The Impact of Very High Frequency Surface Reverberation on Coherent Acoustic Propagation and Modeling

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LONG-TERM GOALS

The long-term science objective is to develop a physical model of high-frequency scattering of underwater acoustic signals from the sea surface under a range of wind-driven conditions. The model will focus on signal coherence, and second-order amplitude and Doppler statistics. A second long-term goal is to measure and model very high frequency underwater sound generated by processes at the sea surface, relevant to the high-frequency underwater acoustic communications problem.

The scattering of sound from the sea surface is important for the operation of underwater sonar and underwater acoustic communications systems. Studies of low to mid-frequency surface reverberation have a long history, but studies of very high frequency (>300 kHz) surface scattering in the literature are rare. The physics of very high frequency (VHF) scattering is expected to be strongly dependent on wind speed, which controls surface roughness and wave breaking, which injects bubbles into the ocean. The amplitude, Doppler spread and temporal coherence of VHF scattering is important for the performance of high frequency sonars and underwater communications systems in operating scenarios where energy from the sea surface cannot be screened. The generation and propagation of high frequency underwater noise is also important to VHF underwater acoustic communications.

OBJECTIVES

There are three primary objectives. The first is to study the underlying relationship between the amplitude, Doppler and coherence of VHF acoustic signals scattered from a rough ocean surface driven by a range of wind speeds. The second is to investigate the impact of surface scattered VHF acoustic energy on coherent VHF underwater acoustic communications. Recent work by Dr. James Preisig at WHOI has shown that the optimal spacing of receiver elements in a vertical communications array depends on the vertical wave number spectrum of the acoustic field in the medium frequency regime, and surface scattering is a primary determinant of this spectrum. However, in the VHF regime increased surface bounce losses may increase the importance of other water column physics, such as internal scattering by turbulence, on the angular spread of the received field. Addressing the relative importance of surface versus water column scattering will be important in the design of optimal arrays for VHF systems. The third primary objective is to characterize high frequency wave noise in environmental simulators, the surf zone and the open ocean.

In addition, the physics of Doppler statistics, which scales with frequency, and scattering from small scale surface waves, which is dominated by ultra-gravity and capillary waves in the VHF regime are expected to be quite different from those encountered at low to midrange frequencies. We are proposing a series of laboratory and field experiments to quantify these different physical scattering regimes.

APPROACH

The technical approach is divided between field and laboratory campaigns and propagation and surface scattering model development. We are 19 months into this 36 month project, and work in this initial phase has focused on laboratory measurements of high frequency surface scattering, simulations of the scattered signal and high frequency measurements of wave noise. Experiments have been done at a transmission frequency of 300 kHz using small, omnidirectional transducers with Dr. Sean Walstead and at 570 kHz using an array of transducers with Dr. James Preisig at JP Analytics. All experiments to date have been conducted in a wind-wave simulator at Scripps Institution of Oceanography, and will transition next year to the littoral zone off La Jolla Shores Beach.

WORK COMPLETED

Initial experiments were conducted in the glass and wind-wave channel in the Hydraulics Laboratory at SIO (https://scripps.ucsd.edu/hlab/facilities). The glass channel is 33 m long, 0.5 m wide and is typically filled to a water depth of 0.6 m. This simulator is used to create controlled and repeatable breaking wave packets. The wind-wave ocean wave simulator is 40 m long, 2.4 m wide, and filled with seawater to a depth of 1.25 m. Surface waves can be generated with a hydraulic paddle at one end of the tank and winds up to 15 ms^{-1} can be generated in the headspace above the water surface. The data reported here were taken with a stationary paddle and winds in the range 0 – 6 ms^{-1}. Also included are results from a study an experiment to study VHF noise radiated by breaking laboratory waves.

Statistics of VHF sound scattered from wind-driven waves.

Bistatic forward-scattered sound at 300 kHz was measured in the wind-wave simulator. The experimental configuration is shown in Fig. 1. The initially flat water surface developed capillary-gravity waves as the wind speed was gradually increased from 0 to 7 ms^{-1}. Broad-band, 2-cycle acoustic pulses centered at 300 kHz were transmitted throughout the experiment to capture the changing scattering regime.

A overall summary of the experimental data can be found in the 2014 annual report for this grant. The data presented here is an analysis of the scattering scintillation index (SI), which provides a metric for saturation in the surface-scattered arrival intensity variance. The SI for a flat sea surface is 0 and asymptotes to 1 when the intensity variance is saturated. Measurements of the SI are shown in Fig. 2 (solid line) along with model calculations of the SI (dashed line).

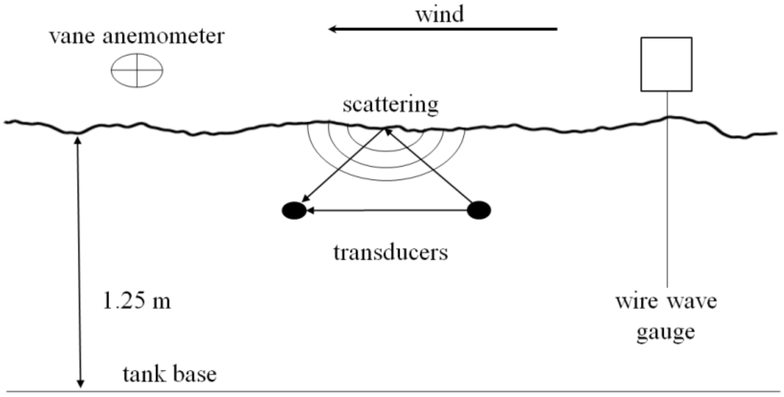

Figure 1. Experiment configuration for the VHF bistatic forward scattering at 300 kHz. The transducers were International Transducer Corp. 1089D spheres. Wave waves were measured with a wire wave gauge and wind speed was measured with a vane anemometer. The transducers were placed 40 cm apart and at a depth of 12.3 cm.

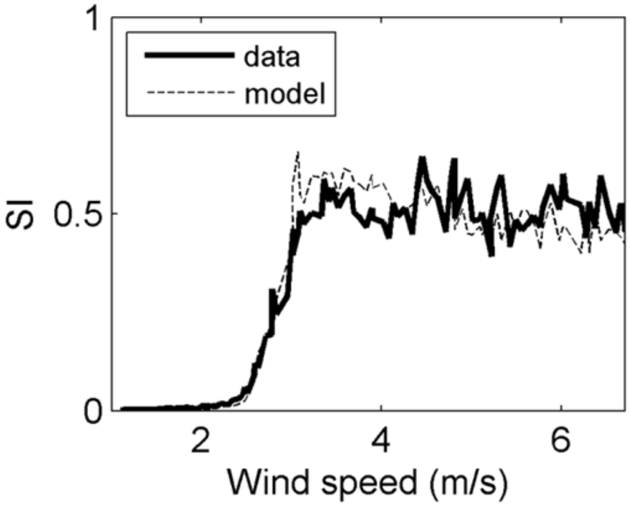

Figure 2. Normalized intensity variance (scintillation index) vs. wind speed. SI values are computed from measured (bold line) and modeled (dashed line) forward scattered pulses. The scattering model uses surface wave realizations generated from wave gauge data synchronized with the acoustic measurements. The curves are not generally smooth because of the limited period of data collection (10 s) used in the statistical averaging.

The model calculations in Fig. 2 are based on a Helmholtz-Kirchhoff wavenumber integral in the time domain with surface wave realizations derived from the wave gauge data. Both data and model show a SI of 0 up to 2 ms^{-1} wind speeds, with a relatively sharp transition to a saturation value of 0.5 between 2.5 to 3 ms^{-1}. The transition to saturation is associated with the formation of small-scale gravity-capillary waves on the water surface that begins at wind speeds of around 2.5 ms^{-1}.

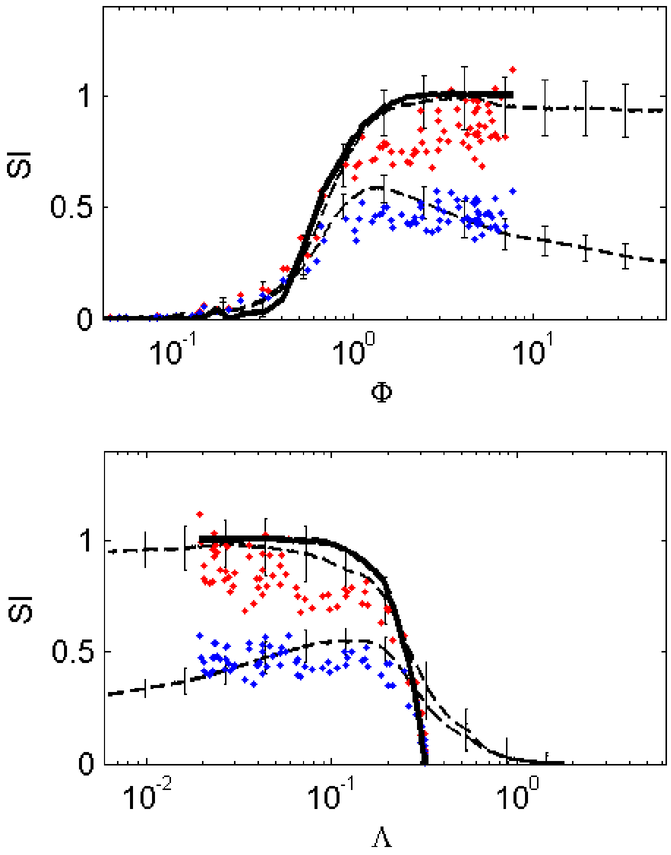

Figure 3, top and bottom. SI versus the scattering parameters ϕ (top) and Λ (bottom). Red and blue symbols are data from the experiment. Dashed lines show simulations based on the measured surface wave field. The top and bottom dashed lines in each figure represents SI^* and SI respectively. Error bars above and below the trend line denote 1 standard deviation. The solid curve is the analytical result of Yang, Fennemore, and McDaniel (1992).

The saturation of the SI at 0.5 and not the narrow-band, asymptotic value of 1 can be linked to the broad-band nature of the acoustic pulse, which for the chosen source-receiver geometry resulted in two distinct surface-scattered arrivals at wind speeds exceeding 3 ms^{-1}. The high-frequency, broad-band scattering data collected here can be compared with narrow-band theory by generalizing the definition of scintillation index. Multiple arrivals from the sea surface can be accommodated by introducing an ‘adjusted scintillation index’ $SI^* = n_aSI$, where n_a is the number of arrivals which saturates at 1, comparable to the narrow-band case. Surface scattering theory is described in terms of the normalized vertical roughness scale and normalized horizontal diffraction length, ϕ and Λ respectively. Figure 3 shows measured, simulated and theoretical values for narrow-band and adjusted scintillation index as a function of these two parameters, which vary according to wind speed. The theoretical values of SI is based on an analytical prediction given by Yang, Fennemore, and McDaniel (1992).

Experiments on VHF scattering using a vertical, broad-band 570 kHz transceiver array.

Two experimental campaigns have been conducted in the wind-wave ocean simulator in the summer and fall, 2015 in collaboration with Dr. James Preisig who provided the transducers and participated in the experiment design and execution. These experiments were similar to those described above (see Fig. 1), expect that the transmission frequency was increased from 300 kHz to 570 kHz and vertical arrays of receivers were used. In addition to broad-band pulses, a suite of channel probe and coherent acoustic communications signals provided by Dr. Preisig were transmitted. The data from these recent experiments is still being analyzed.

Measurements of VHF sound radiated by breaking laboratory waves.

The performance of VHF acoustic communications systems is limited by both channel and boundary variability, and noise considerations. There have been many measurements of the underwater ambient noise due to breaking waves in laboratory simulators and the open ocean. However, almost all of these datasets are limited in frequency to a few 10's of kHz. Experiments have been conducted in the glass channel to acquire VHF underwater noise from laboratory breaking waves. Figure 4 shows an ITC 1089D high frequency transducer adjacent to a plunging breaking wave and its sub-surface plume of bubbles. The bubble plume is roughly 20 cm in vertical scale.

Although the glass channel is a highly reverberant environment, noise measurements serve to detect the presence or absence of VHF noise from breaking waves. Three different types of waves were studied: plunging (see right), small plunging and spilling.

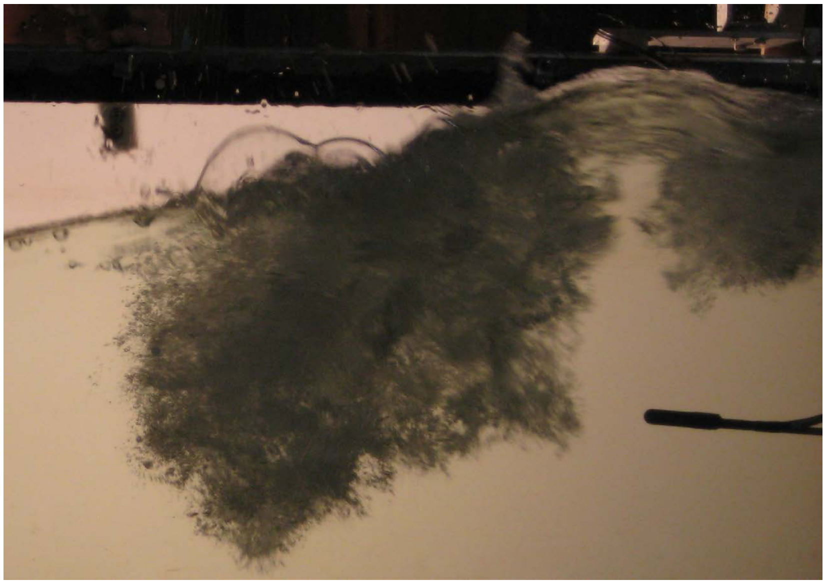

Figure 4. A photograph through the glass channel side wall showing a sub-surface bubble plume entrained by a plunging breaking waves. The horizontal, black cylinder in the right hand side of the image is an ITC 1089D broad-band transducer.

Nosie recorded during these experiments is plotted in Fig. 5 as power spectral density estimates, along with background noise levels recorded between breaking events and a reference line with a slope of -17 dB/decade, which is the typical spectral slope of oceanic noise associated with breaking waves.

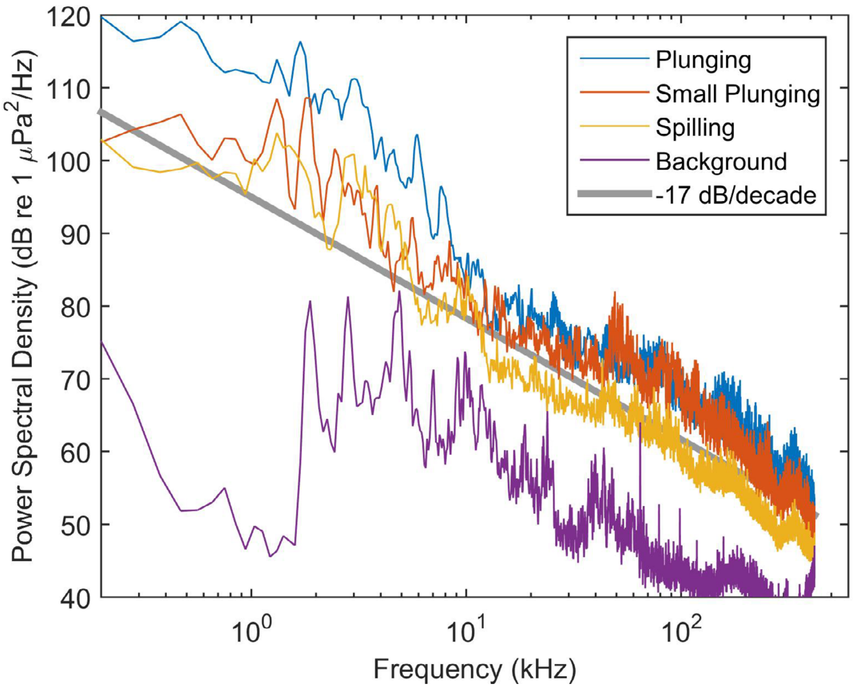

Figure 5. Power spectral density estimates of wave noise versus frequency. The light gray line shows the spectral roll-off for open-ocean wave noise (-17 dB/decade) and the purple line shows noise background between wave breaking events.

RESULTS

The wind-wave simulator experiments show that the broad-band surface-scattered arrival amplitude statistics are well-modeled by an adjusted scintillation index that accounts for multiple arrivals. The measured, simulated and modeled scintillation indices are all in good agreement. The interesting result here is that surface-scattered arrival variance statistics saturate at low wind speeds (< 2 ms^{-1}), associated with the onset of capillary-gravity waves driven by wind shear stress. Although our data is collected in a wind-wave simulator, the limited fetch available in the experimental facility ensures that our wind speed estimate for SI saturation is an upper bound – oceanic values of wind speed at which statistics saturate can be expected to be lower. The great sensitivity of the scattered signal statistics to capillary-gravity waves may also mean that the processes is sensitive to whether or not biological surfactants and/or pollutants are present on the sea surface.

The broad-band wave noise measurements show that breaking waves radiate sound well into the VHF region, beyond 400 kHz. The spectral slope of the noise is consistent with open ocean noise measurements. The origin of the noise is unkknown, but is most likely associated with the formation of microbubbles entrained near the sea surface by the overturning wave crest and its associated fluid turbulence and sea spray. These results run counter to the idea that natural sources of underwater noise above 100 kHz in the open ovean are essentially limted to thermal effects. The noise measurements need to be repeated in the open ocean. If verified in the field, VHF wave noise has important but unexplored implications for the performance of VHF underwater communications systems.

IMPACT/APPLICATIONS

This work has application to the design and operation of high frequency underwater communications systems operated near the sea surface. The results from these experiments and simulations will be applied to the design of signal processing algorithms to improve the performance of underwater communications systems in the presence of surface reverberation and wave noise.

RELATED PROJECTS

Related ONR contracts are N00014-14C-0230 and N00014-14P-1063.

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