High Frequency Radar Observing Systems in SEACOOS: 2002-2007 Lessons Learned

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Abstract
From 2002-2007, the Southeast Coastal Ocean Observing System (SEACOOS) deployed high frequency (HF) radars to overlook several venues stretching from the West Florida Shelf to the North Carolina Shelf. Based on extensive deliberations within SEACOOS, we decided to assess the two differing types of coastal ocean current radars within the southeast that were on the commercial market. The long-range SeaSondes (SS) were deployed to sense surface currents at hourly intervals and a 6 km resolution along the West Florida Shelf and the North Carolina Shelf. The medium and long-range Wellen Radars (WERA) were deployed along the Florida Straits and along the South Atlantic Bight with spatial resolutions of 1.2 to 3 km sampling at time scales of minutes. A common theme in these deployments was to sense the Loop Current, Florida Current and the Gulf Stream, which transport heat poleward as part of the gyre circulation.

Several lessons were learned as part of these deployments, such as the need to protect against lightning strikes and the challenge of providing robust communication links between the remote sites and a central hub to make the data available in near real-time. Since states in the southeast and surrounding the Gulf of Mexico are prone to the passage of hurricanes, surface current and wave measurements during hurricanes are invaluable for improving storm surge and inundation models that are now being coupled to surface waves. In addition, significant wave heights (and directional surface wave spectra) are critical in the model assessment. Data quality and accuracy of the surface current and wave fields remain a central issue to search and rescue and safe maritime operations and to understanding the limitations of these radar systems. As more phased array systems (i.e., WERAs) are deployed for surface current and wave measurements, more attention needs to be placed on the interoperability between the two types of systems to insure the highest quality data possible is available to meet applied and operational goals. To insure the highest quality data possible, a full-time technician and a half-time IT specialist are needed for each installation as well as access to spares to keep these systems running consistently and to make quality observations available in near real-time.

Coast and the West Florida Shelf. One of the programmatic goals focused on testing the latest technologies to acquire data from both long-range (lower-resolution) and medium-range (higher-resolution) HF radars using both systems. The experimental program sought to exploit other measurement capabilities such as surface waves (both significant wave heights and directional wave spectra) as well as surface wind direction.

One of the concepts introduced in this program was the development of HF radar testbeds where sensors and instruments could be tested in the coastal ocean. For example, during the summer of 2003, a dual-station WERA system was deployed along the West Florida Shelf overlooking acoustic Doppler current profilers (ADCP) moorings deployed within the University of South Florida Coastal Ocean Modeling and Prediction System (COMPS). These cross-shelf arrays provided an opportunity to assess WERA-derived surface currents over these moorings where the uppermost bin was located at 4-m depth. In 2005, a “mini-waves” experiment was conducted where tri-axial surface wave instruments (courtesy of National Data Buoy Center and Georgia Institute of Technology) and bottom-mount acoustic profilers were deployed on two moorings over a two-month
period in assessing WERA-derived wave measurements within the Florida Straits (see Voulgaris et al., this issue). The results indicated fairly good agreement between the buoy and WERA-derived significant wave heights and directional wave spectra using algorithms developed by Wyatt et al. (2003). Another important aspect of the SEACOOS HF radar undertaking was a link to the data management activity. The interaction permitted the near real-time aggregation and visualization of the current observations from the HF radar, in situ ADCPs and drifters in the SEACOOS footprint and demonstrates the feasibility of sharing the observations with the community of interested users.

The objective of this paper is to provide a perspective on these differing radar systems based on our collective SEACOOS experiences; and, more importantly, lessons learned from these deployments in differing venues where the dynamic range of the currents is large, as shown in Figure 1. The manuscript describes the basic radar premise and experimental designs in Section 2, including results of the acceptance test along the West Florida Shelf. In Section 3, time lines and a subset of interesting observations are described. In section 4, an overview of surface wave and wind measurements from HF radar techniques including directional waves is presented. Section 5 is a summary of lessons learned followed by concluding remarks.

2. Experimental Design

For both DF and BF techniques, the approach utilizes backscatter from surface waves of one-half the radar wavelength (i.e. Bragg wave) to form a Doppler Spectrum (Crombie 1955; Stewart and Joy, 1974). First-order returns in this spectrum are associated with the frequency shift from the Bragg frequency that are proportional to the radial surface current of the dominant peak in the spectrum for either receding or advancing waves toward the radar site. To map the two-dimensional surface current vector, each experimental domain requires at least two radar sites. The ratio of the first-order Bragg peaks of the advancing and receding waves is related to the wind direction, and with two or more stations the ambiguity in resolving the wind direction is removed. Surface wave signatures, however, are derived from the second-order returns for both the significant wave heights (H) and directional wave spectrum (WERA only) following Wyatt et al. (2003). The domain over which surface waves can be mapped is a function of the noise floor that increases with distance offshore. Waves can be mapped over 55 to 65% of the radar domain.

2.1 Radar Characteristics

Radar characteristics for both DF and BF techniques are summarized in Tables 1 and 2. The key aspects for SEACOOS are spatial and temporal resolution, range and data processing requirements. Determining how often the surface current measurements are needed is a function of the oceanic regime and the HF coastal radar application that differs for each regional association. Horizontal resolution depends on bandwidth and must be part of the licensing request to the Federal Communication Commission (FCC). A principle data processing issue is enabling a real-time capability in observing the coastal surface currents and waves. Basic characteristics of the SS systems are listed for the normal-range (medium-resolution) to long-range (low-resolution) systems in Table 1. There is the tradeoff between transmission frequency and bandwidth, which determine range and resolution, respectively. The SS system uses a whip transmit (Tx) antennae and one crossed-loop/monopole receiver (Rx) antennae. The least squares fitting procedure of Lipa and Barrick (1983) has been replaced by MUSIC algorithm which allows for more than one azimuthal direction of the surface current (DePaolo and Terrill, 2007). An important consideration for SS systems is the measurement of the receiver beam pattern (Kohut and Glenn, 2003; Emery et al., 2004). Especially for deployment sites in developed areas, the measured beam pattern can depart significantly from the ideal beam pattern and failure to use the correct beam pattern in processing can significantly impact the accuracy of the current estimates. At lower transmitting frequencies in the 5 to 10 MHz range for longer range transmissions (Bragg wavelengths of 30 and 15 m, **FIGURE 1**

HF radar deployments (and radial coverage) with surface current vectors in April 2007 (EFS and MAB) and October 2007 (WFS) in the SEACOOS domain relative to bottom terrain.
range systems there is typically an hourly output that is an updated, three-hour running average.

The WERA system transmits a frequency modulated continuous wave (FMCW) chirp that avoids the 3 km blind range in front of the radar which is an issue with pulsed systems (Gurgel et al., 1999; Essen et al., 2000). The temporal resolution of WERA is a function of the chirp characteristics (0.26 s) and can be as little as a few minutes up to hourly intervals (Table 2). For transmission frequencies of 8 and 16 MHz, Bragg wavelengths are 18.7 and 9.35 m, respectively. The four-element transmitter is arranged to encompass about a 120° swath. WERA has the flexibility to be configured into a DF array (such as SS) where 4 antennae may be set up in a square where the distance between elements is proportional to the Bragg wavelength. A linear array is set up consisting of 4n elements (n =2,3,4….), and for accurate surface wave directional finding average.

### TABLE 1

SeaSonde specifications and capabilities in long-range (-6 MHz) and medium-range (~25 MHz) systems.

<table>
<thead>
<tr>
<th>Range (km)</th>
<th>6 MHz</th>
<th>25 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>180-200</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>6-12</td>
<td>1-3</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE 2

Capabilities of the WERA system in Beam Forming (BF) mode using a phased array for the 8 and 16 MHz. The system can be configured in Direction Finding (DF) mode where the array is arranged in a square. For waves 16-elements are needed to resolve the directional part of the signals.

<table>
<thead>
<tr>
<th>Range (km)</th>
<th>8 MHz</th>
<th>16 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>175-200</td>
<td>80-100</td>
<td></td>
</tr>
<tr>
<td>Resolution (km)</td>
<td>2.4-4.8</td>
<td>0.6-1.2</td>
</tr>
<tr>
<td>Depth of Measurement (m)</td>
<td>1.4</td>
<td>0.7</td>
</tr>
<tr>
<td>Accuracy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radial Current (cm s⁻¹)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Current Speed (cm s⁻¹)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Vector Direction (°)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Baseline Distance (km)</td>
<td>75-100</td>
<td>40-60</td>
</tr>
<tr>
<td>Transmit Elements</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Receive Elements (BF)</td>
<td>12-16</td>
<td>12-16</td>
</tr>
<tr>
<td>Receive Elements (DF)</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Average Power (W)</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

2.2 West Florida Shelf Acceptance Test

A 16 MHz dual-station WERA system was deployed along the West Florida Shelf starting 23 Aug and ending 25 Sept 2003 to sample surface circulation over moored ADCPs deployed by USF (Shay et al., 2007; Liu et al., 2007). This short-term deployment was conducted to confirm the functionality of the WERA system which was the first deployed on the U.S. mainland. A 33-d nearly continuous time series of radial and vector surface currents was acquired at 30-min intervals. Coastal surface currents were mapped over an approximate 40 km x 80 km domain (Figure 2) with sites located in Venice Beach, FL and along Coquina Beach, FL, equating to a baseline distance of 45 km (i.e. ~half the radar range). Each site consisted of four-element Tx and sixteen-element Rx arrays. A total of 1628 snapshots of the vector surface currents were acquired with only 70 samples respectively), available bandwidth tends to be limited by the FCC compared to Very High Frequencies (VHF: >50 MHz) where bandwidth is available to sample high spatial resolution (< kilometer). The region of the shelf where standard processing can produce reliable velocity estimates is limited to water depths where the surface waves producing the Bragg scattering can be considered deep water waves. This constraint limits the inshore coverage region on shallow shelves and is a concern for the longer range (lower frequency) systems used. All SS systems are omni-directional and use a pulsed swept frequency continuous wave with pulse widths of 100-200 µs in normal mode compared to 1000-2000 µs in low-resolution mode. For the long-range systems there is typically an hourly output that is an updated, three-hour running average.

The WERA system transmits a frequency modulated continuous wave (FMCW) chirp that avoids the 3 km blind range in front of the radar which is an issue with pulsed systems (Gurgel et al., 1999; Essen et al., 2000). The temporal resolution of WERA is a function of the chirp characteristics (0.26 s) and can be as little as a few minutes up to hourly intervals (Table 2). For transmission frequencies of 8 and 16 MHz, Bragg wavelengths are 18.7 and 9.35 m, respectively. The four-element transmitter is arranged to encompass about a 120° swath. WERA has the flexibility to be configured into a DF array (such as SS) where 4 antennae may be set up in a square where the distance between elements is proportional to the Bragg wavelength. A linear array is set up consisting of 4n elements (n =2,3,4….), and for accurate surface wave directional finding average.

### FIGURE 2

Percentages of good data (colors: left panel) and accuracy estimates HF radar-derived radial currents (cm s⁻¹: right panel) from Coquina and Venice Beach based on a weighted signal-to-noise ratio from the Doppler Spectra averaged over the 33 days of measurements over the WFS. Triangles (black) represent moored COMPS ADCPs and the diamond is a CMAN station (from Shay et al., 2007).
missing from the vector time series. Comparisons to subsurface measurements from ADCP profiles revealed RMS differences of 1 to 5 cm s$^{-1}$ for both radial and current components. Regression analyses for the vector current components (u-positive east, and v-positive north) indicated slopes close to unity with small biases between surface and subsurface measurements at 4-m depth at EC4 (20-m isobath) and NA2 (25-m isobath) moorings from the COMPS array (Weisberg et al., 2002).

Radial current accuracy estimates, based in part on Signal to Noise Ratio (SNR), are an important feature to build into the HF radar network (Figure 2). An approach to estimating radial current accuracy that has been generalized to both DF and BF techniques based on Doppler spectra has been proposed by the University of Hamburg. The SNR is used as a weighting function to the backscattered power variances in these accuracy estimates (K.-W. Gurgel, 2007, pers. comm.). The resultant radial current accuracy estimates for the DF approach ranged from 2 to 7 cm s$^{-1}$ over the grid with larger uncertainty in the far field compared to the core of the radar domain. A similar approach can be implemented for DF algorithms.

### 2.3 Southeast Florida Shelf

After completion of the acceptance test in summer 2003, WERA was deployed at two sites (Key Biscayne, North Key Largo) in May 2004 and became a real-time, web-based product in Sept 2004. Each site consists of a 16-element linear Rx and a 4-element Tx array (16 MHz) configured in a rectangle. The HF radar products are surface current speed and direction, and significant wave heights. Sampling intervals have ranged from 10 to 20 minutes and velocities are accurate to less than 6 cm s$^{-1}$. Since June 2004, WERA measurements have stretched from the shallow near-shore waters to approximately 100 km offshore -50% of the time, and penetrate -0.7 m in depth. With the exception of a few interruptions (i.e. Nov, Dec 2005 after Hurricane Wilma), these radar sites have been working nearly continuously for more than four years (Figure 3). Measurements acquired during hurricane Jeanne indicated an energetic coastal ocean response to surface winds of up to 25 m s$^{-1}$ (not shown).

While Hurricane Jeanne made landfall in West Palm Beach, an eastward current response emanated from the Biscayne Bay on the south side of Jeanne. As the hurricane made landfall, winds increased to more than 24 m s$^{-1}$, forcing surface currents of 1 m s$^{-1}$ out of Biscayne Bay. During strong events, the HF radar response in the far-field tends to lose signals as the noise floor and the Bragg peaks may not be distinguishable in the Doppler spectra (Shay et al., 1995). Given fetch-limited conditions (offshore wind) and that the measurements were acquired along the south side of Jeanne's wind field, the observations suggest WERA can remain operational for moderate winds up to 25 m s$^{-1}$ winds if the electrical power grid remains on.

From September 2004 to June 2005, a bottom-mounted, upward-looking ADCP operating at 300 kHz was deployed at 86-m depth (Parks et al., 2008). This instrument was deployed at a location inside the WERA array at approximately 0.5 km from the nearest cell. As shown in Table 3, monthly RMS differences were calculated as well as slopes and biases from a regression analysis over the 9-month record. RMS differences ranged from 0.1 to 0.25 m s$^{-1}$ between the surface and 14-m depth, or 1 to 2 cm s$^{-1}$ m$^{-1}$ consistent with previous measurements on the western flank of the Florida Current. First-order statistics reveal a highly variable domain dominated by the Florida Current where the northward surface velocity in the v-component were more than four times larger than in the u-component of current.

### Table 3

Summary statistics from a comparison of WERA surface currents and 14 m subsurface currents at a moored ADCP on the shelf, including RMS differences and regression parameters (cm s$^{-1}$) from Sept 04 to June 05. The last column is for 9 months of the ADCP deployment.

<table>
<thead>
<tr>
<th></th>
<th>Sept</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>April</th>
<th>May</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>uRMS</td>
<td>29.1</td>
<td>29.3</td>
<td>10.0</td>
<td>8.8</td>
<td>9.5</td>
<td>13.9</td>
<td>13.1</td>
<td>12.1</td>
<td>15.5</td>
<td>16.6</td>
</tr>
<tr>
<td>Slope</td>
<td>-0.1</td>
<td>0.0</td>
<td>0.4</td>
<td>0.4</td>
<td>0.5</td>
<td>0.1</td>
<td>0.4</td>
<td>0.3</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Bias</td>
<td>7.2</td>
<td>15.4</td>
<td>11.5</td>
<td>10.2</td>
<td>5.8</td>
<td>7.2</td>
<td>6.3</td>
<td>8.2</td>
<td>12.3</td>
<td>11.3</td>
</tr>
<tr>
<td>vRMS</td>
<td>13.2</td>
<td>10.4</td>
<td>14.6</td>
<td>14.7</td>
<td>12.3</td>
<td>22.2</td>
<td>29.7</td>
<td>22.7</td>
<td>24.2</td>
<td>18.9</td>
</tr>
<tr>
<td>Slope</td>
<td>1.1</td>
<td>1.1</td>
<td>0.8</td>
<td>0.8</td>
<td>1.0</td>
<td>0.9</td>
<td>0.9</td>
<td>1.0</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Bias</td>
<td>-11.5</td>
<td>-7.7</td>
<td>10.6</td>
<td>2.8</td>
<td>-5.0</td>
<td>-12.0</td>
<td>-21.0</td>
<td>-3.3</td>
<td>-21.1</td>
<td>-8.8</td>
</tr>
</tbody>
</table>

**FIGURE 3**

Time line of operational WERA measurements beginning in May 2004 till March 2008 for Crandon Park (upper), North Key Largo (middle) radial currents and the resultant vector time series.
These weaker subsurface currents in the east-west direction emphasize dramatic differences throughout the period. However, of interest are periods of flow reversal between surface and subsurface currents that decouple (or decorrelate) surface from subsurface currents as observed in Oct 2004. By contrast, the v-component has a dynamic range of 2.2 to -0.7 m s\(^{-1}\) and the surface and subsurface currents are highly correlated.

2.4 South Atlantic Bight
Two shore-based WERA systems have been operational since April 2006 over the South Atlantic Bight with sites on St. Catherine and Prichard Islands in Georgia and South Carolina, respectively. Based on the design of Gurgel et al. (1999), this long-range WERA system operates at a frequency of 8.3 MHz with a daytime range of 220 km, reaching across the broad shelf and over the shoreward flank of the Gulf Stream (Figure 4). At the present time, this WERA system includes 12-element Rx arrays, allowing determination of range and azimuth for current estimation, and permit use of the second-order returns for mapping significant wave heights. Percent data return for vector velocities over the entire record illustrates the areal coverage achieved with these two installations. A strong diurnal cycle is seen with lower areal coverage occurring between the hours of 8 and 11:30PM EST when background noise is at its peak, decreasing the SNR. During peak SNR hours (11AM to 2:30PM EST), the areal coverage is quite good, and at the shelf edge, the 70 to 100% coverage zones extend along the shelf approximately 140 km. Thus, the engineering design criteria for this radar installation for sensing the Gulf Stream have been achieved in the highly dynamic regime.

2.5 West Florida Shelf
Three long-range SS were deployed at Redington shores, Venice, and Naples, FL in Fall 2003 to Spring 2004. The Venice station is in collaboration with Mote Marine Laboratory and Rutgers University close to a nearby U.S. Coast Guard Station.
An example of potential coverage is shown in Figure 5, during a recent interval when all three radars were working and the winds were sufficient to support a well developed wave field. Observations like this have been the exception rather than the norm over the WFS as results have been mixed over the deployment period. For example, a myriad of problems have plagued the installation and have ranged from lightening strikes to interference by Homeland Security communications on nearby frequencies in the 5 MHz range. When the systems have been working well, a measure of their collective performance based on radial coverage’s from three sites is shown in Figure 5 (right panels) for Redington Shores, Venice, and Naples. A comparison of radials to in situ observations by ADCPs in the COMPS array at 2-m depth indicates the RMS differences have been 8 cm s⁻¹ between surface and near-surface radials. This equates to about 4 cm s⁻¹ m⁻¹ compared to those from the phased array deployment in summer 2003 of 1.5 to 2 cm s⁻¹ m⁻¹ and more recently on the East Florida Shelf (Parks et al., 2008).

### TABLE 4

Summary statistics (cm s⁻¹) from a comparison of SS standard processed currents with ADCP-observed subsurface currents 3 m below the surface on the shelf off Oregon Inlet, NC between April and Aug 2004.

<table>
<thead>
<tr>
<th>摘要</th>
<th>cm s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>uRMS</td>
<td>17.0</td>
</tr>
<tr>
<td>Slope</td>
<td>0.47</td>
</tr>
<tr>
<td>Bias</td>
<td>-1.6</td>
</tr>
<tr>
<td>vRMS</td>
<td>19.9</td>
</tr>
<tr>
<td>Slope</td>
<td>0.49</td>
</tr>
<tr>
<td>Bias</td>
<td>1.5</td>
</tr>
</tbody>
</table>

2.6 North Carolina Shelf

Two long-range SS systems were deployed at the United States Army Corps of Engineers (USACE) Field Research Facility (FRF) in Duck, NC in May 2003 and at the United States Coast Guard (USCG) station in Buxton, NC, located just north of Cape Hatteras in August 2003. These sites on the Outer Banks were chosen because of readily available power and communications infrastructure. The systems have experienced a variety of problems but have remained in operation since deployment (Figure 6). Coverage has been highly variable but under optimal conditions vector currents are measured more than 175 km from shore. The operating frequency of the system, near 5 MHz, is in a range of active frequencies and suffers from large diurnal variations in noise, presumably associated with vertical movement of the ionosphere (Teague, 2001), and from intermittent noise sources that are likely of more local origin. More typical daytime and night time coverages are shown in Figure 6 for a time period when other noise sources were minimal. The 15 m isobath off the Outer Banks is relatively close to shore and therefore does not significantly limit the inshore coverage of the radar system at present.

Over the past three years, limited evaluations have been conducted between surface and subsurface currents in this regime. An ADCP mooring has been maintained in 30 m of water in the footprint of the system since 2004. Comparison of the standard processed SS velocity estimates with ADCP currents, acquired between April 1 and August 25, 2004, from 3 m beneath the surface that have been windowed using a boxcar filter similar to the SS processing suggest RMS differences of 15 to 25 cm s⁻¹ in both flow components. Regression of the signals indicates small biases with limited correlation indices between the two signals (Table 4). The v-component visually follows a 1:1 relationship for the majority of the data set, but large outliers in the SS data skew the regression statistics. The same is not true for the u-component, suggesting an underestimate of velocities by the SS in the cross-shelf direction. As discussed in the next section, there are identified problems with the standard processed current estimates; once a revised processing procedure is finalized a more thorough evaluation will be undertaken.

From an operational perspective, the main challenges faced in maintaining a near real-time data feed have been physical damage, power and communications issues. The systems suffered several lightning strikes in the first year of operation that highlighted the lack of protection in the SS system design. This oversight wasn’t too surprising given the lack of systems deployed in the SE and elsewhere and has since been addressed. The other significant physical issue has been beach erosion. At the Buxton site, the installation site was renowned for high erosion rates (the system was deployed where the Hatteras lighthouse used to be—not a
wise choice in hindsight) and the antennas have been moved regularly because of the changing shoreline. The moves have required repeated beam pattern mapping efforts that are particularly challenging at this location because it involves running Hatteras Shoals (Graveyard of the Atlantic Ocean). Duck has been much more stable in the long term but both systems have been hit by hurricane storm surges that damaged the systems. We have considered relocating the Buxton system because of all these problems but the National Park Service permitting requirements and establishment of power and communications at a remote site make moving the system an involved process.

Power and communications have also been challenging to establish in a sustained fashion. Power at the Duck site is secure, but power at Buxton site has been shut off several times during mandatory evacuations. A backup generator was installed in 2006 prior to the storm season to address these power outages but it has yet to be pressed into dedicated service. Establishing reliable communications has been challenging but has been robust for the last 1 to 2 years. The initial use of phone lines proved quite unreliable. Switching to cable modems has improved communications but leave the systems at the mercy of the cable provider. Service interruptions are not uncommon, as are configuration changes that go unannounced. The other main challenge faced at Duck is that of shared use of the modem with the FRF. Security issues have complicated the configuration and forced abandonment of the FRF internet service, however the FRF accommodated the HF radar system by purchasing a separate cable line to be shared by the SS installation and visiting scientists at the FRF. Sharing this service with FRF has led to additional hardware challenges, but after a couple of years these are now manageable. Locating the radar at the FRF, which is a test bed for other ocean observing instruments including other radars, has also proven to be a challenge due to local interference (specifically from microwave radar energy) arising from the other ongoing experiments.

FIGURE 7

Time series (top figure) of 10 m winds (40-h low pass filtered) and surface friction velocity (m s\(^{-1}\)) from Fowey Rocks CMAN station (yellow star in panel a below) in the upper two panels. The u and v (cm s\(^{-1}\)) with the surface velocity (blue) and the 14 m current (dash-dot: black) from an ADCP (yellow box in panel a below). Daily correlation coefficients (γ; bars) and phases (radians) of the subsurface current relative to the surface currents in the lowest panel of the top figure. Gray areas represent times of eddy passage in Dec 04 through Feb 05 where the largest signal occurred 20-21 Jan (bottom figure) with an evolution of a sub-mesoscale vortex through the EFS radar domain associated with atmospheric frontal passage with predominately southward winds (yellow arrow) of 12 m s\(^{-1}\) based on Fowey Rocks CMAN station (star). The magnitude of the current is shown in each panel.
3. Observed Surface Current Variability

3.1 Southeast Florida Shelf

As shown in Figure 7, comparison of surface and subsurface velocity time series suggests reasonably good correlation between the WERA and ADCP measurements. Surface winds at 10-m from NOAA Coastal Marine Automated Network (CMAN) Fowey Rocks were used to estimate the surface friction velocity \( u_f \) that ranged between 0 to 0.4 \( \text{m s}^{-1} \) (the higher value observed during a strong atmospheric front). Weaker east-west currents are primarily associated with eddy-like activity along the western flank of the Florida Current. This contrasts with the strong northward current of the Florida Current where the amplitude was a maximum of \(-2 \text{ m s}^{-1}\). The complex correlation coefficients ranged from 0.8 to 0.9 with small phases over the 14-m separation. In this highly energetic regime associated with the Florida Current, typical RMS differences of 1 to 2 cm s\(^{-1}\) indicate significant near-surface current shears. A potential cause is exemplified by a sub-mesoscale surface current feature that occurred during 17 to 22 January 2005 (Year-Day 17 to 22 in Figure 7) within the radar domain shown in Figure 7 (right panels). During this period an atmospheric front moved over the radar domain, exciting a small-scale vortex along the western flank of the Florida Current where the current response indicated currents of about 50 cm s\(^{-1}\) with an elongated vortex along the 200-m contour and cross-shelf scale of about 20 km. Subsequently, the southward flow increased as the vortex center moved north along the 200-m contour as wind decreased to about 8.5 \( \text{m s}^{-1}\). By 2100 GMT 20 Jan, the vortex was reduced in relative size as the wind subsided as the atmospheric front moved further offshore. The vortex moved out of the domain and the Florida Current moved back towards the coast with larger northward surface velocities, suggesting an energetic surface current response (Parks et al., 2008).

3.2 South Atlantic Bight

Similar frontal eddies are observed off the Georgia Coast, an example of which is shown in a surface current snapshot and a zoomed in image (Figure 8). The grid spacing is 3 km but it increases to 6 km at the shelf edge. Along the transect (see Figure 4), the mean speed is calculated from April to August 2006 records to show the offshore distance where total data return falls below 25% (Figure 8, panel B). The mean curve is bounded by \( \pm \lambda \) the average accuracy of the measurement, based on the scatter in the spectra from which the velocity estimates are derived (the Rx arrays each have 12 antennae). The Gulf Stream is evident as the current speed averages about 0.2 m s\(^{-1}\) over the shelf then rapidly increasing across the shoreward, cyclonic flank of the Gulf Stream jet located about 150 km that than decreases slowly across the seaward, anticyclonic flank to the east of the axis. Generally, the overall data return is good along this transect—over 40% out to the Gulf Stream axis.

3.3 North Carolina Shelf

From a data quality perspective it is now understood that the environment off the Outer Banks is particularly challenging for a DF radar as two main issues have been identified: 1) The large dynamical range of current velocities present at a given distance from the antenna; and 2) The relatively high noise levels present at the 5 MHz frequencies at which the system operates. These two factors combine to produce radar cross-spectra that have broad and structured Bragg scattering regions. The Bragg peak at significant range often barely rises above the noise floor, at least over part of its bandwidth (Figure 9 a, b). Algorithms to identify the Bragg region for subsequent processing to determine current direction and magnitude fail to capture the full Bragg peak and resulting total vector fields can be obviously wrong over some of the coverage area (Figure 9c).

**FIGURE 8**

Snapshots of surface current over the entire domain (left panel A) and a zoom in at the shelf edge (right panel A) from 10:15 EST 7 August 2006 where a frontal eddy is located at ~31.5\(^{\circ}\)N and 79.8\(^{\circ}\)W. Black dots on shelf are towers with planned or present instrumentation. Mean current speed along the transect (panel B) in Figure 4, bounded by accuracy, from spectral scatter in 12 Rx antenna returns. Percent data return along the transect is also shown, for the entire record and for daytime returns between 1:00 and 2:30 PM local time. x-axis is distance from a point onshore midway between the two installations, and not distance from the installations themselves, so does not accurately represent the ranges of the individual installations, which routinely exceed 220 km.
Experimentation with the parameters of the algorithms that identify the first-order Bragg peak indicate that improved current fields can be achieved with appropriately modified parameters. The other important change that appears to have a significant impact on data quality is raising the minimum number of valid solutions used in each average (Figure 9d). Experimentation with the Bragg peak selection algorithm indicates a single set of revised parameters are insufficient to reprocess data from differing time periods. Evaluation of the best way to reprocess the multi-year dataset is ongoing.

The vendor has supported the installations on the Outer Banks by allowing more user control over the processing algorithms so that users can experiment with differing settings that may improve performance. Their willingness in this regard has permitted progress in understanding the issues faced on the Outer Banks seen to date. As of July 2007, the Outer Banks system has expanded coverage to the north through a partnering with NASA Wallops which has several installations in Virginia. The additional coverage has a positive influence on the quality of the vector solutions in the area where the problems have been most noticeable and may largely alleviate the data quality issues in the northern half of the domain simply by providing more consistent coverage. If confirmed this finding suggests more complete coverage has the added benefit of improving data quality because of the availability of three radial estimates in the overlap region where the system has been problematic.

4. Other HF Radar Capabilities

4.1 Significant Wave Height

Estimation of the wave field at discrete gridpoints is an advantage of the BF approach over the DF approach (Figure 10) in estimating significant wave height (Hs) and wave direction as part of the standard distribution, using the empirical estimation technique of Essen et al. (1999) and Gurgel et al. (2006). The estimation of directional wave spectra at each point is also possible based on the inversion techniques of Wyatt et al. (2003). Preliminary assessment of the standard distribution wave product has begun suggesting that inclusion of a bathymetric correction (possible in existing software) may be necessary for the lower frequency systems (i.e. <10 MHz). Note the wedges of nearly uniform wave heights near the shore-based HF radar installations in the uncorrected wave field example. The significant wave heights can be determined over about 60% of the radar footprint. By contrast, DF radar uses the Doppler spectrum measured at a fixed range close to the radar site to
estimate significant wave heights (Wyatt, 2005). This spectrum integrates backscatter over all angles from the radar site and its inversion requires knowledge of the beam pattern. The DF approach either doesn't have sufficient SNR to extend the wave measurement beyond a range close to the radar site or current variability makes it much more difficult to separate 1st and 2nd order returns contained within the Doppler spectrum at the longer ranges that encompass a wider area.

4.2 Directional Wave Spectra

Directional wave spectra have been estimated using the Wyatt et al. (2003) techniques on both the South Atlantic Bight and Southeast Florida Shelf WERA data using a few day samples (Figure 11). Results suggest that the directional wave estimates are sensitive to both the length of the phased array (12 Rx versus 16 Rx) and the length of the sample. Tests with 2048 samples (20-minute samples) revealed less noise and more steady estimates than those with just 1024 samples (10 minutes). Directional wave spectra from the WERA measurements are shown for the passage of Jeanne over the WERA grid near to the Fowey Rocks measurement site. These wave spectra are possible from the second-order Doppler spectral returns by an integral inversion technique. The wind seas respond to the strong wind stresses containing most of the wind-driven energy. By contrast, there was little indication of a strong low-frequency wave (swell) component moving with the storm since the islands presumably filtered out this faster moving wave component. These strong wind-driven current events are being looked at more closely to assess the performance of WERA surface current mapping and the accurate determination of the forced surface wave directional

**FIGURE 11**

Polar plots of the directional wave spectral energy measurements during Hurricane Jeanne passage on 24 Sept (left) and 25 Sept (right) relative to the direction of the surface winds observed at Fowey Rocks. WERA cell 595 was located close to Fowey Rocks CMAN station. Notice the agreement in the direction of winds between WERA and the Fowey Rocks CMAN station, which is yet another application of phased array radar technology (Processed wave data from Seaview Remote Sensing LTD).

**FIGURE 12**

WERA grid with percentages of good vector data and radial coverage over an 11-month record relative to the vector and radial grids (insets) from the SS measurements from 02 UTC 16 April to 2300 UTC 23 April 2005 (left panel). Radial comparisons have been made between the WERA Key Largo (KL) site and the SS JHPN and DVCV sites located south of KL. The ADCP position is shown that overlapped this period of the SS deployment and the red square is where a WERA/SS comparison was made. Eight-day averaged comparisons (right panel) between a) WERA and b) SS radial current from the NKL and JHPN sites, and c) WERA and d) SS (cm s⁻¹) vectors from concurrent records in April 2005. The area of interference derived from the SS measurements is visible in panel d.


4.3 Interoperability

An important issue for the U.S. National Network (Paduan et al., 2004) is combining radial data from BF and DF approaches to form surface current vectors (Figure 12). Since the frequency of the transmitted signal and the corresponding Bragg wavelength set the integrating depth (= 0.2 m difference) of the remotely sensed measurement (Stewart and Joy, 1974), combining radials from two systems require careful development of the technique to map them onto a common grid. For any vector retrievals, the Geometric Distortion of Precision, which is a function of the angles of intersection of the radial current measurements, limits the quality of the retrieved radar data (Chapman et al., 1997). This optimal angle lies between 30 to 150° as shown in published studies. Although this can be relaxed somewhat given the radar configuration, the proof is in how well vectors are resolved in the near and far-fields of these radars. A second aspect is the horizontal resolution of the radars and how 3 or 6 km resolution of surface currents map onto a 1 to 3 km resolution.

In this framework, initial comparisons between a 12.6 MHz SS and a 16 MHz WERA data set in the southern part of the domain from an 8-day concurrent time series are shown in Figure 12. During the period of 16 to 23 April 2005, there was also a moored ADCP as discussed above. Generally, the directions of the 8-day averaged vector currents were in good agreement over both domains with maximum surface currents of about 1.4 m s⁻¹ (Table 5). Following Kundu (1976), the complex correlation coefficients between the WERA and ADCP data were 0.9 compared to 0.42 between the SS and ADCP measurements. The complex correlation angles indicated a clockwise veering of the current with depth relative to the surface current. Moreover, the variance and standard deviations of the surface velocity signals varied significantly over the domains. The standard deviations for the u-component were a maximum of 28 cm s⁻¹ for WERA along the inshore edge of the Florida Current compared to those from SS of about 15 cm s⁻¹. In the v-component, standard deviation distributions reversed with a standard deviation of almost 80 cm s⁻¹ for SS compared to a maximum of 28 cm s⁻¹ from WERA. While an 8-day concurrent time series is insufficient to draw any conclusion, however, radials from these two radars can be combined to form vector fields.

5. Summary and Concluding Remarks

SEACOOS experiences with HF radars were positive as it allowed us to assess system performances of both systems under differing venues with large differences in the dynamic ranges and horizontal scales of surface current variability. Collectively, a near real-time surface velocity measurement system was developed where data were visualized on the SEACOOS website. For the WERA technology (Gurgel et al., 1999), this was a significant step forward and provided a viable alternative of BF capability to the HF radar community and has recently been posted on the U.S. National Network. Strong collaborative ties were established within the southeast with the Universities of South Florida, North Carolina, South Carolina, Skidaway Institute of Oceanography and Georgia Institute of Technology regarding HF radar technologies and in situ measurements. Splitting a pair of installations between two Institutions (i.e., Skidaway Institute of Oceanography and University of South Carolina), so that neither institution has the minimum two stations makes it difficult to construct useful surface vector current field quickly. In this context, command and control, troubleshooting, data-flow, and data analysis are complicated, and require coordination between multiple institutions at multiple levels of management to progress. Based on our collective experiences, the HF radars used here were not necessarily turnkey and all systems need to be maintained with spares and routine maintenance to insure the highest quality of data return possible. In the southeast as well as in the Gulf of Mexico, we must consider hurricane season and potential landfall scenarios (Marks and Shay, 1998). Not only will hurricanes disrupt data acquisition procedures as electrical power grids get turned off, but hurricanes potentially inflict severe damage to the radar sites as in hurricane Wilma in 2005.

The two radar groups using BF techniques (WERA) were in general pleased with the wealth of data provided by this system, including the possibility of near real-time directional wave capabilities. These measurements are not only important to the modeling programs, but are needed to interpret radar-derived surface velocity fields and directional waves in strongly sheared ocean regimes (i.e. Florida Current). In collaboration with our European colleagues, more significant inroads must be made in this area of radar-derived directional waves as it is an exciting area of scientific and research inquiry that has operational potential. This remote sensing capability is a plus in regimes such as the Gulf Stream and Florida Current where surface buoys are difficult to deploy and maintain over long periods. Notwithstanding, there were drawbacks with this BF system: 1) Cabling necessary to support the independent Rx antennae makes the system difficult to relocate quickly. However, the nearly constant criticism on the number
of Rx antennae along the beach, deemed a drawback by the radar community, has not been an issue for our installations. 2) Processing and post-processing software is in need of improved documentation, but it is open source to the user groups, which we consider a significant advantage. 3) Support of the system is forthcoming from the vendor, but is logistically difficult to acquire, given the time zone offset between the U.S. East Coast and Germany, and some communication difficulties. This issue has been minimized since the vendor now has a North American partner in Canada although that firm will need training in the deployment, operations and maintenance aspects of the radar. Finally, 4) there is a need to determine the optimal time integration to acquire good directional wave estimates where the installations must have at least 12-element Rx arrays.

The two radar groups using DF techniques (SS) experienced a number of difficulties as well: 1) The 5 MHz band is noisy and at times is used in governmental maritime operations (UNC had to stop transmitting at two of its permitted frequencies at the request of the FCC). 2) Reliable measurements of surface currents off the Outer Banks remains elusive due to the combined effect of increased noise levels and broad Bragg peaks; the result can be a sizable decrease in useful data owing to vectors that were not oriented correctly. 3) Significant wave height is valid over the domain and not individual cells or bins as in BF mode. Since only one antenna system is used, the directional wave capability from DF algorithms may provide an estimate of the direction of the dominant wave but have limitations. Finally, 4) the parameters in the MUSIC algorithm (DePaolo and Terrill, 2007) need more exploration to establish both the strengths and weaknesses of the system for the NOAA IOOS-sponsored U.S. National Network. Accuracy and error statistics (i.e. uncertainties) are important for this purpose for not only radial velocities, but just as importantly for the vector surface currents as well.

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