event, providing a time series of foam area growth and decay.

Scale Model Laboratory Experiments. Two seperate experiments scale model experiments were contucted to study the connection between sub-surface bubble plumes and the reconstruction of surface wave profiles from scattered sound. The sub-surface plume experiment was carried out in the glass-walled wave channel at SIO. A range of breaking types from spilling through plunging were generated, and the sub-surface and surface patterns of air entrainment were recorded with high-speed imaging cameras. The idea here is to draw quantitative conclusions about the physics controlling the observed patterns of foam decay in the SPACE08 field data (described above) through laboratory observations of foam and sub-surface bubble plumes generated by breaking waves. When combined with observations of bubble size distributions within the bubble plumes (taken as part of earlier experiments), this data also provides a means of calculating the acoustical properties of the sub-surface bubble plumes.

The second experiment was a scale model tank experiment (also conducted in the glass-walled wave channel) to test the surface shape inversion work that extended Berry's echo-based studies of ice shape. These acoustic scattering experiments were carried out at a range of frequencies between 100 - 300 kHz using ITC 1089D spherical transducers. Sound scattered from surface gravity waves generated by a mechanical flap at one end of the wave channel was recorded along with wire wave gauge measurements of the water surface elevation. The overall approach here is to test the acoustic model and surface shape inversion algorithm using reverberation from a real surface in a controlled environment.

WORK COMPLETED

This report concludes the second year of a three-year period of investigation. Three significant objectives have been accomplished during this period: (1) the analysis of SPACE08 whitecap data and a laboratory study of breaking waves to study the physical and acoustical properties of wave-induced bubble clouds, (2) a laboratory study of sound reflected from surface waves to study the measurement of sea surface shape through reflected acoustic pulses has been completed and (3) an algorithm to determine surface shape from reflected sound pulses has been formulated and verified using an existing data set.

The Analysis of SPACE08 Whitecap Data and Laboratory Flume Study

As the surface expresison of sub-surface bubble clouds, whitecaps provide a valuable tool for improving our understanding of the acoustical properties of the ocean surface. The analysis of whitecap decay times is a relatively new activity; previous studies have been anecdotal and limited to less than a dozen images. The completed study consists of decay time curves for 552 discrete wave breaking events. The analyzed breaking events have also been analyzed to provide an estimate for the Phillips parameter, which provides information about the wave breaking kinematics. Following the decay time analysis, two hypotheses for the behavior of whitecap decay were proposed. These hypotheses (discussed in the results section) were tested in the laboratory flume study. The flume experiment was designed to enable us to relate the surface properties of whitecaps to the sub-surface bubble plumes entrained by spilling and plunging seawater waves. The experiment was divided into surfactant-free and surfactant-added phases to study the effects of seawater chemistry on foam persistence. A sequence of breaking events using a mechanically-generated wave packet of specified amplitude, slope and underlying horizontal scale were executed during each phase. A total of 20 breaking events were analyzed into time series of foam patch area and cross-sectional area of bubble plume.

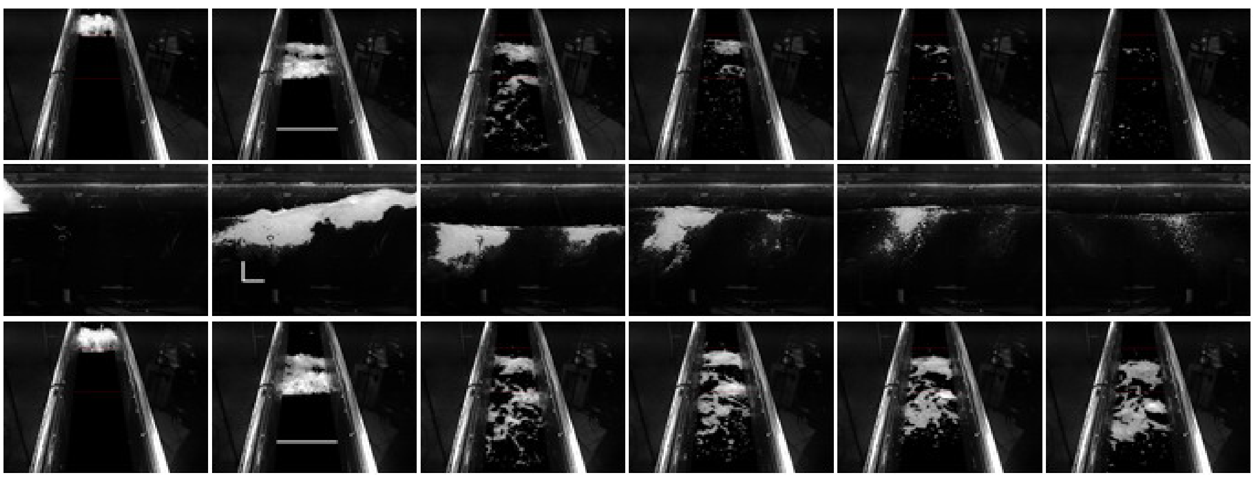

Figure 1. A film strip of images of breaking waves from an overhead and side-view camera in the laboratory flume study. Consecutive images in each row are separated in time by 2/3 s. The middle row shows the bubble plume images as seen through the side wall of the flume. The top and bottom rows show surface foam without (top row) and with (bottom row) the addition of a surfactant to stabilize the foam. The horizontal white lines in the second image from the left in the top and bottom rows are 42 cm in scale. The length of the tank in these images is 2.8 m. The horizontal and vertical white lines in the second image in the middle row are 10 cm in scale. These images show that surface foam and sub-surface bubble plume persistence times are the same in the absence of surfactants. When surfactants are present, surface foam persists on time scales longer than the sub-surface plumes.

Determining Surface Waves from Acoustic Transmissions

The work completed in this phase of the project consists of: 1) the creation of an inversion algorithm to determine the shape of the ocean surface from the inteference structure of reflected acoustic pulses, 2) the successful application of the algorithm to an existing high-frequency, scale model tank experiment and 3) the completion of a second experiment to test some critical concepts that arose during the first data set analysis, which are discussed in detail below.

RESULTS

Analysis of SPACE08 Whitecap Data and Laboratory Flume Study

A key result of the SPACE08 data analysis and flume study is shown in Fig. 2. This figure shows that, in the absence of surfactants, the lifetime of sub-surface bubble plumes is strongly correlated with the persistence of surface foam. This is true for high air-fraction bubble plumes containing large (> 0.3 mm radius) bubbles that are acoustically relevent to surface scattering at underwater acoustic communications frequencies. A major impediment to studying these plumes has been their transient and shallow nature, making imaging with sonar systems difficult. In fact, despite their importance to surface reverberation, very little is known about how their penetration depth and persistence vary with wind speed and sea state. Considerably more is known about the plumes of small bubbles (< 0.1 mm radius) that persist on time scales of 100's of seconds, but they are less significant acoustically in the 10 kHz - 30 kHz frequency band than the denser plumes under study here. These results open the door to studying sub-surface bubble plumes through images of surface foam, which are relatively easy to collect. When coupled with measurements of near-surface fluid turbulence, analysis of whitecap imagery will enable us to predict transitions in surface scattering regimes (from wave-dominated to bubble-screened) as a function of wind speed and and acosutic frequency.

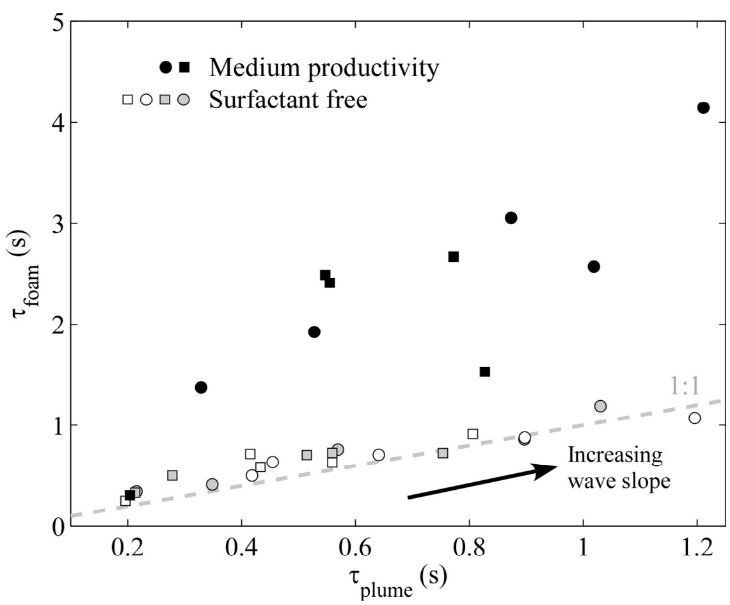

Figure 2. A scatter plot of foam decay time versus plume decay time for various wave slopes in surfactant-free (open and gray filled symbols) and surfactant-present (black filled symbols). Surfactant concentration in the surfactant-present study was equivalent to concentrations in oceanic regions of medium biological productivity. Values of sub-surface bubble plume decay time were varied by varying the slope of the breaking wave generating the foam and bubble plume. Circles and squares correspond to waves of different horizontal scale. The dashed, gray line represents a 1:1 correspondence between foam and plume decay times.

Determining Surface Waves from Acoustic Transmissions

A key result of the surface inversion work is verifying that surfaces can be reconstructed accurately only in a Fresnel zone around specular reflection points. This is illustrated in Fig. 3. A means to circumvent this limitation is to use multiple receivers, thereby introducing more specular reflection points along the surface. This addition to the inversion method has been tested with an additional experiment, but the data is still under analysis.

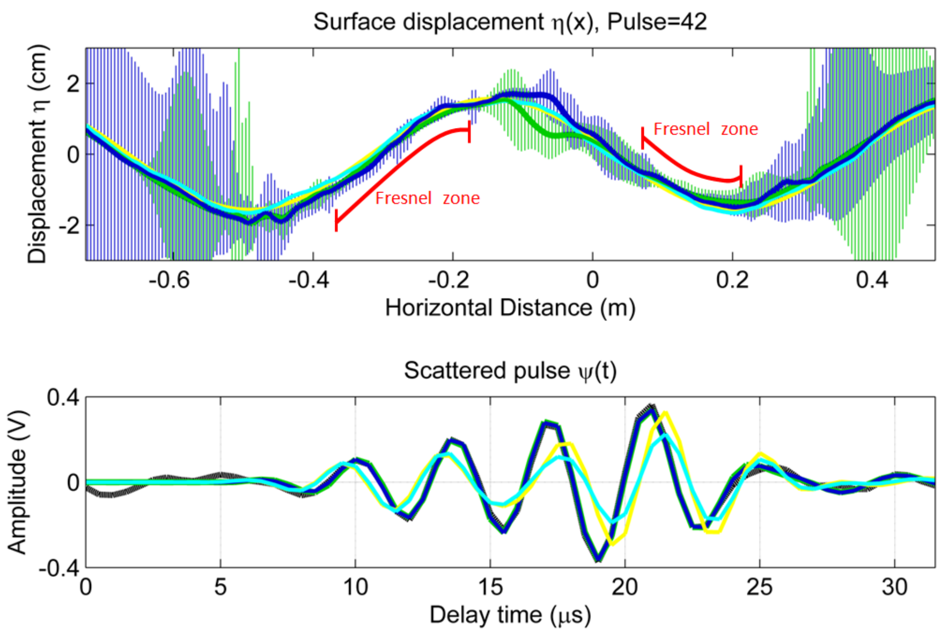

Figure 3. Example of a surface profile inversion from the scale model tank experiment. The top plot shows the reconstructed wave from an initial profile of a sine wave (green line) and wire wave gauge measurements (blue line). The yellow and cyan lines show the initial sine and wave gauge profiles. Vertical lines show the level of uncertainty in the inversion. The bottom plot shows the observed and reconstructed pulse shapes when scattered from the surface. This example shows two isolated specular reflection points with highly divergent optimized surface profiles between the two Fresnel zones. Even though the optimized scattered signals in the lower panel are in very good agreement, the diverging optimized surface profiles around $x = -.1$ m illustrate that outside of Fresnel zones the surface cannot be accurately known.

IMPACT/APPLICATIONS

The analysis and modeling of the SPACE08 data has impact and applications for developing a predictive capability for underwater acoustic communications performance accounting for the effects of a rough sea surface and Doppler-shifted, wave-focused arrivals at the receiver. The modeling effort also suggests that there is an optimal source-receiver geometry available to help mitigate the effects of surface-focused arrivals on underwater acoustic communications equipment. The work on screening of the surface by bubble clouds also has implications for this technical area.

RELATED PROJECTS

A100530: Underwater Acoustic Propagation and Communications: A Coupled Research Program.

PUBLICATIONS

Czerski, H. and G.B. Deane, "The effect of coupling on bubble fragmentation acoustics," J. Acoust. Soc. Am. **129**, 74-84 (2010). [published, refereed].

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