Evaluation of Algorithms for Wave Height Measurements With High Frequency Radar

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***Abstract*— Ocean wave conditions impact navigation, offshore operations, recreation, fisheries, safety of life at sea and hence the economic stability of any country's maritime sector. Making accurate measurements of wave conditions will help validate wave models and will help with forecasts of the wave conditions over the next few days. The United States has put forth "A National Operational Wave Observation Plan" to meet this need. It has called for 133 wave measurements in the coastal zone. High Frequency radar systems that are already in place can be one type of sensor to fill this measurement gap. Seven 13 MHz HF radars collected wave data along the coast of New Jersey from February 1, 2012 to June 1, 2012. The measurements from the radars utilizing existing algorithms were compared with wave measurements from accelerometer measurements aboard National Buoy Data Center platforms. Since there were large distances between the comparison points we first determined what the correlation was amongst the various buoy platforms to gauge the variability within the region. This provided a baseline for the comparison between the HF radar measurements and the nearby buoy measurements. We then evaluated three new wave measurement algorithms at one of the radar stations to see if that improved the measurements. The correlation of the radar wave measurements with that of the buoy varied considerably. We then chose one radar station that had good correlation with the buoy measurement and tested new algorithms to extract the wave information from the radar spectra. In each case, the comparison between the in situ record with the new algorithm showed improvement. The measurement of wave information with the radar showed moderate correlation with the in situ measurements. The four algorithms each showed improvement over the existing one. HF radar could be a sensor to play a role in the US national waves plan.**

Keywords—radar, remote sensing, algorithm, wave, measurement, MARACOOS

I. Introduction

The Mid Atlantic High Frequency radar network consists of three components. The first is a 5 MHz long range network that covers from Cape Hatteras to Cape Cod with a 150 km range offshore. The second are five 25 MHz networks that provide high resolution sampling of the major estuaries in the region : Chesapeake Bay, Delaware Bay, New York Harbor, Western Long Island Sound and Block Island Sound. The third component of the HF radar network is a 13 MHz network that provides mesoscale coverage along the coast of New Jersey. See [1] for a detailed description of the network.

The main purpose for the Mid Atlantic radar network is measurment of ocean surface currents. These measurements have been used to characterize the climatology of the region [2, 3] and study flow events with shorter time scales[4, 5]. Wave height, period and wind direction are secondary measurements that can be made by each of the individiual radar stations. The method for wind and wave extraction is still has trailed that of the surface current measurement because of the complicated second order electromagnetic scattering that is utilized to extract the wind and wave information.

Each radar station in the Mid Atlantic is a SeaSonde HF radar manufactured by CODAR Ocean Sensors. CODAR provides a wave measurement package [6] as part of the software suite. This package has shown good results when applied off the California coast [7]. However the bathymetry off the coast of California deepens very quickly and is quite different from the East Coast of the United States that has a broad and shallow continental shelf. This is important as the existing CODAR wave software assume infinte water depth, which complicates the application of the wave software on the East Coast. Through this research paper we seek to determine if the existing wave software from CODAR can be applied to the radar stations in the Mid Atlantic.

II. Methods

A. In Situ Wave Measurements

Wave data from National Data Buoy Center (NDBC) for the time period between February 1, 2012 to June 1, 2012 was utilized as the reference measurement. Wave height measurements from buoy 44008, 44097, 44025, 44065. 44009 and 44014 were utilized in this study. The record for buoy 44066 only covered from February 1, 2012 to February 26, 2012 when the buoy broke free of its mooring, so it was removed from the analysis.

B. High Frequency Radar

Wave data from seven High Frequency radar systems was collected and processed from February 1, 2012 to June 1, 2012. The radar network operated at the 13 MHz band and was established to study the offshore wind resource for the state of New Jersey [8]. The radar stations were located in munipalities of Sea Bright (SEAB), Belmar (BELM), Seaside Park (SPRK), Brant Beach (BRNT), Brigantine (BRMR), Strathmere (RATH) and North Wildwood (WOOD). The four letter site code for each radar station is given in the parenteses after the municipality.

The radar spectra from each station was processed with the software provided by the manufacturer. Table 1 provides the software version numbers for each of the tools used in the wave processing.

Table 1: Version numbers for the wave tools used in the SeaSonde software.

SeaSonde Wave Tool	Version
WaveModelForFive	10.6.4
SpectraToWavesModel	10.8.4
WaveModelSlider	11.2.6
WaveModelArchiver	11.2.5
AnalyzeSpectra	10.7.7

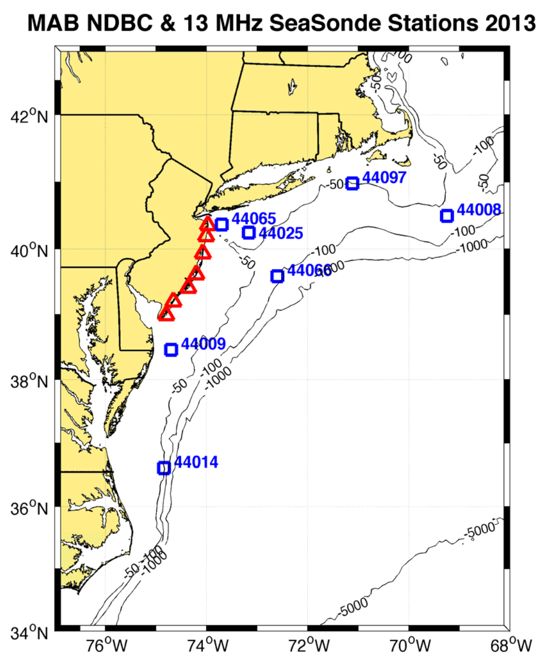

Figure 1: Study area of the Mid Atlantic Bight showing the location of the High Frequency radar stations (red triangle) and NDBC buoys (blue square).

III. Results

Since there was a large spacing between the HF radar and NDBC wave measurements, we first calculated the variability of the wave environment in the Mid Atlantic using all the NDBC buoy data. The correlation (Figure 2) and root mean square error (rmse) (Figure 3) was calcuated amongst the six wave buoys used in the study. These values were then plotted as a function of distance between the measurements to see how they vary spatially over the domain. This will be useful when comparisons are drawn between the HF radar and NDBC measurements as there is some distance between these measurements.

Figure 2 shows that correlation between the wave measurements of the NDBC buoys decreases as the distance between them increases. Figure 3 shows that the root mean square error between the wave measurements increases as the distance between the measurements increases.

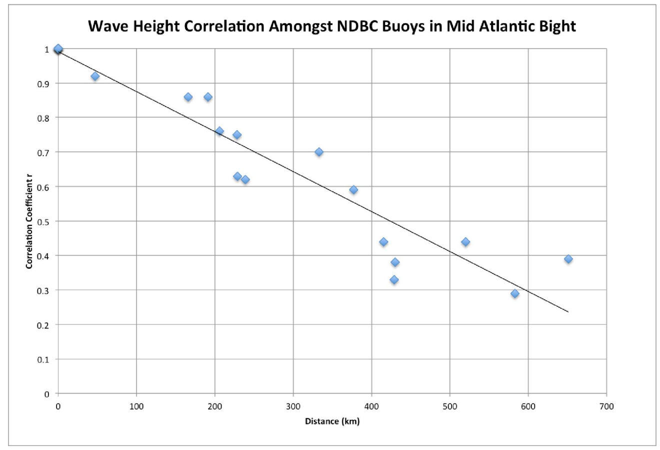

Figure 2: Wave height correlation between the NDBC buoys in the Mid Atlantic Bight as a function of distance (km) between the buoys.

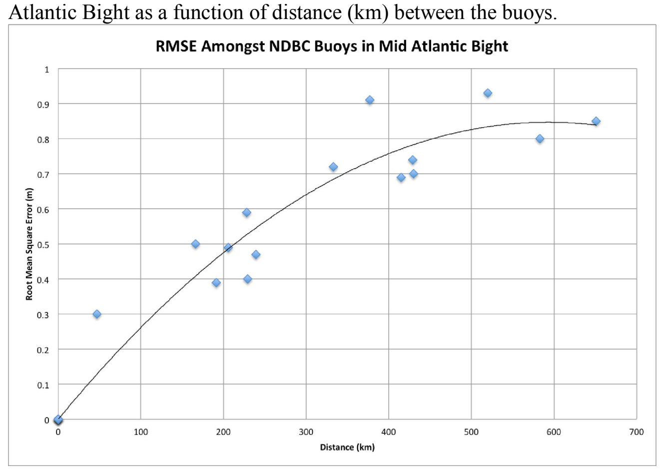

Figure 3: Root mean square error (m) between the NDBC buoys in the Mid Atlantic Bight as a function of distance (km) between the buoys.

Table 2 gives the distance in kilometers between the HF radar stations and each of the NDBC buoys. NDBC buoys 44065 and 44025 were used for comparison against the HF radar stations. The distance between the radar stations and buoy 44065 was 23-180 km and for buoy 44025 it was 69-198 km.

Based on Figure 2 we should expect the wave height correlation between the HF radar measurements and either buoy 44065, 44025 or 44009 to be between 0.9 and 0.7. We should also expect the root mean square error between the HF radar measurements and the three NDBC buoys to be between 0.1 and 0.5 m.

For the operational SeaSonde software the measurements did not meet these expectations. Table 2 gives the wave height correlation and rmse between NDBC buoy 44009 and 44025 and each of the seven HF radar stations. The table is ordered by lowest rmse at the top to highest at the bottom. The correlation was moderate to weak for each of the radar stations and did not meet the bounds of 0.7 to 0.9 that we expected. The lowest rmse was 0.56 m between buoy 44009 and radar station WOOD and was also outside the bounds of 0.1 to 0.5 m that we expected from the NDBC measurements.

One possible explanation for the low correlation and high rmse between the HF radar measurements and the in situ measurements is that radar measurements were made in water depths less than 30 m. The operational SeaSonde software assumes infinite water depth [9]. Shallow water effects become significant for the second-order spectra in water depths less than 30 m for the 13 MHz transmit frequency band used in this study. For instance, Figure 4 shows a time series plot for May 2012 of significant wave height from the radar station in Brigantine, NJ versus buoy 44025. On several occasions the radar measurements overestimate wave height. This is due to the failure of the operational SeaSonde algorithm to account for the increase of the radar coupling coefficient in shallow water [9].

The general trend of the wave environment is captured by the HF radar as seen in Figure 4. Some adjustments to the data processing steps or the radio wave form could improve the comparison between the two data sets. For this endeavor we utilized four algorithms to extract the wave height information from the radar spectra. The four algorithms are an 1) **Integration** - method similar to the Barrick method [10] without the weighting function 2) **Peak Ratio** - where the ratio of the first order Bragg peak to the second order Bragg peak gives wave height 3) **Peak Ratio Exclusion** – where the second order harmonic is excluded from the peak ratio algorithm and 4) **Integration With Beam Forming** where a beam is formed from the two loops of the SeaSonde and the data is processed with algorithm 1.

Each of the new algorithms was tested with the radar data from the Brigantine radar station for May 2012. Figure 5 shows a time series comparison of algorithm 4 with the wave buoy. It shows a marked improvement over the existing method. Table 4 gives the correlation coefficient between the different wave algorithms and the nearby wave buoys. Each of the new algorithms showed improved correlation with the in situ buoys. The algorithm that provided the highest correlation was the integration method after beam forming with the two cross loops.

Table 2: Distances (km) between the HF radar stations and the NDBC buoys.

	44008	44097	44025	44065	44009	44014	44066
SEAB	400	250	69	23	220	424	145
BELM	405	259	71	32	202	405	138
SPRK	414	276	85	58	173	376	132
BRNT	433	302	113	94	136	339	137
BRMR	453	326	139	121	109	314	152
RATH	484	360	173	153	82	288	182
WOOD	503	384	198	180	59	264	200

Table 3: Wave height correlation (r), root mean square error (RMSE) and number of data points (N) between NDBC buoys 44009 and 44025

NDBC Buoy	SeaSonde	r	RMSE (m)	N
44009	WOOD	0.41	0.56	1652
44009	SPRK	0.47	0.63	1978
44025	WOOD	0.29	0.67	1683
44025	SPRK	0.45	0.68	2009
44009	BRMR	0.39	0.71	2173
44009	RATH	0.42	0.75	2182
44025	BRMR	0.33	0.76	2204
44025	RATH	0.41	0.77	2213
44025	SEAB	0.46	1.12	2099
44009	BELM	0.14	1.15	1444
44025	BELM	0.16	1.18	1475
44009	SEAB	0.28	1.24	2068
44025	BRNT	0.22	1.54	1840
44009	BRNT	0.17	1.58	1809

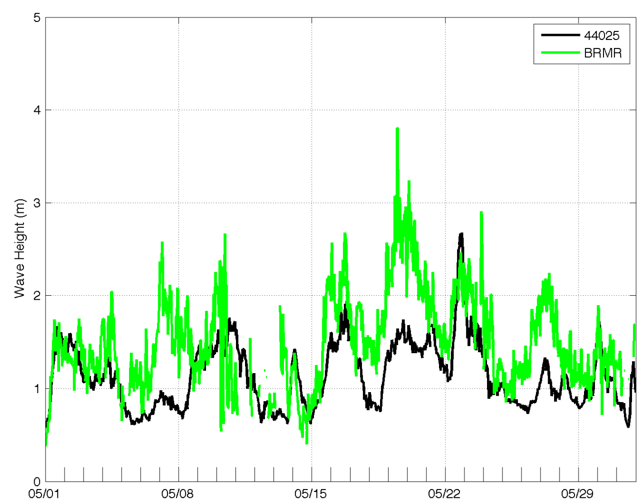

Figure 4: Time series plot of significant wave height as measured by the HF radar station with the SeaSonde operational algorithm at Brigantine (green) and NDBC buoy 44025 (black) for May 2012.

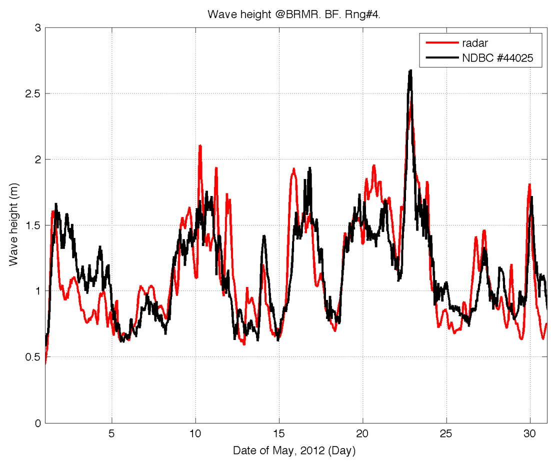

Figure 5: Time series plot of significant wave height as measured by the HF radar station with algorithm 4 integration with beam forming at Brigantine (red) and NDBC buoy 44025 (black) for May 2012

Table 4: Correlation coefficients between NDBC buoys and BRMR radar using different wave extraction algorithms. The time period of the comparison was for May 2012.

Method	NDBC Buoy	Correlation
SeaSonde Software	44025	0.53
SeaSonde Software	44065	0.50
Integration	44065	0.70
Peak Ratio	44065	0.74
Peak Ratio Second Harmonic Peak Excluded	44065	0.71
Integration after Beam Forming	44025	0.79

IV. Conclusions

Wave height comparisons were made between remotely sensed measurements with High Frequency radar and in situ wave buoys. The spatial variablility of the wave environment was provided by the wave buoys in the Mid Atlantic. This served as a backdrop for the comparisons between the radar measuremts and buoy measurements as the two were not colocated. The existing operational software for radar wave measurements showed moderate correlation with the wave buoys. Four new wave algorithms were tested on a month long data set and each showed an improvement over the exisiting method.

HF radar is a backbone technology of the United States Integrated Ocean Observing System (US IOOS). The surface current product from the HF radar network is widely used and operational with the US Coast Guard for search and rescue. The wave product from the individual radar stations shows good promise to becoming an operational product. These stations would fit well into the "National Operational Wave Observation Plan".

Acknowledgment

This work was funded by NOAA Award Number NA11NOS0120038 "Towards a Comprehensive Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS)". Sponsor: National Ocean Service (NOS), National Oceanic and Atmospheric Administration (NOAA) NOAA-NOS-IOOS-2011-2002515 / CFDA: 11.012, Integrated Ocean Observing System Topic Area 1: Continued Development of Regional Coastal Ocean Observing Systems.

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