Shallow Water Propagation and Surface Reverberation Modeling

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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.

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

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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 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 is divided between field and laboratory campaigns and propagation and surface scattering model development.

Field Deployments. The field experiments consist of the SPACE02 and SPACE08 UW COMMS deployments (which have already happened) and a third experiment executed in the fall of 2011 (KAM11). Data from the SPACE02 and SPACE08 experiments are being analyzed for percentage whitecap coverage of the sea surface, ambient noise levels and the properties of surface-scattered arrivals along 20 m and 200 m propagation paths. For the KAM11 deployment, the goal is to test the capability of the Wavefronts model to model the high-frequency ACOMS environment. Water column sound speed profiles and time series of surface wave height will be used to predict the amplitude, intensity and time delay statistics of surface-scattered arrivals.

Scattering Model Development. The SPACE08 propagation data will be modeled deterministically with the Wavefronts acoustic model. Surface waves were measured during the SPACE08 experiment with a high-frequency, upward-looking sonar mounted on the seafloor, mid-way along the 60 m propagation path deployed by Andone Lavery at WHOI. Amplitude, delay and Doppler shift of surface-reflected arrivals will be modeled using the Wavefronts code with the wave height time series as an input and compared with the SPACE08 data. A initial analysis has shown that accurate estimates of the surface-reflected arrival delay can be made using the wave height data once the acoustic and wave height data streams have been synchronized. The comparison will be extended to focusing intensifications and Doppler shifts. The ultimate goal is to understand the connection between the properties of the surface-scattered field and the amplitude statistics of the gravity wave field.

Collaborations. This work is being done in collaboration with Dr. James Preisig at WHOI and Prof. Chris Tindle at the University of Auckland, New Zealand. Dr. Preisig, one of the world's leading experts in the development and application of signal processing techniques to UW ACOMS, will take data and model products developed as part of this proposal and incorporate them into models of communication performance and improved algorithms for signal detection. The Wavefronts model has been specifically developed to deal scattering from curved surfaces in the time-domain. It is possible that this model will prove useful in the interpretation and modeling of sound scattered from ice sheets, and this will be studied in collaboration with Dr. Preisig.

WORK COMPLETED

This report concludes the first year of a three-year period of investigation. Two significant goals have been acomplished during this period: the KAM11 experiment has been undertaken and an analysis of acoustic transmission data from SPACE08 relating scattering by surface waves to the amplitude of surface-scattered acoustic arrivals has been completed.

The KAM11 Experiment.

The KAM11 experiment took place at the Pacific Missile Range Facility (PMRF), 117 nautical miles off Honolulu from 23 June through 12 July, 2011. The UNOLS ship R/V Kilo Moana operated by the University of Hawaii was used to deploy and recover all equipment. The Chief Scientist for the experiment was Bill Hodgkill from SIO, and the cruise included participants Woods Hole Oceanographical Institution and the College of Marine and Earth Studies at the University of Delaware. Three systems were prepared and deployed by the PI during the KAM11 experiment: an autonomous array of vector sensors, a high-resolution camera system to monitor whitecap formation and a commerical acoustic system to measure populations of micro-bubbles in the upper ocean boundary layer.

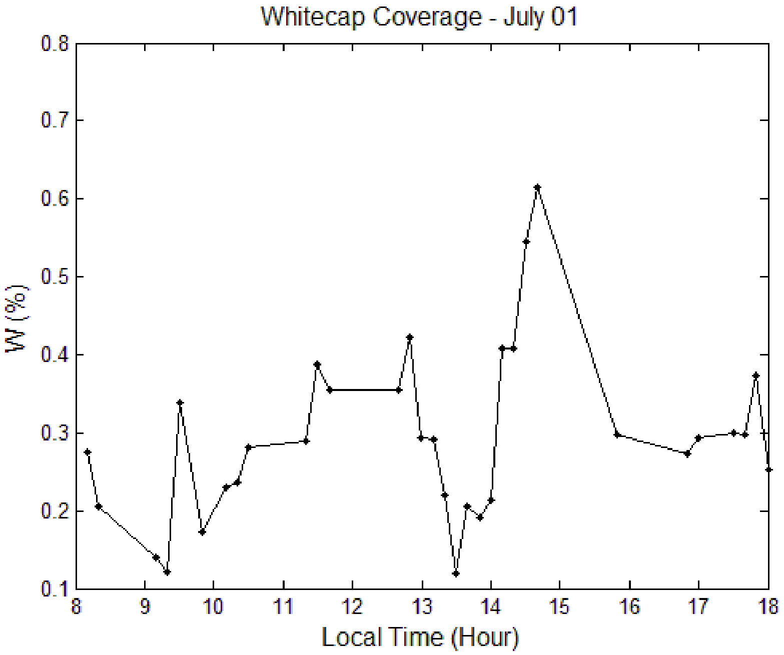

Figure 1. A plot of the fractional coverage of whitecaps expressed as a percentage versus time on July 1st, 2011 during the KAM11 experiment. Approximately 18,000 images were analyzed. The data show variations in whitecap coverage associated with changes in wind speed.

The surface-monitoring camera system consisted of a 5 Mega-pixel POE-based camera mounted inside a weatherproof security housing. The camera was mounted on one of the ships masts and the tilt and direction of the camera system controlled remotely from the data collection laboratory. Data was streamed to hard drive at a rate of 10 frames per second during recording intervals. Data was collected during periods of moderate to high winds when whitecaps were visible. When analyzed in terms of fraction whitecap coverage, this data will provide quantitative information about air entrainment rates and the spatial distribution of sub-surface populations of micro-bubbles injected into the upper ocean boundary layer by breaking waves. During periods of high wind speed, these bubbles significantly impact sound reflected by the sea surface at coherent underwater communications frequencies by scattering and absorption. Fig. 1 shows an analyzed segment of data taken during the daylight hours on July 1st, 2011.

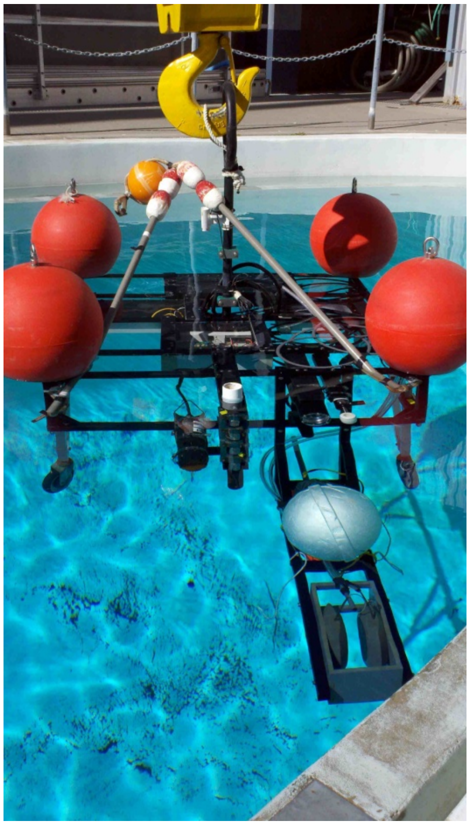

Figure 2. The surface-following environmental frame housing the Acoustical Bubble spectrometer to measure wave-induced bubble plumes. The frame was tethered to the stern of the Kilo Moana and left to drift approximately 100 m behind the vessel.

The acoustic vector sensor array was designed, build and tested by The Deane Laboratory and the Technology Applications Group at SIO. An array of 4 VS-205 Wilcoxon acoustic vector sensors was mounted on a spar buoy with a 33 cm element spacing at a depth of 20 m, providing a freely-drifting, autonomous platform deployable for a period of up to 4 hours. The spar buoy decoupled the array from surface motions which helped minimize levels of flow noise on the velocity sensor elements. The vector sensors were configurable for data acquisition of 5.0 kHz or 45.045 kHz depending on the configuration, the latter being without anti-aliasing filters. A National Instruments Data Acquisition Software package was written to acquire and store the vector sensor acoustic and orientation data. The spar buoy was tested in the near-shore waters off the La Jolla Shores Beach before being packed and shipped to Hawaii for the KAM11 experiment. The system was successfully deployed three times during the source of the experiment.

The third system deployed during KAM11 was the Acoustical Bubble Spectrometer (ABS) manufactured by Dynaflow, Inc. The ABS is an acoustic system designed to quantify bubble size distributions with air fractions of 10^{-7} up to around 10^{-4}. It was deployed on the surface-following environmental frame shown in Fig. 2. The ABS acoustic transducers are the gray disks visible on the lower right hand side of the picture. This system worked in laboratory tests and on the deck of the Kilo Moana but failed to collect data when deployed in the ocean. The failure mode for the instrument remains to be determined, but the most likely scenario is rejection of data by the instrument because of interfering underwater noise from the Kilo Moana's differential positioning system. Moving into years two and three, we are pursuing the construction of in-house acoustical resonators to replace this commercial system. Preliminary discussions to collaborate with scientists at the Institute of Ocean Sciences in British Colombia, Canada who have successfully built and deployed acoustical resonators in the open ocean have been favorable.

Analysis of the SPACE08 Data

Data collected during the SPACE08 acoustic communications experiment at Martha's Vineyard, Woods Hole have been analyzed and modeled to study the connection between ocean surface conditions and intensifications in the reflected acoustic field associated with gravity wave focusing. The results of this analysis are discussed below.

RESULTS

The data from the KAM11 expeirment are still under analysis, and there are no significant results from this deployment to report yet. Data from the SPACE08 underwater acoustics experiment have been analyzed to study the link between surface wave activity and intensifications in the surface-reflected sound associated with surface gravity waves. Fig. 3 shows one of the results of this study.

The data show that the statistics of surface reverberation arrival time and energy are sensitive to both the energy in the surface gravity wave field, and the distribution of that energy in frequency. This is experimental verification of an important theroretical result, which is that the intensity of surface-reflected arrivals depends on the curvature of the surface gravity waves, which is a function of both wave amplitude and wave and frequency. The implication is that any predictive capability of underwater acoustic communications performance based on acoustic models that include surface reverberation must include realistic parameterizations of the surface gravtiy wave spectrum.

The good agreement between the data and model calculations suggests that the scattering calculations used here are of sufficient fidelity to accurately model surface scattering processes. Plots similar to those shown in Fig. 3, but on a logarithmic scale (not shown here) show that the agreement between theory and experiment continues well into the arrival amplitude distribution tails and extends over two orders of magnitude in energy.

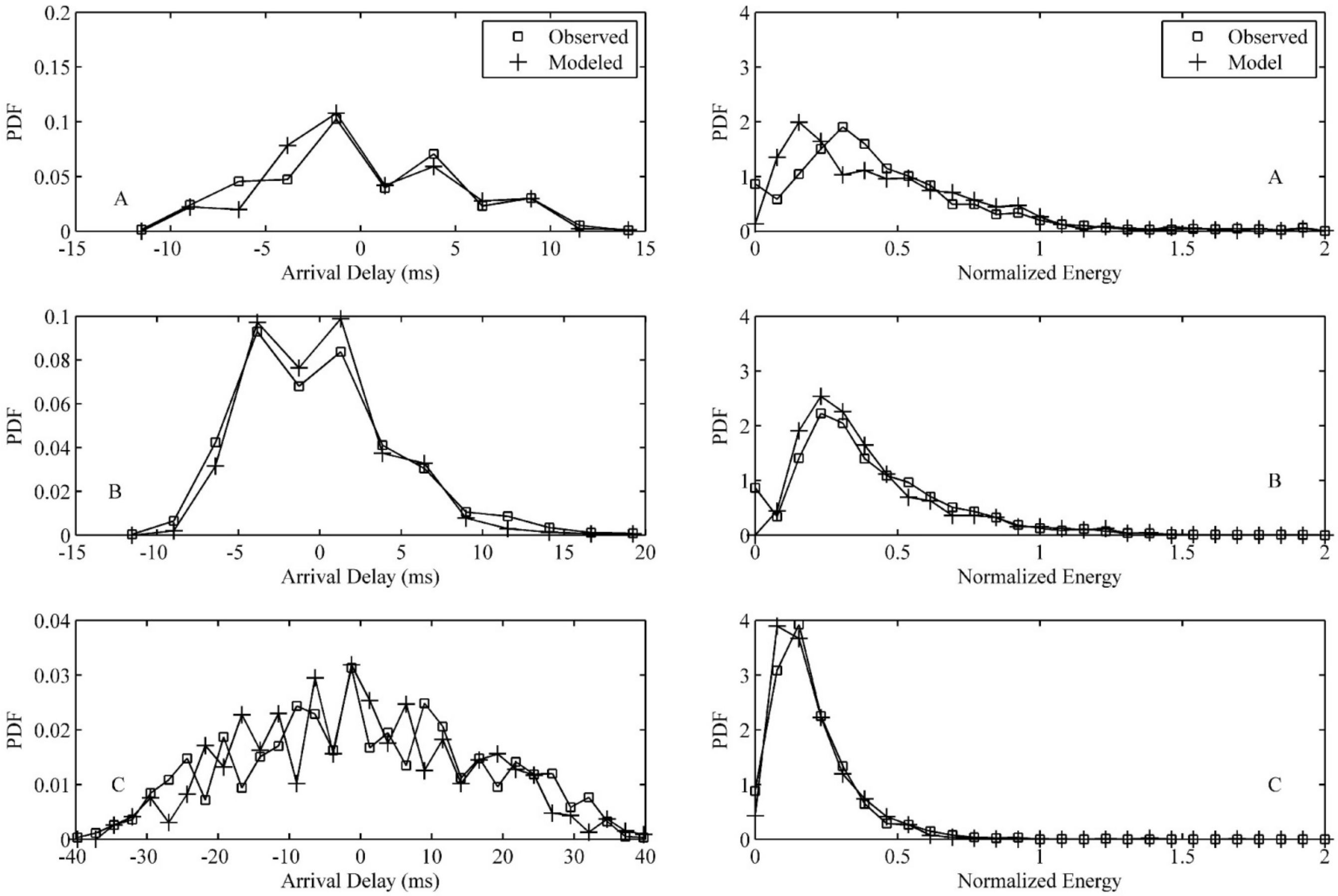

Figure 3. A collage of the arrival delay (left-hand column) and normalized energy (right-hand column) of acoustic pulses scattered from the sea surface during three different sea states. The first row corresponds to 1 m significant wave height swell. The second row is also for a 1 m significant wave height, but for a wind and swell-mixed sea. The third row corresponds to a 3 m significant wave height, wind-driven sea. Squares indicate measured data and pluses indicate model results. The model predictions include an ad hoc. term to account for absorption and scattering by bubble clouds.

Model calculations based on the scattering theory indicate that an optimal geometry to avoid intensifications associated with gravity wave focusing is a source placed as close as practical to the sea surface and a receiver placed as far below the sea surface as practical.

Important effects remain to be studied, including out of plane scattering associated with three dimensional wave field effects, wave-induced Doppler shifts and the effects of sound speed profiles in the water column on acoustic-surface interactions. Acoustic arrivals that have undergone more than a single surface interaction face the interesting possibility of being focused more than once, and the distributions of these arrivals need to be modeled.

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.

RELATED PROJECTS

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

PUBLICATIONS

Deane, G.B., J.C. Preisig, C.T. Tindle, A. Lavery and M.D. Stokes, "Coherent forward scatter from surface gravity waves," J. Acoust. Soc. Am. [SUBMITTED].

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