High Frequency Radar Observing Systems: SECOORA Gap Analysis

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1. Introduction:

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.

We leaned several lessons as part of these deployments such as protecting against lightening strikes and improving communication links between the sites to a central hub to place the data on real-time web sites. Since states in the southeast (SECOORA) and surrounding the Gulf of Mexico (GCOOS-RA) 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 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 one versus sixteen antennae systems to insure the highest quality data possible for applied and operational goals. To insure the highest quality data possible, a full-time technician and a half-time IT specialist are needed for every three sites as well as access to spares to keep these systems running to obtain quality real-time data on the web sites.

In this document, a systematic HF radar gap analysis is proposed that includes several research institutions in the SECOORA and GCOOS-RA footprints. Collectively, the group decided to provide a phased instrumentation plan using the HF radars over years 2010-2014 where a total of 27 medium to long range systems will be deployed from North Carolina to the Florida Panhandle. HF radar units in the western part of the panhandle will be sponsored by GCOOS-RA (those run by FSU). The approximate cost of deploying these radars (maximum of six radars per year) is about $8M using a cost of $290K for hardware and deployment costs on average. In subsequent years (2015 through 2017), we propose to deploy several pairs of Very High Frequency radars (~50 MHz) to overlook important ports and harbors in the SECOORA footprint. In this context, we are coordinating these plans with those from the GCOOS-RA for full coverage in the Gulf of Mexico and the Florida Straits and continuity between SECOORA and MACOORA to the northeast. Such coordination is critical for the success of any HF radar network. We believe that the staffing ratio for these sites should be 1 technician for every 2 to 2.5 sites as discussed at the Ocean.US meeting.

2. Active Radar Sites:

As part of the Office of Naval Research-sponsored SouthEast Atlantic Coastal Ocean Observing System (SEACOOS), High Frequency (HF) Radars were deployed in four differing venues over the five years of the program (Figure 1). These HF radar systems used either direction-finding (Coastal Ocean Dynamics Application Radar SeaSonde: SS) or beam-forming techniques (Wellen Radar: WERA) to acquire radial currents from the Bragg peaks in the Doppler spectra. By mapping the radial current structure from at least two stations, the vector surface velocity fields were mapped in near real-time along sections of the continental shelves of North Carolina, South Carolina and Georgia, Southeast Florida 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.

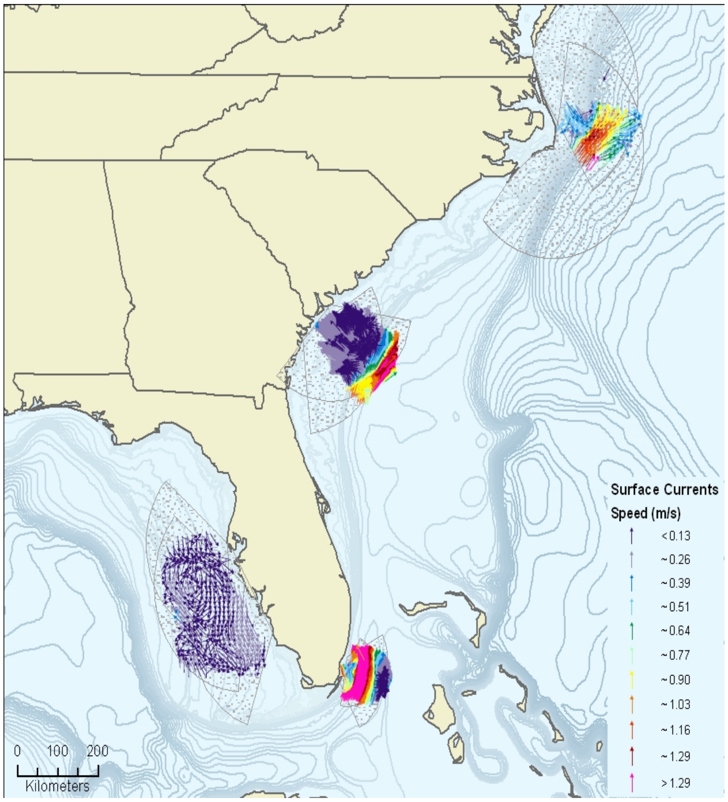

Figure 1: HF radar deployments (and radial coverage) with surface current vectors in April 2007 (EFS and MAB) and Oct 2007 (WFS) in the SEACOOS domain relative to bottom terrain in the SECOORA and GCOOS-RA footprint.

One of the concepts introduced in this program was the development of HF radar testbeds where sensors and instruments could be tested. 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. 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.

Group and Radar Type	Station Location	Latitude (^{o}N)	Longitude (^{o}W)	Frequency (MHz)
USC/WERA	Folly Beach, SC	32.65	-79.94	8.3
USC/WERA	Prichard Island, SC	32.30	-80.51	8.3
SKIO/WERA	St.Catherine, GA	31.69	-81.13	8.3
SKIO/WERA	Jekyll Island, GA	31.06	-81.41	8.3
UM/WERA	Dania Beach,FL	26.08	-80.12	16.0
UM/WERA	Virginia Key, FL	25.74	-80.15	12.6
UM/WERA	Crandon Park, FL	25.71	-80.15	16.0
UM/WERA	Key Largo, FL	25.24	-80.31	16.0
UNC/SS	Duck, NC	36.18	-75.75	5.0
UNC/SS	Cape Hatteras, NC	35.26	-75.52	5.0
USF-COMPS/SS	Rd. Shores, FL	27.83	-82.83	5.0
Mote/Rutgers/SS	Venice, FL	27.08	-82.45	5.0
USF-COMPS/SS	Naples FL	26.16	-81.81	5.0
USF-COMPS/ WERA	Ft. DeSoto Park, FL	25.54	-82.72	12.6.
USF-COMPS/ WERA	Venice, FL	27.07	-82.45	12.6
FAU/SS	Hillsborough Inlet, FL	26.26	-80.12	25.
FAU/SS	Haulover, FL	25.90	-80.12	25.
USM/SS	Destin, FL	30.29	-86.25	5.

Table 1: HF radars currently (or in the process) of being deployed in the SECOORA domain with their respective frequencies where **USC:** University of South Carolina, **SKIO:** Skidaway Institute of Oceanography, **UM**: University of Miami, **USF**: University of South Florida, **FAU**: Florida Atlantic University: **MOTE**: MOTE Marine Lab (Rutgers). **USM**: University of Southern Mississippi (GCOOS): **SS**: Seasonde, **WERA**: Wellen radar and **COMPS**: Coastal Ocean Mesoscale Prediction System (USF).

3. HF Radar Gap Analysis:

The objective of this document is to provide a gap analysis for SECOORA and link directly to GCOOS-RA along the west Florida Shelf and MACOORA to the northeast. A key aspect will be to outline a challenge we face in the southeast and GOM states (hurricanes), and the large dynamic ranges of the currents due to Loop Current, Florida Current and the Gulf Stream. Our approach uses the qualities of both WERA and SS to maximize the utility of surface current radars. Recent investigations have pointed to the use of such devices to map surface winds, which is an area of active research. In this context, our lessons learned from both systems are included. Potential users would like concurrent directional wave measurements that can only be achieved only with beam-forming technology. In discussion with forecasters at the National Weather Service in Miami forecasting Office, they want to these types of realtime measurements in the Florida Current where wave states significantly differ between the coastal and offshore regimes for daily forecasting. This is critical to the commercial and recreational boating communities.

As per Figure 2, we need to procure hardware and install 27 HF radar sites from North Carolina to the panhandle of Florida. We have provided the possible pecking order in how these sites should be deployed over the 20-10-2014 time frame with an emphasis of filling large gaps (i.e. between North Carolina and South Carolina and Georgia and South Florida, and from Tampa to Pensacola . With these latter sites we intend on working with our GCOOS-RA colleagues in developing the network. Sharing expertise and experiences will be advantageous to both regional associations which is central to the IOOS theme.

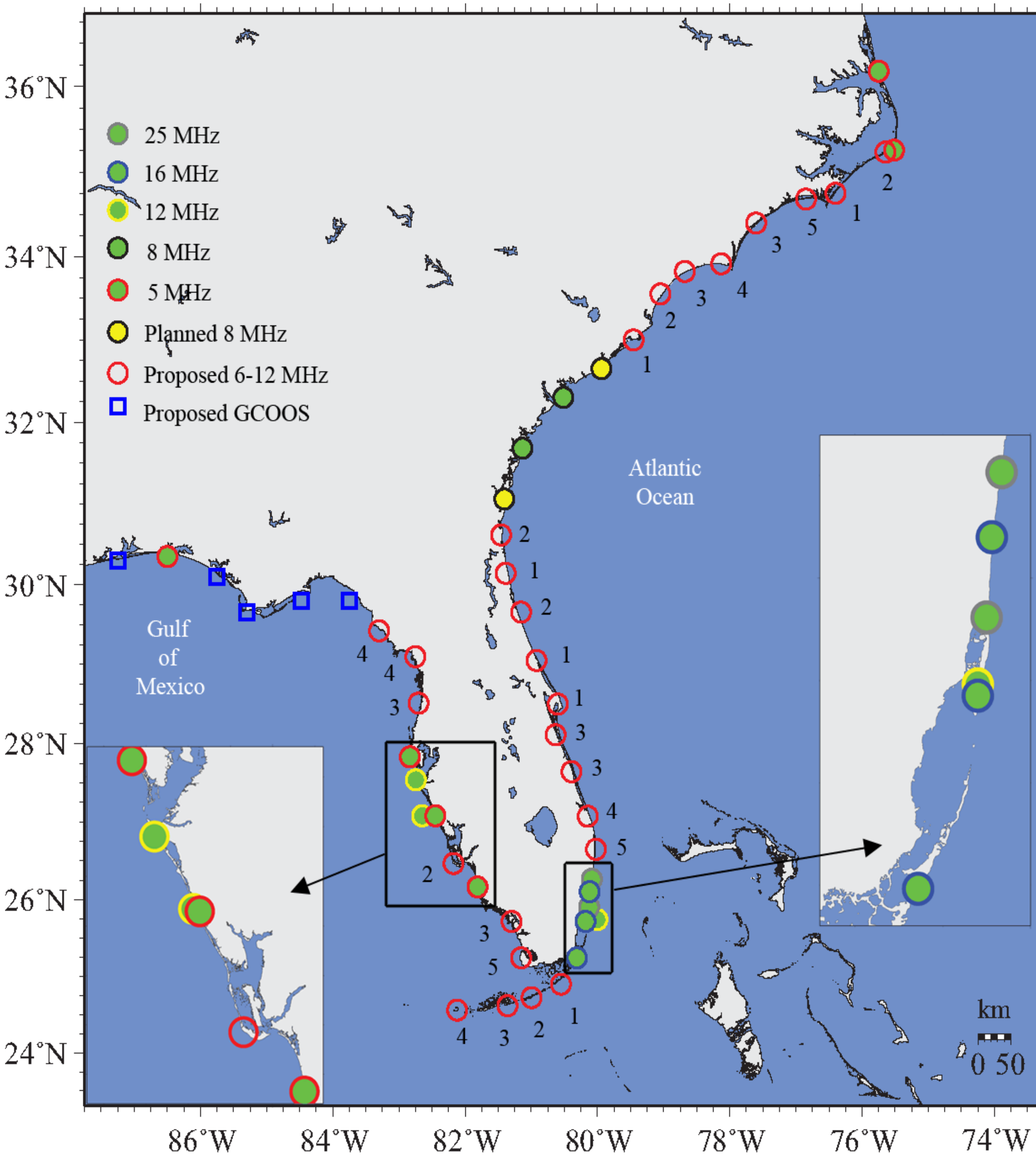

Figure 2: Deployed and planned high frequency radars with differing frequencies from years 2010-2014 including the **Insets** that represent HF radar testbeds developed along the east and west Florida Shelves where the dynamical range of the currents and the forcing mechanisms is large.

Research Group	Station ID	Latitude (^oN)	Longitude (^oW)	Frequency (MHz)	Yr
UNC	South Cape Hatteras, NC	35.23	-75.65	6-12	2
UNC	Cape Lookout, NC	34.75	-76.40	6-12	1
UNC	Pine Knoll Shores, NC	34.68	-76.80	6-12	5
UNC	Surf City, NC	34.40	-77.60	6-12	3
UNC	Oak Island, NC	33.92	-78.13	6-12	4
USC	North Myrtle Beach, SC	33.82	-78.68	6-12	3
USC	Murrells Inlet, SC	33.55	-79.05	6-12	2
USC	Cape Romain, SC	33.00	-79.45	6-12	1
SKIO	Amelia Island, FL	30.62	-81.45	6-12	2
UNF	Ponte Vedra, FL	30.14	-81.38	6-12	1
UNF	Marineland, FL	29.66	-81.15	6-12	2
FIT	New Smyrna Beach, FL	29.05	-80.92	6-12	1
FIT	Cape Canaveral, FL	28.50	-80.60	6-12	1
FIT	Melbourne, FL	28.12	-80.63	6-12	3
UM	Vero Beach, FL	27.64	-80.39	6-12	4
UM	Hobe Sound, FL	27.08	-80.14	6-12	4
UM	Palm Beach, FL	26.65	-80.02	6-12	5
UM	Upper Matacumbe, FL	24.90	-80.55	6-12	1
UM	Marathon, FL	24.73	-81.00	6-12	2
UM	Big Pine Key, FL	24.62	-81.36	6-12	3
UM	Marquessas Key, FL	24.56	-82.12	6-12	4
UM	Everglades Park, FL	25.24	-81.16	6-12	5
USF	Duck Rock, FL	25.71	-81.30	6-12	3
USF	Sanibel Island, FL	26.46	-82.17	6-12	2
USF	Coon Key, FL	28.51	-82.70	6-12	3
USF	Cedar Key, Fl	29.43	-83.30	6-12	4
USF	Horsebeach, FL	29.80	-83.75	6-12	4
FSU	St Marks, FL	29.78	-84.65	6-12	3
FSU	Alligator Pt, FL	29.90	-84.35	6-12	4
FSU	Cape St George, FL	29.59	-85.05	6-12	4
FSU	St Andrew Sound, FL	30.10	-85.75	6-12	2
FSU/USM	Pensacola, FL	30.35	-87.25	6-12	?

Table 2: Planned HF radar stations to fill gaps in the SECOORA (**GCOOS-RA**) footprint with approximate positions, year of deployment where 1: 2010, 2:2011; 3:2012,4:2013 and 5: 2014 with the research group that oversees the sites **UNC:** University of North Carolina; **USC:** University of South Carolina; **SKIO:** Skidaway Institute of Oceanography; **UNF**: University of North Florida; **FIT:** Florida Institute of Technology; **UM**: University of Miami; **USF:** University of South Florida; and **FSU:** Florida State University. The total number of new stations is 27 for SECOORA from North Carolina to the Florida Panhandle. From Coon Key to St Andrew Sound, these FSU sites would be supported with **GCOOS-RA.**

The total number of new station and staffing are summarized in Table 3 from 2010-2014 for research groups in the footprint. The total number of new stations is 27 (with an additional four radars sponsored by GCOOS-RA at FSU and a radar at Pensacola). This totals thirty one radars spanning from North Carolina to the Florida Panhandle without the additional VHF radars for ports and harbors.

Research Group	2010	2011	2012	2013	2014	Total (new)
UNC	1	1	1	1	1	5
USC	1	1	1	0	0	3
SKIO	0	1	0	0	0	1
UNF	1	1	0	0	0	2
FIT	2	0	1	0	0	3
UM/EFS	0	0	0	2	1	3
UM/FL Keys	1	1	1	1	0	4
USF	0	1	2	2	1	6
Total	6	6	6	6	3	27
FSU/GCOOS	0	1	1	2	1	5/32

Table 3: Planned new stations from 2010 to 2014 in the SECOORA footprint for the long-range systems using one technician for every two sites. We have included a maximum of six stations per year over the region in the budget.

The approximate budgeting is shown in Table 4 where a deployment cost on the average about $100K which including PI, technician salaries and fringe benefits, travel to and from the sites, installation of electricity and phone lines, computer node charges and software modifications for communications, miscellaneous supplies, costs of permits, and shipping of the instrumentation to the location. If the sites are nearby, deployment costs may be less but if sites are large distances, travel will also involve lodging and per diem for the deployment. Thus, some flexibility has to be maintained in the deployment cost number. The hardware costs are $190K for new radar units (for a 12-channel system with antennae) with cables and computers. Given the weak dollar on foreign markets, the European vendor is battling with costs to keep the pricing of the WERA reasonable.

Research Group	2010	2011	2012	2013	2014	Total (new)	Total (Staff)
UNC	290K	580K	290K	290K	290K	1450K	2.5
USC	290K	290K	290K	0	0	870K	1.5
SKIO	0K	290K	0	0	0	290K	1
UNF	290K	290K	0	0	0	290K	1
FIT	580K	0K	290K	0	0	870K	1.5
UM/EFS	0	0	0K	580K	290K	870K	1.5
UM/FL Keys	290K	290K	290K	290K	0	1160K	2
USF	0K	290K	580K	580K	290K	1450K	3
Spares	160K	160K	160K	160K	100K	**740K**	**14**
Total	1900K	1900K	1900K	1900K	970K	**8570K**	**14**
FSU/GCOOS	0	290K	290K	580K	290K	1160K	2.5

Table 4: Yearly costs (in increments $1000 US: K) of the planned new stations from 2010 to 2014 in the SECOORA footprint for the long range systems assuming $190K in hardware costs and $100K for each radar deployment and <u>staff requirements which equates to a technician for every two stations with spares at roughly 10% of the costs.</u>

The Very High Frequency (VHF) radars around ports and harbors surrounding the coastline of SECOORA. As shown in Figure 3, ports staring at Wilmington to Tampa are shown. Given the eight harbors with two VHF radars per, this equates to 16 VHF radar stations. Given the shorter baseline distances, deployment costs tend to be less than for the longer range HF radars because of the reduced travel time (closer spacing) and the logistics is a bit easier A breakdown is given in Table 5. We envision one VHF radar technician per port given its import to ship traffic in and out of major ports.

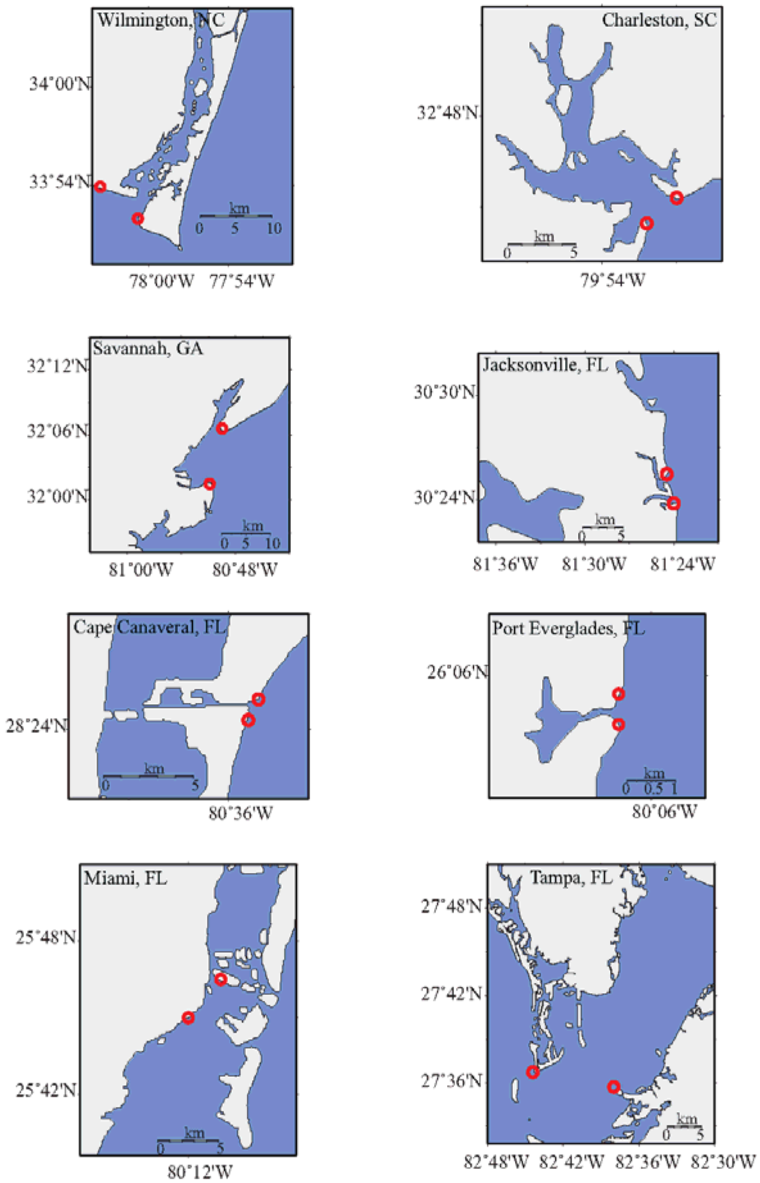

Figure 3: Major ports in the SECOORA footprint that require VHF radar units with ranges of about 20 km and high spatial and temporal resolution transmitting at frequencies greater than 45 MHz with more than 2 MHz of bandwidth.

Research Group	2014	2015	2016	Total (new)	Total (Staff)
UNC/Wilmington	290K	0	290K	580K	1
USC/Charleston	0	290K	290K	580K	1
SKIO/Savannah	0	290K	290K	580K	1
UNF/Jacksonville	290K	290K	0	580K	1
FIT/Port Canaveral	0	290K	290K	580K	1
UM/Everglades	0	0	580K	580K	1
UM/Miami	0K	580K	0K	580K	1
USF/Tampa	580K	0K	0K	580K	1
Total	1160K	1740K	1740K	**4640K**	**8**

Table 5: Yearly costs (in increments $1000 US: K) of the planned new VHF stations from 2014 to 2016 in the SECOORA footprint assuming $190K in hardware costs and $100K for each radar deployment and staff requirements which equates to a technician for each port site.

4. Challenges:

The SECOORA and GCOOS domains have to contend with the passage of hurricanes (Figure 4) and strong fronts (Noreaster's) and cold-air outbreaks. Climatologically, Neumann (1993) quantified the mean direction of the tropical cyclone tracks from 1886-1989 (103 years) Of particular significance here is that if the storms begin to recurve east of 60^{o}W, in an average sense, the storm will not landfall along the US coastline. Specifically, Neumann found a relative maximum of 70 hurricanes in the center of the Gulf of Mexico, and a maximum 85 TCs located in an area off Cape Hatteras, North Carolina. Of relevance here is that approximately 60 hurricanes have occurred between Melbourne, Florida and Chesapeake Bay, which constitutes a large fraction the SEA-COOS domain. Given the possibility of a landfalling storm in the SEA-COOS regional domain, the oceanic response could be measured at several observatories situated along the coast, which would augment the ocean sampling from NOAA sea-level stations, NDBC bouys and synoptic snapshots from NOAA aircraft. Such measurements would add to the limited data base of oceanic observations observed during storm passage. Given the two months that transpired after hurricane Wilma's passage in 2005, **spares for the radar sites are absolutely critical as well as portable generators.** No other RA's face this problem with the exception of the northwest with strong storms affecting Alaska and the Northwest RA.

For severe hurricanes, one way to minimize this challenge is to deploy the radars in a trailer that can be towed by a pick-up truck or SUV. The WERA North Key Largo site has such to get the radar out of harms way. Note that in the Florida Keys, often times evacuations need to start 3 days in advance of the hurricane to enable residents to have enough time to prepare their homes prior to evacuating.

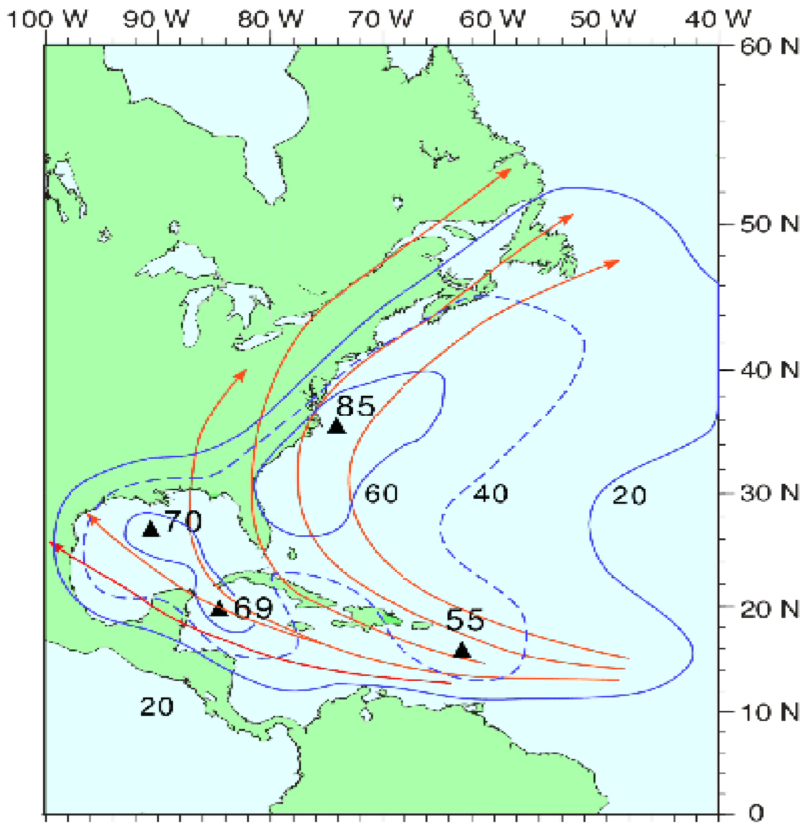

Figure 4: Tracks (red) and frequency of occurrence (blue contours) of tropical cyclones influencing the Gulf of Mexico and Eastern Seaboard of the United States based on 103 years of data starting in 1886 (adapted from Neumann, 1993). Contours and digits represent maximum of storms occurring within 140 km of the point.

5. Lessons Learned:

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 BF system:

- 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.

- 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.

- 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.

- 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:

- The 5 MHz band is noisy and at times is used in Homeland Security operations (UNC had to stop transmitting at two of its permitted frequencies at the request of the FCC).

- 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.

- Significant wave height is valid over the domain and not individual cells or bins as in BF mode. Since only one antennae system is used, the DF algorithms do not provide the directional wave capability.

- Parameters in the MUSIC algorithm need more exploration to establish both the strengths and weaknesses of the system for the NOAA IOOS-sponsored U. S. National Network.

Regardless of the radar systems, 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.