Acoustic Focusing in Shallow Water and Bubble Radiation Effects

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LONG-TERM GOALS

The long term goals are to: (1) understand the impact of bubbles in the upper ocean boundary layer on the performance of underwater communications systems and their role in ambient noise generation, (2) study the impact of focusing by surface gravity waves on Doppler sonar and acoustic communications systems in shallow water, and (3) study the performance of acoustic vector sensors in very shallow water.

OBJECTIVES

The objectives of the research are to address the questions in each of the following areas.

1. Bubbles and ambient noise.

Can bubble creation mechanisms inside whitecaps be understood well enough to infer surface bubble conditions from measurements of wave noise? Bubbles impact underwater communications bit error rates and channel availability by introducing frequency-dependent scattering and absorption. A detailed knowledge of the number, sizes, and persistence of wave-induced bubbles would be a valuable aid in the design of signal modulation schemes and front-end equalizers for underwater communications systems. A secondary objective is to understand the role of bubbles in scattering and absorbing sound in the surf zone. This work was motivated by the anecdotal reports of surf noise 'hot spots' that occur along the coast. The underlying idea is that low frequency surf noise could be absorbed and scattered by the clouds of bubbles entrained in the surf zone. The width of the surf zone varies between beach and headland areas, which could introduce a natural variability into surf noise level.

2. The focusing of sound by surface gravity waves.

Shoaling waves create focal regions in surface-scattered sound in the very near shore region, which impacts the performance of underwater communications systems and acoustic Doppler sonars. The objective is to understand and model the intensity, phase, and Doppler shift of the focal regions measured deterministically in the field and study their impact on sonar performance and the front-end equalizers of underwater modems.

3. Study the performance of acoustic vector sensors in very shallow water. The three goals of this research are to: (a) determine how closely the performance of an array of vector sensors deployed and operated in a real ocean environment approaches theoretical predictions, (b) compare the performance

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of an array of vector sensors and an equivalent array of pressure sensors, and (c) determine if any differences in performance can be related to the relevant physical properties of the water column, such as internal wave activity.

APPROACH

The various components of the research (bubble and ambient noise studies, surface wave focusing, and the vector sensor studies) are undertaken with a combination of field work, data analysis, and interpretation through modeling with appropriate theories. Experiment programs have been established to measure surface wave focusing effects, the noise radiated by fragmenting bubbles in both fresh and salt water, bubble effects in the surf zone, and to support the vector sensor work.

- Surface gravity wave focusing and its impact on underwater acoustic communications algorithms have been studied in the littoral zone of La Jolla Shores Beach, and deeper waters off the Martha's Vineyard Coastal Observatory Air/Sea Interaction Tower. Plans have been made this year to augment these experiments with a high-frequency flume study, which will yield precise measurements of the amplitude, phase, and Doppler shifts associated with micro-path reflections form surface waves. These experiments will be carried out in the first quarter of 2007.

- Bubble work over the past year has centered on experiments to analyze the sound of isolated bubbles fragmenting in turbulence. These experiments are based on earlier studies of bubble creation processes within laboratory breaking waves, and are expected to yield information on the relationship between bubble creation rates and noise radiated by breaking wave crests.

- The vector sensor studies will be based on the deployment of an array of sensors currently under construction by Wilcoxon.

WORK COMPLETED

Bubbles, ambient noise generation, and bubbles fragmenting in turbulence.

- A system to inject individual bubbles beneath two colliding fluid jets has been overhauled and improved. The 'bubble smasher' injects bubbles into the water just below a region of high shear stress created by the opposing fluid jets. High-speed camera images of bubbles fragmenting in the high-shear region provide estimates of bubble elongation before rupture and instantaneous fluid shear estimated from the velocities of the fragmentation products. The sound of the bubble fragmentation is monitored with a hydrophone mounted near the bubble-jet interaction region. Measurements of the sound from fragmenting bubbles has been made in both fresh and salt water. A large dataset has been analyzed to determine the amplitude and decay rate of the pulses of sound radiated by fragmenting bubbles.

- In addition to the bubble fragmentation experiments, measurements of surf noise were made from the SIO pier to measure the absorption of low frequency surf noise by surf-induced bubble clouds. Two hydrophones were deployed from the side of the pier along with a video recorder to measure the absorption and scattering of low frequency (< 1000 Hz) wave noise by the clouds of bubbles injected by breaking surf. The acoustic data from the experiment has been analyzed and compared against a bubble absorption model.

The focusing of sound by surface gravity waves.

The main effort on this component of the research this year has been to participate in planning the SPACE07 underwater communications and surface processes experiment scheduled for deployment in October, 2007 at the Martha's Vineyard Coastal Observatory. In addition, a high frequency wave flume experiment scheduled for January, 2007 at the SIO hydraulics facility has been planned.

Vector sensor performance.

An experiment was carried out in the shallow waters north of the Scripps Pier to obtain preliminary data on the performance of a Wilcoxon Vector Sensor in the very near shore region. The vector sensor was deployed with environmental sensors to record acoustic pressure and velocity, temperature, salinity, and surface waves. The sensor failed with 24 hours of deployment and no useable acoustic data was obtained. The reason for the sensor failure is unknown, but the most likely cause is flooding. A definite answer will have to wait until the sensor has been examined by Wilcoxon. A second deployment will be undertaken in 2007 using an array of vector sensors currently under construction by Wilcoxon and SIO.

RESULTS

Bubbles fragmenting in sheared flow.

The main result of this work has been to determine the amplitude and decay rate of the acoustic emissions of bubbles fragmenting in sheared fluid flow (see Figures 1 and 2). This data is an expansion of results reported in 2005. Fresh and salt water experiments are reported with more fragmentation events and a refined parameter estimation for bubble emission properties. The data do not show any significant differences in amplitude, decay rate and frequency of bubbles fragmenting in fresh versus salt water. The fragmentation results in a broad range of bubbles sizes, which can be determined from their frequency of oscillation.

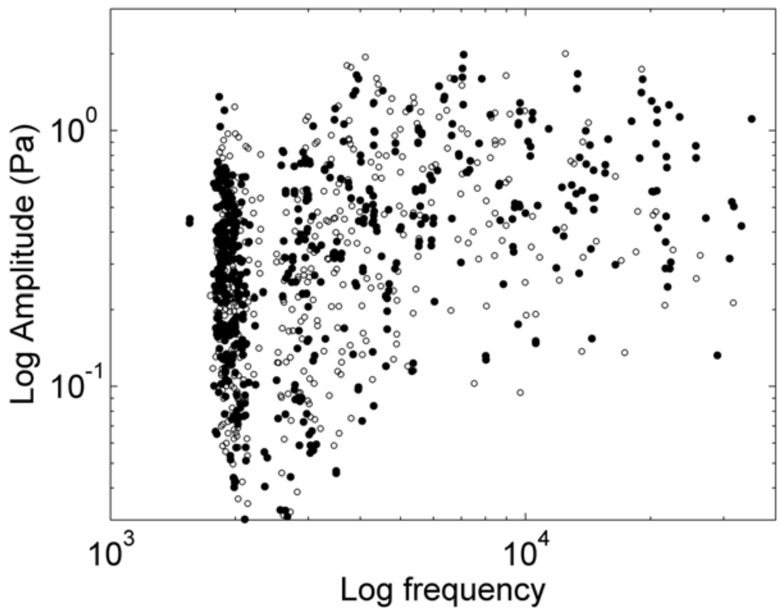

Figure 1. A scatter plot of the estimated amplitude of acoustic emissions from 505 binary fragmentation events (exactly 2 bubble products) versus frequency. The open and filled circles correspond to fresh water (at 14.0 °Celsius) and salt water (at 13.4 °Celsius) environments, respectively.

The amplitude data shows a broad spread (approximately two orders of magnitude) in peak pressure, from 0.03 Pa to about 2 Pa, without a significant frequency scaling.

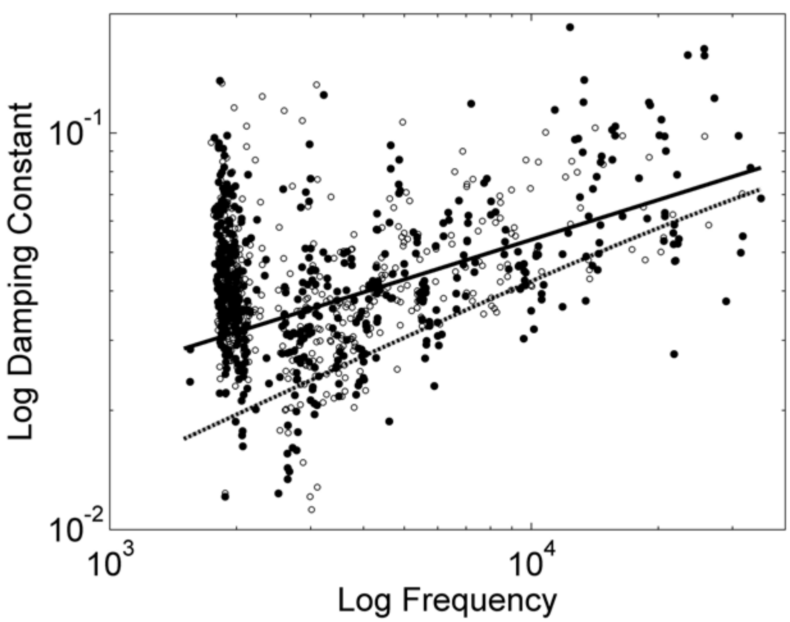

Figure 2. A scatter plot of the estimated decay rate of acoustic emissions from the same fragmentation events in Figure 1. Although there is significant scatter, the data are consistent with the sum of thermal and radiation losses (solid black line) and bounded below by thermal losses (broken black line).

The pressure levels of 0.03 Pa to 2 Pa are consistent with the frequency independent levels reported by Updegraff below gently spilling waves in the ocean. The data show that binary fragmentation can spread an initially monochromatic bubble spectrum into a wide range of bubble sizes.

The estimates of decay rate (summarized in Figure 2) show a considerable spread in value. The lower bound for the losses is largely consistent with thermal damping, and the mean losses are reasonable well predicted by the sum of thermal and acoustic radiation losses.

These result have important implications for understanding the noise radiated by whitecaps. The data suggest that the bubble fragmentation process within whitecaps may be modeled as an ensemble of acoustic pulses over a broad band of frequencies with frequency-independent amplitude scaling and damping determined by thermal and radiation losses. They also suggest that the process of bubble fragmentation may be responsible for the creation of a broader range of bubble sizes than previously thought.

Low-frequency noise absorption by bubble clouds in the surf zone.

Surf noise data was processed into spectrograms and analyzed for asymmetries between the propagation paths between the seaward and shoreward hydrophones. As the seaward propagation path includes absorption by bubbles whereas the shoreward path does not, differences in noise level between the two is impacted by bubble cloud absorption. A typical wave passage is shown in Figure 3. The top and second plates show spectrograms of the wave noise at the seaward and shoreward hydrophones respectively. The passage of the wave over the seaward hydrophone can be clearly seen at approximately 6 seconds into the top spectrogram in the form of a broad-band burst of noise extending from a few hundred Hz up to 10 kHz or so and lasting for a few seconds. Approximately 2 seconds later, the wave reached the shoreward hydrophone, corresponding to the maximum in noise intensity at 8 seconds. The third plate shows the ratio of shoreward to seaward noise, with greater shoreward noise levels appearing in red. The arrival of the wave at the shoreward phone results in a reduction of this ratio, corresponding to the blue patch between 5 and 6 seconds. As the wave propagated shoreward, the noise at the shoreward hydrophone dominated, corresponding to the red patch at 8 seconds. The bottom plot shows the spectral density ratio integrated over frequency. The arrival of the breaking wave crest at the seaward and shoreward hydrophones occurs at the minimum and subsequent maximum in the plot. The asymmetry in the ratio is consistent with bubbles absorbing sound behind the wave crest.

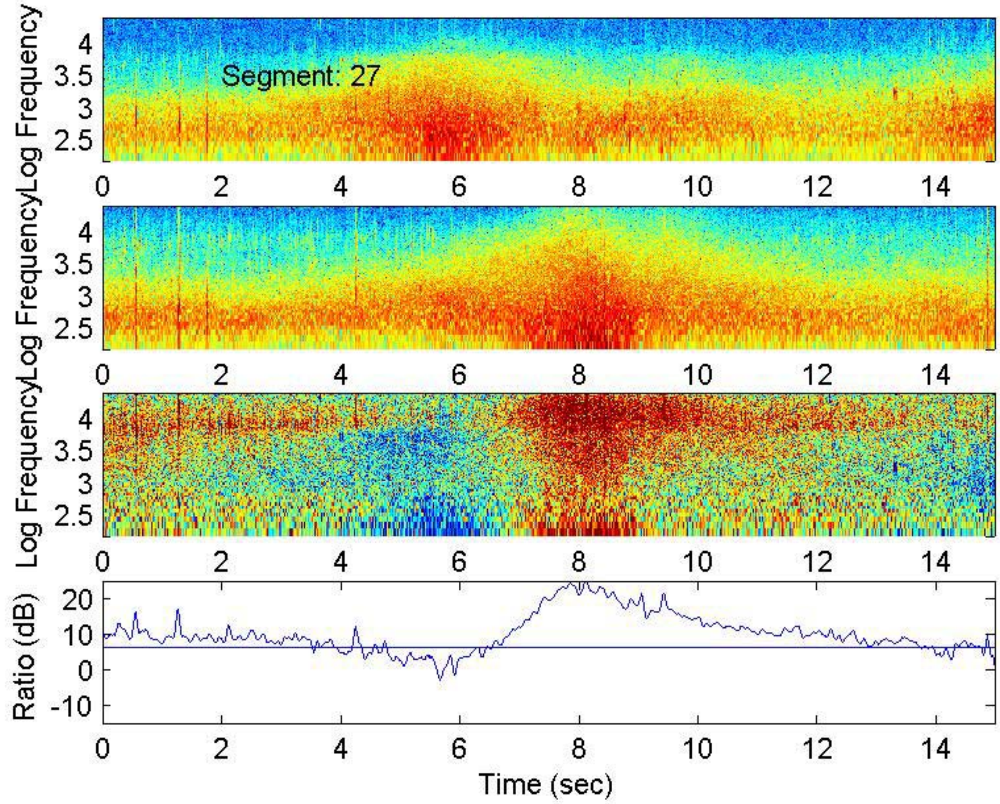

Figure 3. A 15 second segment of surf noise processed into spectrograms and analyzed for spectral differences. The top and second plate show color contour maps of noise power plotted versus log frequency and time for the seaward and shoreward hydrophones. Red corresponds to more intense noise. The third plate is the ratio of shoreward to seaward noise density plotted as a color contour versus log frequency and time. The final plot shows the ratio of noise density integrated across the entire frequency band.

When inserted into a model for surf noise generation based on some assumptions about bubble cloud formation, bubble absorption is able to reproduce the observed dependence of surf noise level on incident wave energy flux (see Figure 4).

Surface gravity wave focusing and underwater communications.

Experiments have shown that the details of the surface-scattered focal regions can be measured

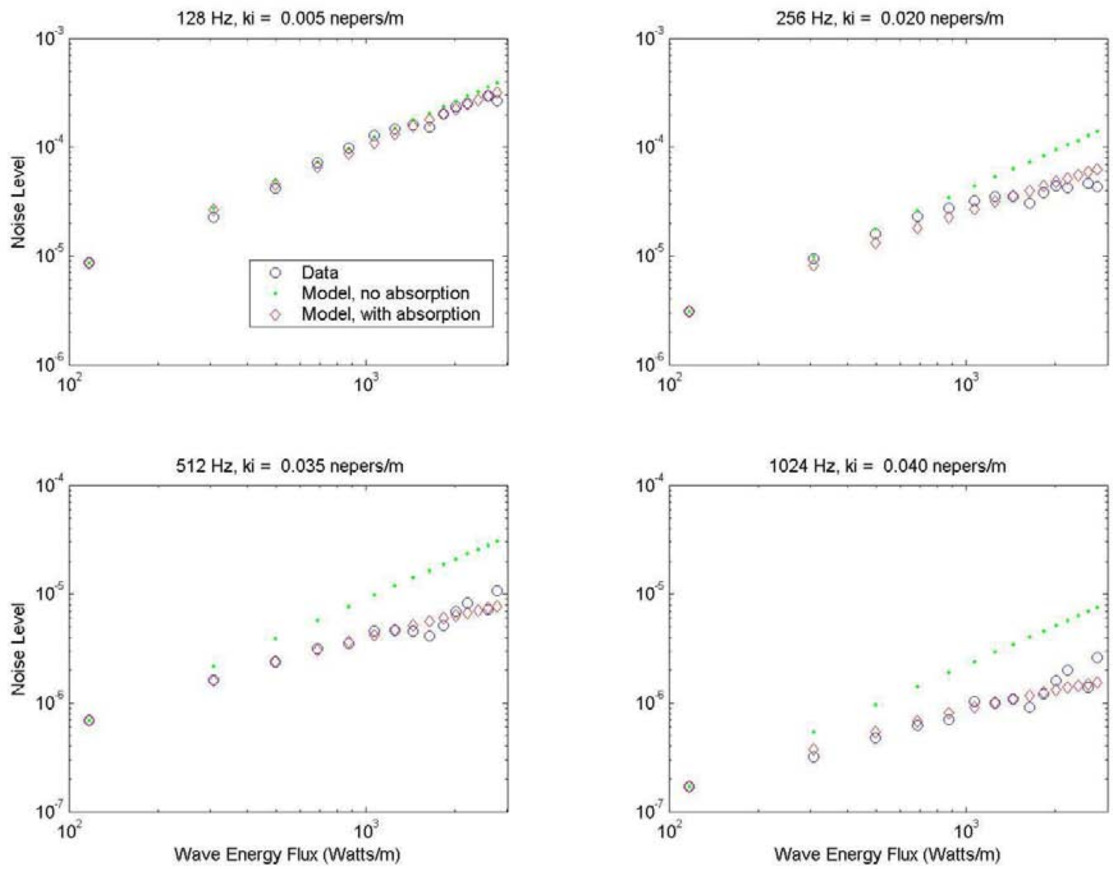

Figure 4. A comparison between measured and modeled surf noise energy for 4 octave-band averages plotted as a function of incident wave energy flux. The blue circles, green dots, and red triangles show data, model without bubble absorption, and model with bubble absorption respectively. The curves show good agreement between the observed and modeled surf noise levels when bubble absorption is included in the model.

deterministically in the very near shore. The channel impulse response and surface-scattered arrival dynamics measured in the shallow waters of La Jolla Beach show intensifications and Doppler shifts associated with individual wave crests. Surface-focused arrivals exhibit a micro-path structure with dynamic, time-varying Doppler shifts. The dynamics of these arrivals can be explained with a wave-fronts model that accounts for the focal region micro-path structure. The main effort this year has been to plan a flume study of micro-path structure for early 2007, and participate in planning a multi-institutional experiment in the early winter of 2007 to study the coupling between environmental factors and communications system performance.

IMPACT/APPLICATIONS

The bubble and wave focusing studies have the potential to impact the development of underwater communication algorithms. One application of the bubble fragmentation studies is to assess surface bubble conditions using ambient noise. The studies of focusing by surface gravity waves have already impacted the development of new algorithms for underwater acoustic communications by Jim Preisig at WHOI.

RELATED PROJECTS

None.

PUBLICATIONS

Deane, G.B. and M.D. Stokes, “The acoustic signature of bubbles fragmenting in sheared flow,” JASA Express Letters [in press, refereed].