Surface current and wave validation of a nested regional HF radar Network in the Mid-Atlantic Bight

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Abstract— **The National High Frequency Surface Current Mapping Radar Network is being developed as a backbone system within the Integrated Ocean Observing System (IOOS). Of the core variables recognized in the IOOS Development Plan, two can be measured by High Frequency Radar (HFR): ocean surface currents and ocean surface waves. Rutgers University operates a nested multi-frequency network of HF Radar systems along the coast of New Jersey. The network provides near real-time current observations with varying coverage from the coast to the shelf break. This is a subset of the larger regional coverage of the 26 site Mid-Atlantic HF Radar Consortium. The primary goal of this consortium is to operate the regional system in a coordinated way to guarantee the delivery of quality ocean current and wave data.**

In this paper we present the validation of both wave and current observations measured with this nested network. Particular emphasis is placed on surface current comparisons with Coast Guard deployed surface drifters (SLDMBs) and nearshore wave comparisons with moorings. The Coast Guard comparisons have a specific focus on quantifying the uncertainty in the HF radar surface current estimates as applied to search and rescue operations. These metrics will be used to ensure that quality data is going to the Coast Guard and that this information is properly incorporated into existing search planning tools. The nearshore measurements focus on algorithm development projects to incorporate shallow water effects into the estimates of nearshore waves.

Index Terms—**Coastal Ocean Processes, HF Radar, Ocean Observing Systems, Remote Sensing.**

I. Introduction

Saving lives at sea and on beaches is a national IOOS priority that is supported by Memoranda of Understanding (MOU's) between NOAA and the USCG to collaborate in the establishment of a national HF Radar network. The nation's oldest & largest triple nested HF Radar network is in the 26-site MA HF Radar Consortium (MAHFRC). The Mid-Atlantic coverage is distinguished by its nested coverage of important bays and sounds. The MAHFRC network is a testbed for the (1) NOAA HF radar research for bistatic operations, which will improve surface current mapping in complicated coastal regions, (2) USCG for evaluation of new products for SAROPS, and (3) DHS/Counter NarcoTerrorism for development of dual-use vessel tracking capabilities. Best practices developed in the MA can be spread nationwide through the NFRA, NOAA QARTOD, and ROWG. In this paper we present validation of HF radar derived surface current and wave fields to improve offshore Search and Rescue (SAR) and nearshore rip current warnings.

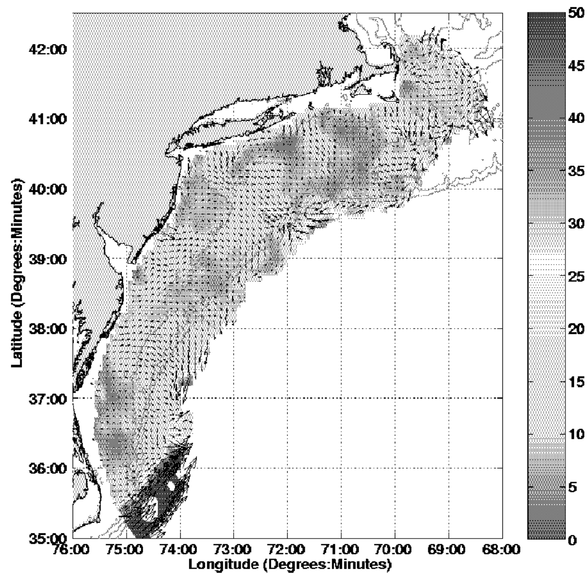

Figure 1. 24 hour average surface current map from the Long-Range MARCOOS CODAR Network.

Nationally, the Coast Guard receives an average of 13 SAR calls per day, of which 10 are successful rescues. To reduce the lives lost, the critical USCG need is to optimize SAR operations to minimize search time. SAROPS uses observed or predicted surface wind and surface current fields from the USCG's Environmental Data Server (EDS) to predict the trajectories of floating objects. During an actual event, or test, a cluster of a few hundred virtual objects is deployed in

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surface wind and current fields downloaded from EDS and allowed to drift over time. The cluster disperses based on the uncertainty estimates in the winds and currents. If SAROPS data has lower uncertainties there is lower dispersion in the cluster, a smaller search area, and greater likelihood for success. The analysis presented here is the result of a partnership with the U.S. Coast Guard R&D center in which expired SLDMBs were deployed in a series of targeted experiments to evaluate the growing data coverage of the HF radar network off the coast of the Mid-Atlantic Bight.

Rip currents are the number one cause of ocean drowning and rescue incidents along the coasts of the United States. According to the United States Lifesaving Association (USLA), 71% of the total surf zone rescues, 12,137 incidents, in 2003 were due to rip currents. Rip currents are strong near-shore features with cross-shore velocities on the order of 1 m/s and along-shore scales of tens of meters. Presently, several NOAA National Weather Service (NWS) Weather Forecast Offices (WFOs) around the country issue rip current warnings as part of a daily surf zone forecast. Within each forecast is a three tiered rip current outlook. The local WFO in Mount Holly New Jersey utilizes a linear regression wave model and local winds to categorize rip current risk as low, moderate, or high. Forecasters at the Mount Holly WFO indicate that the model is data limited and more near-shore wave and current observations are needed to improve the daily rip current outlooks (James Ebberwine, NWS; personal communications).

II. Background

A. HF Radar Surface Current Processing

High Frequency (HF) radar systems, typically deployed along the coast use Bragg peaks within a signal (3 ~ 30 MHz) scattered off the ocean surface to calculate radial components of the total surface velocity at a given location [1]. Crombie recognized that these peaks were the result of an amplification of a transmitted wave by surface gravity waves with a wavelength equal to half that of the transmitted signal [2]. A signal scattered off a wave and back toward the antenna will be in phase with a signal that traveled to the next surface wave (1/2 transmit wavelength further) and returned to the original wave (another 1/2 transmit wavelength). The frequency of the backscattered signal will be shifted depending on the velocity of the scattering surface. Using linear wave theory the phase speed of the surface waves can be separated from the total frequency shift, leaving only that shift due to the surface current. Over a given time period, sites along the coast generate radial component maps of the surface current with typical resolutions on the order of 1-6km in range and 5 degrees in azimuth. The CODAR-type systems discussed here are direction finding systems that use a three element receive antenna mounted on a single post to determine the direction of the incoming signals. The angular resolution, set in the processing, is typically 5 degrees. Since the Doppler shift can only resolve the component of the current moving toward or away from the site, information from at least two sites must be geometrically combined to generate total surface current maps. For the purpose of this paper, all surface current comparisons will focus on the long-range (5 MHz) component of the network.

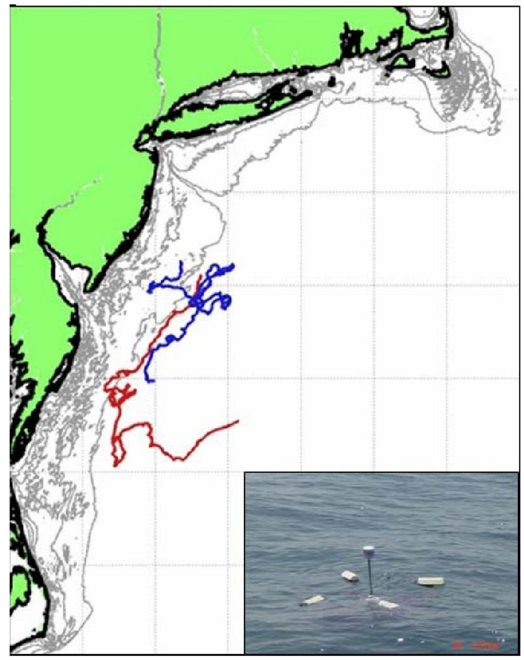

Figure 2. Tracks of the SLDMB deployment in February, 2007. A picture of a SLDMB just after deployment is shown in the lower right.

Every hour the available radial vector maps are combined into a single total vector map (Figure 1). All radial component vectors within 10 km of each grid point were used in the combination. A total vector was only generated if at least 3 radial vectors from at least two remote sites were used in the combination. The uncertainty of the combined totals can be separated into radial vector uncertainty and geometric uncertainty. The geometric uncertainty is based on the angles of the radial component vectors. The further the radials are from orthogonal, the larger the uncertainty. This is described by Chapman et. al. [3] as Geometric Dilution Of Precision (GDOP). These uncertainties increase along the baseline between the coastal sites as well as well offshore. In these regions the radial component vectors are resolving the along-shore and cross-shore velocity components, respectfully. Without a better representation of the orthogonal velocity component, error is introduced in the total vector estimate at the combine step. The relative magnitude of the geometric uncertainty was calculated at each grid point for every current map [4]. Using this scalar as an indicator of the magnitude of the geometric contribution to the uncertainty, data subject to poor geometry were eliminated. All data below a threshold of 1.25 was included in the analysis. This threshold was chosen based on qualitative analysis of previous data.

B. HF Radar Wave Processing

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 used for current mapping. The derivation of the classic model presently employed by several groups for HF wave measurements was done 35 years ago [1]. Lipa first showed how this echo could be inverted to give wave spectral information, and it was first applied to narrow-beam phased array systems [5]. The methods were next extended to the CODAR compact crossed-loop antenna [6]. Since these data are derived from the second order spectrum, the lower signal to noise ratio limits data closer to the coast. The CODAR operational software is based on fitting the radar data with a model of the ocean wave spectrum. Second-order data is collected from the four second-order sidebands of hourly averaged cross spectra. Least-squares fitting of the Pierson-Moskowitz model for the ocean wave spectrum to the radar Fourier coefficients are used to derive estimates of the significant wave height, centroid period and direction. An advantage of this method is that it uses all available data above the noise, including cases where only one sideband is usable. Depending on the operating frequency of the HF radar site, the second order region of the Doppler spectrum becomes saturated for given wave conditions. For the 25 MHz system, any sea state over 4 m significant wave height will saturate the second order spectrum. For the longer range 5 MHz system, this saturation occurs at wave heights over 20m. It is important to note that the waves observed by the CODAR system are limited to those felt by the Bragg waves. As a result, the shortest period wave included in the HF radar data is 5 seconds. This lower bound will increase with increased noise. Additionally, because these are direction finding systems, the wave measurements are an average of the wave field over a measurement arc. The CODAR system has and continues to provide wave spectra, significant wave height, peak period, and direction from the range cells within several kilometers of the coast.

III. Results

A. Surface Current Validation

Self Locating Data Marker Buoy (SLDMB) position data was used to evaluate the CODAR observations. The SLDMBs are surface drifters drogued to one meter depth. Throughout the deployment, velocities based on two SLDMB positions one hour apart were calculated every half hour. These surface velocity estimates were compared to the radial and total vector estimates of the Long Range CODAR network off the New Jersey coast [7],[8]. For both the radial and total vector comparisons, the velocity average was set to match the sampling of the CODAR. The SLDMB data discussed here are from two SLDMBs deployed on opposite sides of the mid-shelf front off the southern coast of New Jersey in February 2007. Horizontal shears associated with the mid-shelf front lead to a large separation between the two with the offshore SLDMB moving quickly to the southwest toward North Carolina (Figure 2). The inshore SLDMB, on the other hand, spent over 40 days within the footprint of 4 remote CODAR sites including Loveladies, NJ, Tuckerton, NJ, Wildwood, NJ, and Assateague, MD. This offers a unique opportunity to look at relatively long time series of surface current data to compare to radial data from a series of sites along the Mid-Atlantic coast. For much of the comparisons discussed here, the sample of concurrent velocity pairs between the SLDMB and CODAR exceeds 900.

For the purpose of this paper we focus on the radial component vectors measured at the Loveladies, Tuckerton and Wildwood NJ CODAR sites as they had the longest data coverage overlap with the SLDMB. For all three sites the SLDMB spent almost the entire period in the 50% or greater coverage area. For each time step the velocity estimates from the SLDMB track was rotated into a coordinate system aligned with the radial direction of each remote site. The rotated SLDMB velocity was then directly compared to the observed CODAR radial current vector. Care was taken to ensure that the averaging time of both the CODAR and SLDMB current estimate matched. For all three sites, the number of comparison points in the sample exceeded 860. Each site shows a strong correlation between the SLDMB and CODAR with an RMS (r^2) ranging from 11.5 (0.62) to the north and 10.2 (0.79) to the south. A time series shows that both are resolving both the larger scale tidal and sub tidal variability throughout the 40-day deployment (Figure 3).

The east (U) and north (V) components of the SLDMB

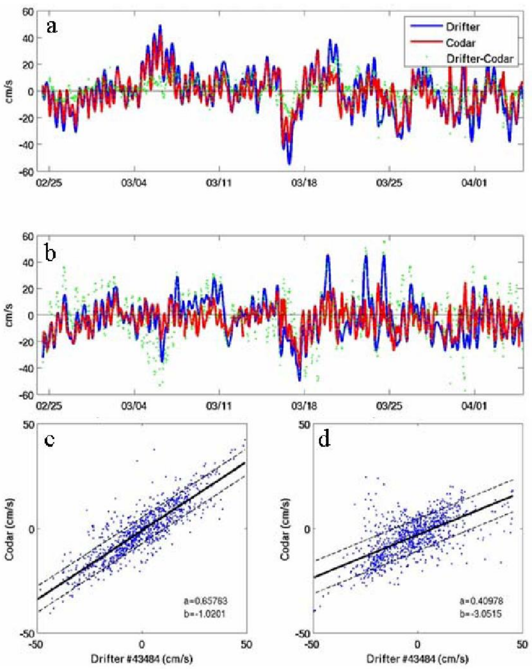

Figure 3. Radial vector time series (split between panel a & b) and (c) scatter of the radial component vector relative to Wildwood New Jersey

velocity estimates are directly compared to the geometrically combined radials from CODAR sites along the New Jersey and Maryland coasts. The radials were combined using the community toolbox with an averaging radius of 10 km. Vectors with a mapping error of greater than 1.25 were excluded from the analysis [4]. Again the data coverage was excellent with 929 velocity pairs throughout the deployment. As with the radial comparisons we see consistency in both the tidal and sub-tidal velocities, (Figure 4) with RMS (r^2) of 8.5 (0.87) and 11.7 (0.63) for the east and north components respectively. The disparity between the east and north component vectors comes for the geometry of the CODAR combination. Since the sites are all oriented along a roughly north/south coastline, the radial component vectors better resolve the east component of the total velocity compared to the north component.

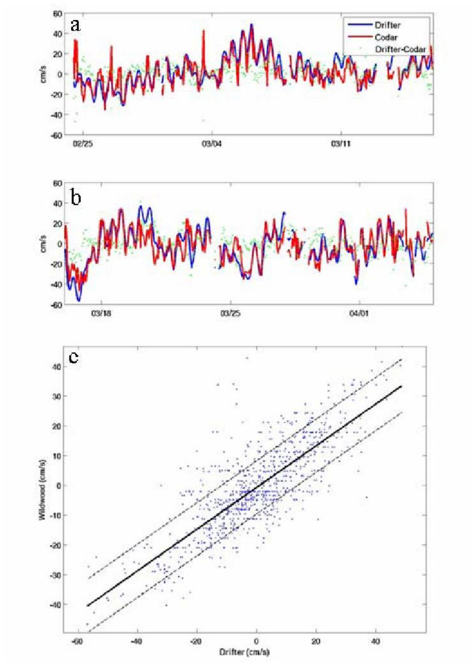

Figure 4. Total vector time series and scatter for the East (a,c) and North (b,d) components

B. Nearshore Wave Validation

The direct comparison results presented here focus on the 25 MHz site in Breezy Point, NY. Time periods were selected that provided simultaneous far-field and near-field observations between December 22, 2005 and January 12, 2006. This time was selected because far-field measurements from the NOAA NDBC buoy 44205 and a bottom mounted AWAC were both available (Figure 5). The NOAA buoy, located 70 km southeast of Breezy Point provided the far field observations and the AWAC deployed within the Breezy Point measurement cell provided the near field measurements. All data were averaged to match the hourly sampling of the HF radar observations.

All three sensors show a mean significant wave height on the order of 1m, with slightly higher waves offshore and smaller waves inshore. The CODAR wave heights compared to the far-field and near-field sensors show significant correlation on the order of 0.65 and 0.71 with an RMS on the order or 0.50-0.75 m (Figure 6). The time series shows that all three sensors are capturing the events with the CODAR observed wave heights falling somewhere between the smaller nearshore waves and the higher offshore waves. The correlation between the CODAR wave period and those of the two in situ sensors is not as strong as seen in the significant wave height. With a mean of 9.25s, the CODAR measurement is biased toward longer period waves. Since the CODAR measurement is based on second order region of the spectrum, it is limited to longer period waves modulating the surface Bragg waves. For that reason, the CODAR measurement is restricted to waves with a period of at least 5 seconds. In direction, the CODAR mean is biased toward waves coming from the southeast. This is likely related to the location of the in situ sensors. Both sensors deployed off the coast, have opportunities to sample waves from a full 360 degree swath. The CODAR, on the other hand, is deployed along the coast and limited to onshore waves only. As the waves approach the coast, shallow water refracts the waves normal to the coast (i.e. southeast).

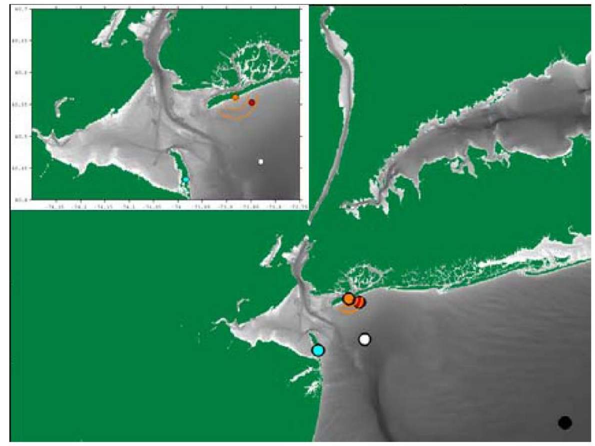

Figure 5. Map showing the locations of the measurement sites, including NOAA NDBC buoy 44205 (black), 25 MHz at Breezy Point (orange), and the AWAC (red). Range cells are also shown for Breezy Point.

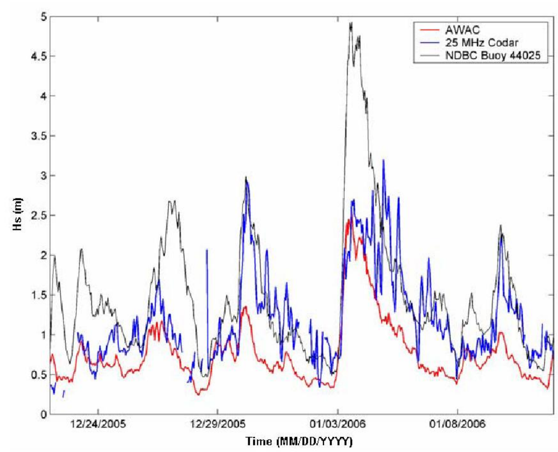

Figure 6. Time series of significant wave height measurements from the 25 MHz CODAR (blue), buoy 44025 (black), and the AWAC (red).

IV. Summary

The SLDMBs have offered an excellent opportunity to better understand both the subgrid scale variability and the uncertainty in the radial and total vector component surface current estimates from an HF radar system. Direct comparisons to CODAR show RMS differences on scales ranging from 8-11 cm/s. Through these deployments and others like them we can properly evaluate these new data streams so that they can be properly integrated into the new search and rescue tool (SAROPS). As part of a recently funded NOAA project (MARCOOS), an even larger HF radar footprint will be made available to the Coast Guard stretching from Cape Cod, MA in the North to Cape Hatteras, NC in the south (Figure 1). In addition these data will be incorporated into four forecast systems. These forecasts will be evaluated against future SLDMB deployments so that they too can be incorporated into SAROPS.

For the near-shore wave observations, the effect of shallow water is to (i) increase the wave height, (ii) affect the wave period, and (iii) to refract the long waves to move more perpendicular to the depth contours. We see evidence of these effects in these baseline comparisons. The RMS waveheight at 25 MHz falls between the nearshore AWAC and the far offshore NOAA buoy. This makes sense physically; one would expect higher waves (all directions) on average, further offshore. We also see a tendency for the mean wave direction to be aligned more perpendicular to the coast in the CODAR data compared to the offshore and nearshore in situ data. These results and others have prompted a focused project to incorporate these bottom effects into the CODAR wave processing software. A project funded by New Jersey Sea Grant will test these new algorithms with a similar multi-frequency approach discussed here including near-field and far-field wave measurements. The baseline evaluation discussed here will be used to evaluate these new algorithms that account for shallow water properly in extracting waves from the 2nd-order echo.

Acknowledgment

The authors would like to acknowledge the efforts off all the participants in the Mid-Atlantic HF Radar Consortium stretching from Cape Cod, MA to Cape Hatteras, MA. We would also like to thank the U.S. Coast Guard R&D Center and Office of Search and Rescue who provided their SLDMBs and expertise in the experiment setup and analysis. Dave Ullman (URI) provided valuable input in the SLDMB deployment design and interpretation of the track data compared to the HF Radar fields. We would also like to thank the crews of the R/V Endeavor and Sorenson Miller for their help with the deployments. The wave validation work is supported by two separate projects funded through NOAA.

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