Measuring Waves with a Compact HF Radar

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Abstract— **Ocean wave conditions impact many ways in which humans interact with the ocean, from the safety of recreation at the beach to the viability of offshore operations. Wave conditions are also topical from a research perspective, controlling processes such as coastal erosion and ocean mixing. Therefore, being able to characterize wave conditions on broad spatiotemporal scales is extremely valuable. A network of High-Frequency (HF) radar systems can provide measurements of wave conditions in near-real time along the coast where better observations are needed. Measurement of wave parameters such as significant wave height, wave period and wave direction is a secondary function of the SeaSonde HF radar. Waves are measured with SeaSonde HF radars from the second-order portion of the echo spectrum. The Doppler shift of the radio transmission from the SeaSonde contains information about the orbital velocity of the primary Bragg waves and the larger waves that they ride on. Since the wave data is dependent upon the occurrence of both Bragg and larger surface gravity waves, there is a minimum threshold for sea states in which reliable wave parameters can be determined. There is also a limiting factor for the radar in large sea states as the first-order spectra merge with the second-order and interpretation of the spectra becomes impossible with existing methods. We have tested methods for wave extraction and will present the results here. Our analysis explores the frequency-dependent threshold wave conditions for reliable wave parameter measurements, and which systems provide the best measurements. We also tested different radio waveform parameters to see which performed best in different environmental conditions. The study focuses on in-situ wave measurements from National Data Buoy Center (NOAA) buoys within the domain of the HF radar network, deployed offshore of Long Island and Delaware Bay, as well as mooring deployments of opportunity closer to the coast. Measurements will also be evaluated within the context of larger scale wave models routinely run in the area by NOAA. The threshold conditions determined by this study will guide the application of HF radar-based wave estimates to surf zone conditions by local weather forecast offices.**

Keywords—radar, remote sensing, oceanography, waves, NOAA, MARACOOS, CINAR

I. Introduction

Ocean wave conditions impact practically many ways in which humans interact with the ocean, from the safety of recreation at the beach to the viability of offshore operations. Wave conditions are also topical from a research perspective, controlling processes such as coastal erosion and ocean mixing. Therefore, being able to characterize wave conditions on broad spatiotemporal scales is extremely valuable for stakeholders interested in making economic use of the ocean as well as researchers addressing larger questions that ultimately interest consumers. High-Frequency (HF) radar systems provide one potential means of measuring wave conditions in near-real time. The Mid-Atlantic HF radar network consists of a 5-MHz long-range network that provides ocean surface current coverage over the entire Mid-Atlantic Bight with a range of 200 km offshore, a 13-MHz mid-range network that provides mesoscale coverage along the coast of New Jersey, and a 25-MHz short-range network that provides high-resolution sampling of several major estuaries. There are 45 SeaSonde HF radars operating in the Mid-Atlantic Bight (MAB) in total; we have chosen the MAB as our study domain because of the extensive spatiotemporal coverage of the network there. The main purpose of the HF radars in the Mid-Atlantic HF radar network is to measure surface currents, which has been their principal function since their inception more than thirty years ago.

Measurement of wave parameters such as significant wave height, wave period and wave direction is a secondary function of the SeaSonde HF radar. Waves are measured with HF radars from the second-order portion of the echo spectrum. This is distinctly separated from the first-order Bragg peaks that make current mapping possible. The derivation of the classic model presently employed by several groups for HF wave measurements was done 43 years ago [1]. Lipa first showed how this echo could be inverted to give wave spectral information. The methods were next extended to the CODAR compact cross-loop antenna [2]. Since these data are derived from the weaker second-order spectrum, its lower signal to noise ratio limits these data closer to the coast. The Doppler shift of the radio transmission from the SeaSonde contains information about the orbital velocity of the primary Bragg waves as they ride on top of the larger waves.

Since the wave data is dependent upon the occurrence of both Bragg and larger surface gravity waves, there is a minimum threshold for sea states in which reliable wave parameters can be determined. There is also a limiting factor for the radar in large sea states as the first-order spectra

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merge with the second-order and interpretation of the spectra becomes impossible with existing methods. Also, the perturbation theory on which the inversion model is based breaks down for higher sea states [3]. We have tested methods for wave extraction and will present the results here. Our analysis explores the frequency-dependent threshold wave conditions for reliable wave parameter measurements, and which systems provide the best measurements. We also tested different radio waveform parameters to see which performed best in different environmental conditions. The study focuses on in-situ wave measurements from National Data Buoy Center (NOAA) buoys within the domain of the HF radar network, deployed offshore of Long Island and Delaware Bay, as well as mooring deployments of opportunity closer to the coast. Measurements will also be evaluated within the context of larger scale wave models routinely run in the area by NOAA. The threshold conditions determined by this study will guide the application of HF radar-based wave estimates to surf zone conditions by local weather forecast offices.

II. Background

Radar was first developed for military applications. The development of radar systems was almost simultaneous across Europe as well as in the United States and Russia [4]. Since then, it has been used in the operation of semi-active missile seekers, experimental lunar surface mapping, grounded aircraft intruder detection (security), and ionosphere observation [5].

The SeaSonde Coastal Ocean Dynamics Applications Radar (CODAR) used in monitoring ocean surface currents is different from most radars in a few respects—it operates in the High-Frequency (HF) range, like amateur radio, as opposed to the microwave range that airplane detection and mapping applications use; it has low directivity as a result of the lower HF frequencies; and direction scanning is limited due to the fact that the radar units are limited to the azimuthal direction [4]. The fundamental measurements of the radar are range to target, direction to target relative to reference azimuth, Doppler frequency of target, and power returned from target.

The instrument consists of a transmit and receive antenna positioned on a coastline connected to a computer that stores the collected data and controls the antenna settings. The form of the SeaSonde antenna varies—in the past it was more common for receive antennas to have large "whips" but as of late an omnidirectional whipless configuration is favored—but the concept of its operation remains mostly unchanged. The transmit and receive antennas can be collocated (monostatic) or geographically separated (bistatic). The pulse can reflect off of or be deflected by conducting materials, which is why it is important to install the antennas in a relatively isolated place. Some fraction of the energy is reflected and received at the receive antenna, which carries with it information about the reflecting surface which can be made meaningful through spatial and temporal averaging and processing in the computer.

All stations (or sites) employ a linear frequency sweep to resolve range to target, and can be timed to begin their sweeps with high precision, of the order of ten nanoseconds. This enables backscattered echo to be discerned from background noise [6]. The SeaSonde stations emit radio waves, which go out a certain distance then bounce back off of wave fronts, and can be 'heard' at nearby stations. Dominant echoes appear in the radar spectra as peaks, often called 'Bragg peaks' in reference to the physical phenomenon that gives rise to the increased return from waves of the Bragg wavelength. The first-order peaks give information about the surface currents: the frequency shift of these peaks from the radar frequency belies a Doppler shift, and hence a velocity of the currents being observed relative to the radar. There are also second-order peaks that give information about the waves themselves: the Doppler shift of this second-order peak gives information about the orbital velocity of shorter gravity waves riding on the longest waves present, that are sea surface reflectors for SeaSonde-emitted radio waves. Wave theory provides a means of inferring other characteristics of the surface gravity waves.

III. Methods

Spectra files from the Bradley Beach (BRAD, Figure 1) site from February to June of 2015 were utilized for this study. These spectra files were reprocessed using different averaging schemes to test the hypothesis that poor temporal coverage and random echo noisiness in the data were caused by small number of observations going into the wave characteristic calculations. Previous studies analyzed the wave measurements from the SeaSonde with the default averaging time of 75 minutes [7, 8]. In this study several different averaging schemes were used. The 10-minute spectra files were reprocessed with wave averaging times of 30, 60, 100, 120 and 180 minutes. The resulting significant wave heights and average wave periods as measured by the BRAD SeaSonde in the second range cell were plotted alongside the same measured wave parameters from nearby NDBC buoy 44065. Since our analysis focuses on the quality of the data (presence or absence of gaps and spikes), the distance between BRAD and Buoy 44065 is not important, although it must be kept in mind that Buoy 44065 is in deeper water and hence experiencing wave conditions with somewhat greater heights and longer periods. 44065 is taken to represent wave conditions in the locality of the BRAD observations with only this caveat. We expect the correlation between wave height measurements to be on the order of 0.9 since the distance between the measurements is 30 km [8].

To study the effects of modifying the radar waveform on wave parameterization quality, the 5 MHz site BRIG was set to use enhanced blanking and compared with the nearby 5 MHz site LOVE, which utilized the conventional waveform. The conventional waveform is optimized to listen for echoes from the farthest range cell to maximize the signal-to-noise ratio in outer range bins where surface current measurements are desirable. Enhanced blanking is optimized to listen for echoes in the near range cells where wave parameterizations can be made. It is safe to assume that the wave field does not change significantly between BRIG and LOVE, so observed differences in wave estimates are mostly due to the change in the waveform.

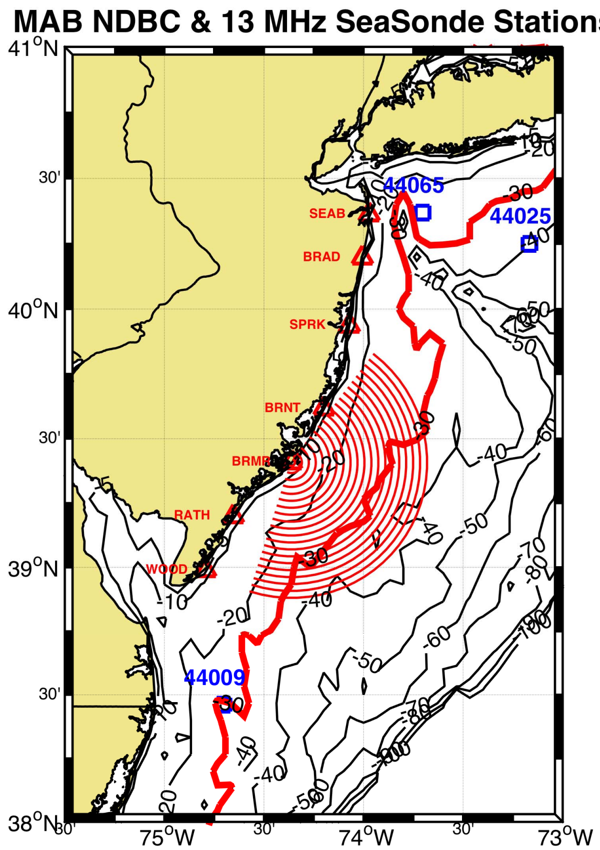

Figure 1: Map of the study area showing the location of the radar stations (red triangles) and buoys (blue squares). Each station is identified with a four-letter site code, and each buoy is identified with its serial number. The bathymetry is marked with the 30m contour as the thick red line. The range cells from the HF radar in Brigantine are the red semicircles.

IV. Results

We began our analysis with a comparison of wave real-time measurements from HF radars operating at different frequencies. Figure 2 shows wave estimates from the 25 MHz site SILD. 25 MHz sites provide higher spatiotemporal resolution wave and current observations over a relatively small region. Figure 3 shows wave estimates from the 13 MHz site BRAD, which provides measurements over a broader spatial range than the 25 MHz. In Figure 4, it is apparent that the long-range 5 MHz systems exhibit more gaps and spikes than the other systems—this is further emphasized by comparison with Figure 5, which is a 5 MHz system without enhanced blanking. The enhanced blanking waveform used at the BRIG site improved measurement quality by increasing temporal coverage. The enhanced blanking is not meant to remove spikes in the wave measurements.

Based on a qualitative comparison of data quality among sites of different frequencies, we decided to pursue improvements in the 13 MHz wave parameterizations first, and used BRAD as our test site. The five month record of reprocessed wave data is shown in Figure 6 along with the measurements from buoy 44065. A one month zoom in on the record is shown in Figure 7.

Time series of wave parameters using different averaging schemes demonstrate an improvement in temporal coverage with increased averaging scheme, with a maximum tradeoff between increase in coverage and loss of information around a two-hour average (Table 1). However, reduction in the number of spikes could not be definitively observed in any averaging scheme (Figures 6-7). Interesting is the observation that gaps could not be avoided for times during which the average wave periods were lower than 5-6 seconds. It is also possible that spikes are due to low wave height conditions. Both of these observations point to the possibility that additional processing techniques will need to be developed or adopted to make inferences about the wave conditions during these times.

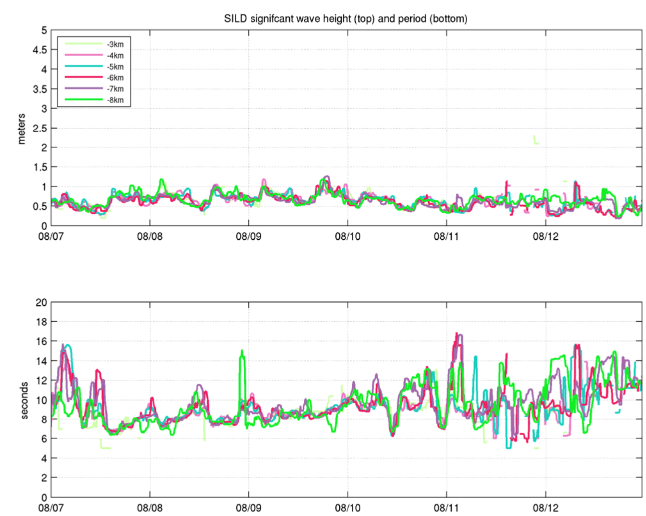

Figure 2: Wave estimates (top: wave height and bottom: wave period) from the SILD 25 MHz site from August 7-13, 2015. The different colors represent the range cell of the wave measurement.

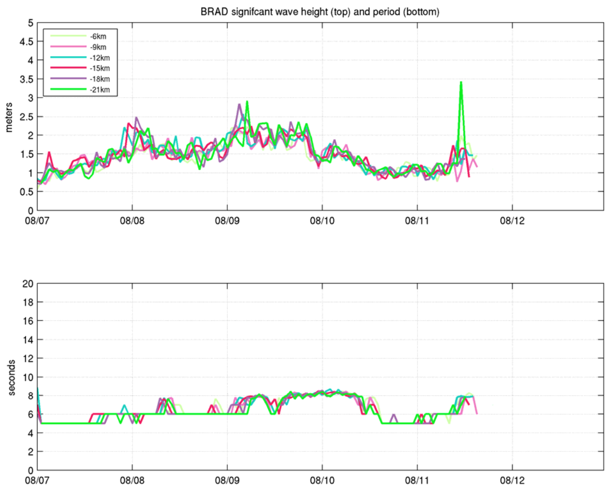

Figure 3: Wave estimates (top: wave height and bottom: wave period) from the BRAD 13 MHz site from August 7-13, 2015. The different colors represent the range cell of the wave measurement.

Figure 4: Wave estimates from the BRIG 5 MHz site, using enhanced blanking. Temporal coverage is improved relative to expected coverage based on the nearby LOVE site at the same time.

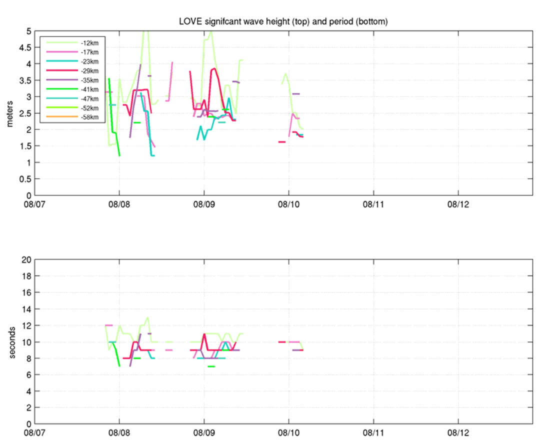

Figure 5: Wave estimates from the LOVE 5 MHz site, which does not use enhanced blanking. Serious gaps and many spikes are evident in the data.

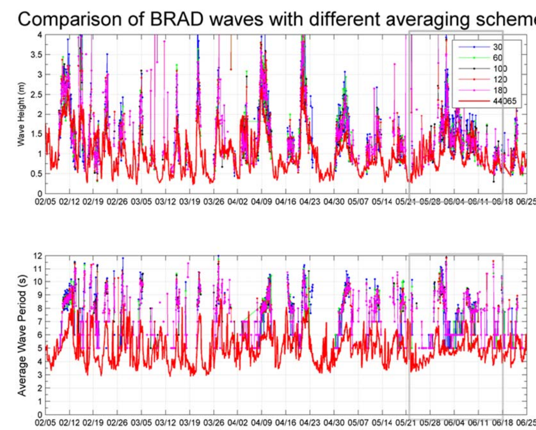

Figure 6: Plot of significant wave height (top) and average wave period (bottom) over time between February and June of 2015 as measured by BRAD in a variety of averaging schemes and compared to the nearest NDBC buoy, 44065 (see legend). The grey box is expanded in Figure 7.

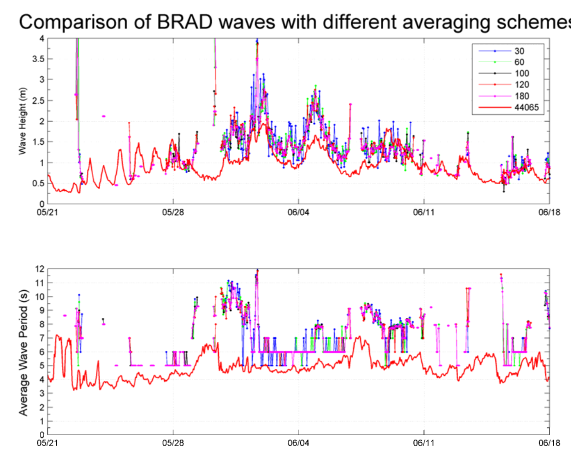

Figure 7: A close-up of the previous figure (grey box, Figure 5), exhibiting the decrease in number of gaps as averaging time goes up, and persistence of spikes.

Table 1: Temporal coverage from February to June 2015 for each averaging scheme. Coverage increases with averaging time, but there is a diminishing return with increase in averaging time.

Averaging Time	Temporal Coverage
30	32%
60	40%
100	43%
120	45%
180	49%

V. CONCLUSIONS

The averaging time used in generation of wave parameterizations from SeaSonde HF radar impacts temporal coverage. The default averaging time is 75 minutes; reduction of the averaging time to 30 minutes reduced temporal coverage, and with increasing averaging time temporal coverage increases. However, there is a diminishing return with increase in averaging time, and averaging over unnecessarily long periods of time is undesirable because it represents a loss of information. Reduction of frequency of spikes could not be definitively observed in any averaging scheme. However, outlier-removal techniques are under development and will be implemented soon, similar to those used by NDBC to clean up their raw buoy data outputs. Since gaps seem to correlate with low average wave periods and spikes seem to correlate with low significant wave heights, additional processing may be possible to fill in expected values in place of spikes and during periods of low wave periods. Use of enhanced blanking led to improvements in wave estimates at the BRIG site based on comparison with the nearby LOVE site.

During high sea states, the HF radar overestimated significant wave height because of the shallow 10 – 12 m depth in Range Cell 2 (6 km offshore); see Figure 7. This factor was studied in [9]. Second-order echo increases significantly, while wave height (e.g., measured by the buoy) does not. Improving operational techniques to handle shallow water (including enhanced blanking that allows observation farther out) is the subject of our continuing investigations.

SeaSonde HF radars in operation are presently optimized for measuring surface currents, since this is the primary and highest priority function of HF radars. In the future it may be practical to optimize some radars for measuring waves operationally.

VI. ACKNOWLEDGMENTS

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