SECOORA
Southeast Coastal Ocean Observing Regional Association

High Frequency Radar Observing System: Gap Analysis

This document presents a gap analysis for High Frequency Radar (HFR) observations in North Carolina, South Carolina, Georgia, and Florida. It will serve as a guide for future HFR investments in the Southeast Coastal Ocean Observing Regional Association (SECOORA) region.

Version 2 Updated April 2022

Version Table

Version	Date	Revisions	Author(s)
1.0	2008	Initial Draft	Nick Shay and SECOORA HFR team
1.1-1.3	10/1/2021 – 2/9/2022	Revised original 2008 SECOORA HFR Gap Analysis; reviewed new installations; revised based on FCC IT band requirements; updated maps	Jennifer Dorton, SECOORA; Cliff Merz, Univ of South Florida; Mike Muglia, ECU Coastal Studies Institute; Steven Lazarus, Florida Institute of Technology
1.4	2/25/2022	Document review/edits by SECOORA HFR team and IOOS Program Office	
1.5-1.7	3/1/2022 – 3/31/2022	Authors review comments/edits from SECOORA HFR team and IOOS Program Office and make revisions	Jennifer Dorton, SECOORA; Cliff Merz, Univ of South Florida; Mike Muglia, ECU Coastal Studies Institute; Steven Lazarus, Florida Institute of Technology
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Introduction

High-frequency radar (HFR) are land-based systems that measure the speed and direction of ocean surface currents in near real time. These radars can measure currents over a large region of the coastal ocean, from a few kilometers offshore up to about 200 km, and they can operate under varying weather conditions (NOAA 2021a). HFRs provide consistent and more frequent current measurements than previously available from other observations and provide new oceanographic insights. A Plan to Meet the Nation's Needs for Surface Current Mapping presents the uses of HFR, the requirements that drive the measurement of ocean surface currents, and the implementation design for a five-year, national build-out effort. High resolution current data are essential for: oil spill and point source pollution tracking and prediction; Search and Rescue (SAR); marine navigation; harmful algal bloom (HAB) forecasts; marine protected area and ecosystem management; monitoring the effects of climate change on coastal ecosystems and boundary currents; quantifying the ocean current resource for marine hydrokinetic (MHK) energy development (Muglia et al. 2020; Kabir et al. 2015); calibrating and validating of numerical circulation models; and coastal zone management (NOAA 2015; Mantovani et al. 2020).

Figure 1. Skidaway Institute of Oceanography HFR being installed in Canaveral National Seashore, FL. Image Credit: Florida Institute of Technology

The Southeast Coastal Ocean Observing Regional Association (SECOORA) domain encompasses North Carolina, South Carolina, Georgia, and Florida. A common theme that guides HFR operations in this region is the need to monitor the Loop Current, Florida Current, and the Gulf Stream (Parks et al. 2009; Weisberg et al. 2017; Muglia et al. 2022) which transport heat poleward as part of the gyre circulation. The SECOORA region has inadequate HFR coverage to completely monitor coastal ocean currents or meet the goals that HFRs need to address (as described below).

The goal of the SECOORA HFR program is to provide ocean surface current data to address needs related to:

- Blue Economy
    - Marine Transportation

    - Navigation/Safety
    - Marine Hydrokinetic (MHK) Energy Development
    - Offshore Marine Aquaculture
- Search and Rescue (SAR)
- Science and Research
    - Loop Current, Florida Current, and the Gulf Stream continuum
    - Wave/wind direction measurements

HFR Background

HFR remote sensing is based on the scattering of electromagnetic (EM) waves from ocean surface gravity waves, a phenomenon known as Bragg scattering. HFRs transmit EM waves in a frequency band allocated to oceanographic radars in agreement with the International Telecommunications Union (ITU) and permitted accordingly by the Federal Communications Commission (FCC) for the desired surface current measurement range and resolution; typically, in the range of 4–44 MHz. The EM waves propagate along the sea surface and are Doppler-shifted when they are backscattered off ocean surface waves. First-order backscattering resonance occurs when the wavelength of the surface wave is one-half of the transmitted EM wavelength. The ocean waves responsible for the resonant Bragg backscattering are called Bragg waves (Emna et al. 2016; Merz et al. 2021).

HFR systems must first identify the range and bearing of the region of the ocean from which the radar signal was backscattered to assign an associated ocean current radial velocity value, the vector component of the ocean current relative to the HFR bearing. There are two common types of HFR systems, each classified by the technique used to identify the location of the reflected radar wave: beam forming (BF) and direction finding (DF) systems (Liu et al. 2014; Montovani et al. 2020).

BF systems electronically steer the radar signal to the direction of each selected surface ocean region and resolve the Doppler spectrum on a predefined grid with an angular range and resolution defined by the array configuration and radar frequency. Radial current velocities are therefore directly associated with each grid cell. Direction-finding (DF) systems acquire the backscattered spectrum from all the ocean patches falling within a range ring and use the signals received by two loop antennas and a monopole to resolve the signal direction of arrival (DOA) using the MUltiple SIgnal Classification (MUSIC) algorithm. The resolved radial velocities populate a polar grid (Martinez-Pedraja et al. 2013; Montovani et al. 2020).

Two or more HFR systems are needed to resolve the current vector velocity field from the radial velocity data. The sites must be appropriately spaced such that the radial vectors measured from each site overlap in the same ocean region at differing angles. Optimal separation distance is determined by the operational range of each HFR system, which depends on the radar frequency. Separation and frequency also determine the coverage domain where currents can be resolved at the intersection of the radial vectors from individual systems (Shay et al. 2002; Montovani et al. 2020).

Range and Resolution

Range resolution is an important parameter affecting the spatial resolution of HFR current measurements. The bandwidth is directly related to the range resolution (Merz et al., 2015). Long range HFR systems operate in the 4–6 MHz frequency band and have a typical range of 160–200 km with a resolution of 5–6 km. Medium range HFR systems, which operate in the 8–16 MHz frequency band have a range of 60–80 km and a resolution of 1.5–3 km. Long and medium range systems are widely used across the SECOORA region to monitor the Loop Current, Florida Current, and the Gulf Stream. Short range systems operating in the 42–44 MHz frequency band are ideal for monitoring currents at high resolution near port entrances. These systems have an optimum range of 15 km and a resolution of 0.46 km (Shay et al. 2007; Montovani et al. 2020, Merz et al. 2021). Ultimate system selection is based on the size of the phenomenon being investigated and its location.

HFR Systems in Use in the Southeast

Two types/brands of HFR have been deployed in the SECOORA region: the SeaSonde® manufactured by CODAR Ocean Sensors, Inc. (CODAR) and Wellen Radars (WERA) manufactured by Helzel Messtechnik GmbH (Helzel).

CODAR is a DF HFR and the receive antenna contains two orthogonal antenna elements and a monopole to measure the radial direction of the ocean surface current (IOOS 2016). The CODAR compact DF system is the most widely deployed oceanographic HF technology, both within the U.S. and internationally (IOOS 2016). This system is typically configured with one transmit and one receive antenna. Some configurations use a single antenna to both transmit and receive the EM signal. Proprietary CODAR software is used to process the radial data before sharing the data with the National HFR Data Assembly Center (HFR DAC).

WERA is a BF HFR which uses a series of phased-array antennas to measure the radial direction of ocean surface currents (IOOS 2016). The WERA HFR system typically uses a 1 to 4 element array to transmit and a 12–16 element linear array to receive the backscattered radio wave signals (Shay et al. 2007; Merz et al. 2012). Helzel also provides the proprietary software required to process the radial data shared with the National HFR DAC.

Data Sharing

SECOORA HFR deliver hourly surface current radial vector velocity data files to HFR DAC national servers located at the NOAA National Data Buoy Center (NDBC) HF radar data distribution and display server and Scripps Institution of Oceanography Coastal Observing Research & Development Center (CORDC) "HFRNet" HF radar data distribution and display server. Scripps also provides quarterly performance metrics for HFR by regional association and by provider (https://hfrnet.ucsd.edu/diagnostics/). SECOORA provides information on HFR site status and access to the HFR data via an application programming interface (API) or THREDDS (Thematic Real-time Environmental Distributed Data Services) server (https://secoora.org/hfradar/#data).

Data Users

There are a variety of HFR users who access the HFR data via HFRNet or NDBC. The major user of the data is the U.S. Coast Guard which incorporates the data into its Search and Rescue Optimal Planning System (SAROPS). The Emergency Response Division of NOAA is also a key user of these data in their General NOAA Operational Modeling Environment (GNOME) set of modeling tools, for predicting the trajectory of hazardous materials (such as oil) spilled in water and planning emergency response actions accordingly. SECOORA HFR Principal Investigators (PIs) conduct research which incorporates ocean current measurements to inform, for example, surface current eddy identification, wave studies, harmful algal bloom tracking, and renewable energy projects. Fishers in the southeast use the HFR data along with sea surface temperature to locate the Gulf Stream.

Oceanographic HFR Frequency Allocation

The World Radiocommunication Conference (WRC) and the ITU have established requirements that oceanographic HFR operators must meet to ensure they do not cause interference with other radio frequency (RF) spectrum users:

(1) Several RF bands were approved for use by oceanographic HFR;
(2) HFR operators should use frequency sharing techniques to minimize their spectrum usage; and
(3) HFR operators need to broadcast a station identifier in Morse code at least once every 20 minutes (NOAA 2015).

In the U.S., the FCC is responsible for the permitting process for HFR stations.

The U.S., which is in ITU Region 2, has the following available frequency bands and associated bandwidths:

- 4.438–4.488 MHz, 50 kHz
- 5.250–5.275 MHz, 25 kHz
- 13.450–13.550 MHz, 100 kHz

- 16.100–16.200 MHz, 100 kHz
- 24.450–24.650 MHz, 200 kHz
- 26.200–26.420 MHz, 220 kHz
- 41.015–41.665 MHz, 650 kHz
- 43.350–44.000 MHz, 650 kHz

CODAR and Helzel design and sell HFR that operate within the approved Region 2 ITU bands. Older previously deployed systems can be upgraded to an approved frequency band. All SECOORA HFR operators either work within an approved frequency band or will become compliant with the new ITU band requirements by summer 2022. To learn more about ITU band allocations, please review the following documents:

- Radiocommunications Study Groups: Guidelines for the use of spectrum by oceanographic radars in the frequency range 3 to 50 MHz (25 November 2014). https://cdn.ioos.noaa.gov/media/2017/12/final_itu_document_hf_ocean_radar.pdf
- A Plan to Meet the Needs for Surface Current Mapping (NOAA 2015). https://cdn.ioos.noaa.gov/media/2017/12/national_surface_current_planMay2015.pdf

Quality Control (QC) Requirements

The Manual for Real-Time Quality Control of High Frequency Radar Surface Current Data provides an overview of the required, strongly recommended, suggested, and in-development QC tests that should be conducted for all HFR data. Each HFR operator contributes to an annual review of the HFR Data Management Plan which describes data management systems and QC processes by operator. Some tests are embedded in the software that HFR manufacturers provide with their systems (e.g., QA/QC & Related Practices at CODAR) while other tests are conducted at the HFR National Data Assembly Center or by the HFR operator. Additional QC at the radial level has been developed and implemented by HFR operators at the University of North Carolina Chapel Hill, ECU Coastal Studies Institute, and Old Dominion University in Haines et al. 2017. As part of the National Academies of Science, Engineering, Medicine's (NASEM) Understanding Gulf Ocean Systems (UGOS) project, a unified delayed-mode QC routine was developed and implemented that utilizes the tests defined in the Quality Assurance/Quality Control of Real-Time Oceanographic Data (QARTOD) manual for Real-Time Quality Control of HFR Surface Current Data (Smith et al. 2021).

Active Radar Sites

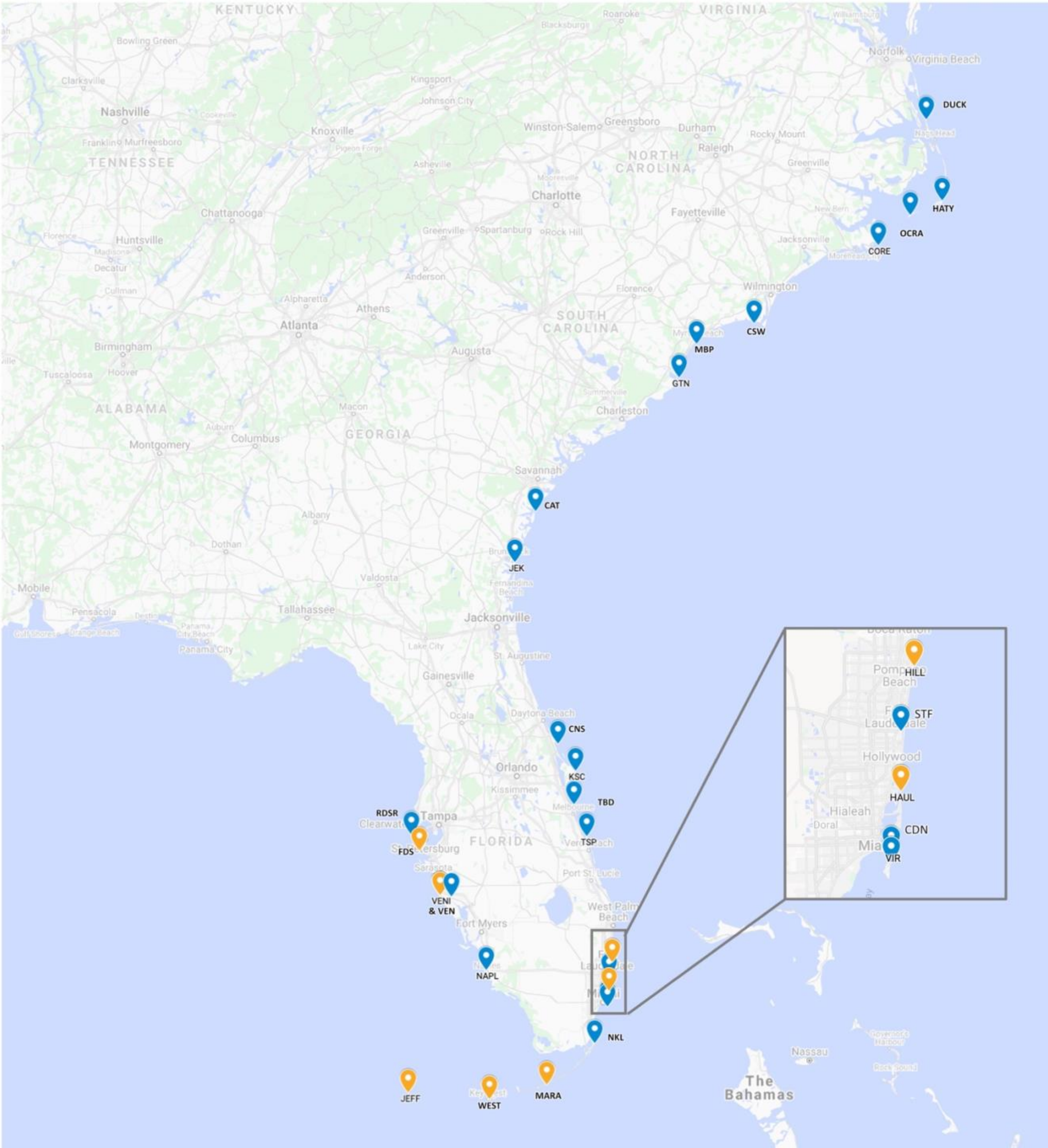

Figure 2. HFR locations in the SECOORA region. Blue symbols represent SECOORA supported HFR. Orange symbols represent HFR deployed and operated in the region that do not receive SECOORA funding. These stations are operated by the USF (FDS, VEN, JEFF, WEST, and MARA) and FAU (HAUL, HILL). Large gaps in HFR coverage exist in central coastal NC, SC, N FL, and the FL panhandle.

SECOORA's HFR installations have been supported through a combination of U.S. IOOS funding, research funding, and state agency investment. Currently, SECOORA supports the operation of 20 HFR in the region. Additionally, funding has been obtained from other sources to operate the following 7 HFR in the region:

- University of South Florida (USF):
    1) operates two WERA HFR on the west coast of Florida covering the mouth of Tampa Bay, providing higher resolution surface current measurement coverage in support of marine transportation, navigation, and safety needs for Port Tampa; and
    2) through funding from NASEM, operates a CODAR SeaSonde HFR in Marathon, FL. Two additional CODAR SeaSonde installations are underway in Key West and Fort Jefferson/Dry Tortugas.
- Florida Atlantic University (FAU) operates two CODAR SeaSondes near Miami, FL.

While these 7 stations do not receive IOOS or SECOORA operational funding, they help fill gaps within the HFR network and support Gulf Stream continuum science and research activities (Muglia et al. 2022).

See Appendix 1 Table 1 for a list of all 27 stations in the region and Figure 2 for a HFR map of existing SECOORA sites.

Challenges for Maintaining HFR in the Region

SECOORA is faced with multiple challenges regarding HFR O&M. The region is frequently impacted by tropical storms which erode beaches where HFR are installed or destroy HFR installations, as evidenced by Hurricane Irma in 2017 where 8 HFR across the 4-state region were damaged. Additionally, the operational footprint for the HFR on the North Carolina Outer Banks will encompass offshore wind turbines, proposed as part of the Kitty Hawk Offshore Wind Project. Scientists are working to understand how the turbines will interfere with HFR operations and identify potential mitigation strategies with HFR vendors. Finally, HFR Operations and Maintenance (O&M) funding has remained stagnant while labor, equipment, and supply costs have increased. These issues are negatively impacting the HFR operations in the southwest.

Tropical Cyclones

The SECOORA region, both the Atlantic and Gulf of Mexico, is prone to tropical cyclones. These storms cause surge, high surf, coastal erosion, and overwash that negatively impact HFR operations. Observing equipment deployed in the harsh coastal environment is much more prone to weathering and corrosion. The oldest operational HFRs in the SECOORA region were deployed in 2003. With aging equipment, spare systems are required to maintain consistent and continuous observations without extended interruptions.

Figure 3. Hurricane Irma damage (2017) to HFR off the coast of Miami, FL. Overwash from the hurricane exposed and damaged the cables, resulting in total loss of communications. Image credit: UM RSMAS

In 2017 Hurricane Irma caused $650,000 in damages to 8 HFR installations in the SECOORA region. Even small, non-landfalling storms can severely damage HFR installations with high surf, winds, and resulting coastal erosion. The return period for hurricanes and major hurricanes is highest in the SECOORA domain, with North Carolina and south Florida (including the Florida Keys and Southwest Florida coast) having return rates of 5-to-8 years for hurricanes and 14–25 years for major hurricanes (Category 3 or greater, NOAA 2021b). South Carolina and Georgia have hurricane return rates ranging from 8-to-11 years.

Wind Turbine Interference

The Department of Energy (DOE) is funding a project to investigate how wind turbines interfere with HFR surface current measurements. The project will develop mitigation strategies to minimize the interference. Several IOOS HFR operators and PIs are working on software solutions with CODAR (Trockel et al. 2021).

Stagnant O&M funding

Overall, funding levels for HFR O&M have remained flat for approximately 10 years. While SECOORA did see increased funding in 2018 as part of the IOOS "Fill the Gaps" campaign, these funds were for the deployment of new HFRs within the region. Unfortunately, the O&M funds have remained level, even though SECOORA partners are operating more HFRs. This impacts up-time for systems as supply and equipment costs have increased without seeing a commiserate increase in O&M funding.

Gap Filling

Shay et al. (2008) completed the High Frequency Radar Observing Systems: SECOORA Gap Analysis, which outlined a plan for expanding the HFR network across the SECOORA domain. Recommendations from this document were included in the Plan to Meet the Nation's Needs for Surface Current Mapping (NOAA 2015), which provided an overview of HFR needs within the U.S. and identified gaps within each IOOS Regional Association. This document outlines 27 locations where HFR are needed to track and monitor the Loop Current, Florida Current, and Gulf Stream.

Eleven of the gaps identified by Shay et al. (2008) were filled with NOAA IOOS or other support (see Appendix 1, Table 2 for a list of identified gaps and gaps that have been filled since 2008). In particular, the IOOS 2018 Fill the Gaps campaign allowed SECOORA and its partners to install 6 HFR in the following locations: Ocracoke, NC, Myrtle Beach State Park, SC, Cape Canaveral National Seashore, FL, Kennedy Space Center, FL, Treasure Shores Park, FL, and one other site (T.B.D.) in Florida that will provide overlapping coverage with Treasure Shores Park. Additionally, NASEM funding to USF provided for the expansion of the HFR network into the Florida Keys, with sites installed in Marathon, FL, as well as those being installed in Key West, FL, and the Dry Tortugas. However, even with these additional HFR, large gaps in spatial coverage remain (see Figure 2).

Shay et al. (2008) also identified the need for Very High Frequency (VHF) radars, which operate within the 41–44 MHz frequency for deployment at major ports and harbors from North Carolina to Florida. Ship navigation and safety into and out of major shipping ports is a concern due to a paucity of information related to current speeds, current direction (especially related to cross currents), water level, and winds. These VHF systems provide high resolution current information needed for navigation and port safety. Two VHF HFR are needed for each of the following ports, for a total of 16 radars to be deployed:

- Port of Wilmington (NC)
- Port of Charleston (SC)
- Port of Savannah (GA)
- Port of Jacksonville (FL)
- Port Canaveral (FL)
- Port Everglades (FL)
- Port Miami (FL)
- Port Tampa Bay (FL)

SECOORA and HFR operators realize that without a large capital investment these gaps will remain largely unfilled. Where possible, SECOORA will partner with PIs on research opportunities, which enable the purchase and deployment of HFR in the region. Leveraging short-term funding opportunities to provide radars for long-term gap filling has already demonstrated significant cost savings within the region. Future opportunities to continue to fill gaps will require coordination between SECOORA, PIs, and outside funding agencies and an expanded HFR operation budget to maintain sites purchased with leveraged external funding. Based on this acknowledgement, SECOORA will prioritize funding for HFR as follows:

1. Support for existing 20 SECOORA HFR, including adequate spare parts and system life cycle replacement costs.
2. Support for the 7 active HFR that are not supported by IOOS/SECOORA operations and maintenance (O&M) funding, so that systems remain operational.
3. Installation of new HFR to fill gaps in coverage along the coastline.
4. New VHF installations to support southeast port operations.

Support for Existing SECOORA HFR

SECOORA provides annual O&M support for existing HFRs. O&M support provides operators with funding for PI and technician salary, travel to field sites, supplies, and manufacturer repairs. As discussed previously, the entire SECOORA region is prone to tropical cyclones which can cause catastrophic damage to HFR installations. Finally, existing HFR depreciation, lightning strikes, and vandalism also degrade HFR coverage. Additional support beyond basic O&M is required to maintain system operation during extreme weather events and to provide adequate spares.

Enhancing system efficiency includes incorporation of generator back-up power where possible, placement of radar equipment inside secure buildings or sheds, upgrading aging infrastructure, incorporating new wind/solar/battery off-grid power solutions, adding additional lightning protection, relocating equipment to accommodate erosion and sea level rise, and increasing site storm resilience. The SECOORA HFR team should have enough equipment and supplies in inventory to replace one HFR system. As spares are used, HFR operators will require funding to replace items removed from inventory. Before additional funds are expended on new HFR installations, SECOORA should work with individual HFR operators to assure that sites are adequately protected from storms and that there are sufficient parts and supplies that a HFR can quickly be brought back on-line after a major weather event.

Operational Support for Non-SECOORA HFR

In the future, there will be opportunities to incorporate HFR not initially supported by SECOORA under the SECOORA/IOOS umbrella. As funding expires for NASEM and other externally funded HFRs, operators should work with SECOORA to continue to maintain and operate these systems. These include the following HFR sites, all located in Florida (in priority order):

1. Venice WERA
2. Ft. De Soto WERA
3. Marathon CODAR
4. Key West CODAR
5. Dry Tortugas CODAR
6. Haulover CODAR
7. Hillsboro CODAR

SECOORA will need to secure additional O&M funding from the IOOS Office to incorporate these HFR into the SECOORA network. Inclusion of these systems will be opportunistic; however, priority will be given to maintaining these existing stations.

New Installations to Fill Gaps in Coverage for Loop Current, Florida Current, and the Gulf Stream

The type of HFR to be installed when filling regional gaps is dependent on several factors, such as, the amount of shoreline that is accessible for antenna placement, landowner permissions, permitting requirements, the desired operating frequency of the HFR, and the performance goals being addressed. Additionally, local partner needs for HFR data should be considered when siting HFR (e.g., booster rocket recovery off the Cape Canaveral coast, wave powered offshore transmitters being developed to enhance Gulf Stream HFR coverage).

As discussed by Montovani et al. (2020), the optimal candidate site should match the following characteristics:

- located as close as possible to the shoreline but safe from waves and flooding
- protected from unauthorized human access and from damage caused by animals
- located in a flat or slightly sloping area allowing human access without hazards
- accessible by vehicles
- have enough space to accommodate antennas, electronics, and cables
- free of electrically conductive objects (e.g., metallic fences, poles, and containers) in the antenna near-field
- free of radio interference at the operating frequency band
- free of obstacles limiting the field of view toward the ocean
- have nearby access to the electrical grid
- have stable and broadband internet connectivity, either wired or wireless.

The site characteristics, permitting requirements, and frequency allocation can also play a role in determining if a DF or BF HFR is best suited for the location. Many locations in the SECOORA region have been without HFR coverage due to challenges related to site selection and potentially technological solutions that are expensive. For example, the Big Bend area of Florida is particularly challenging for HFR siting due to very shallow offshore bathymetry and a low-lying area far inshore. Depending upon operational performance directives, these shallow water conditions may push the HFR to higher frequencies which will increase the number of radars required and a corresponding increase in resources, O&M support, and funding.

Conclusion

Priorities for funding based on SECOORA regional needs:

1. SECOORA's highest priority is to maintain and operate the existing 20 HFR that provide detailed surface current measurements (i.e., current speed and direction) throughout the region. This includes adequate spare supplies and equipment so that systems can be easily repaired when damaged and a replacement option for aging systems.
2. Invest in O&M for non-IOOS supported HFR that fill priority gaps in the region.
3. Purchase new HFR to fill in identified priority gaps that are needed for tracking the Loop Current, Florida Current, Gulf Stream continuum.
4. Purchase new VHF HFR to help meet the needs of regional ports. This would require ports as collaborators.

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Appendix 1

Table 1. The 27 High Frequency Radar installed in the SECOORA footprint are listed below. This includes the 20 SECOORA operated stations plus 7 stations that were installed through other funding efforts. The 7 non-SECOORA stations are located at the end of the table and they are highlighted in light grey.

HFR Operator	Year Installed	Type	Station Location	ID	Lat (°)	Long (°)	System MHz
Coastal Studies Institute & UNC Chapel Hill	2003	CODAR	Duck, NC	DUCK	36.18	-75.75	5
Coastal Studies Institute & UNC Chapel Hill	2003	CODAR	Buxton, NC	HATY	35.26	-75.52	5
Coastal Studies Institute & UNC Chapel Hill	2013	CODAR	Core Banks, NC	CORE	34.76	-76.41	5
Coastal Studies Institute & UNC Chapel Hill	2017	CODAR	Ocracoke, NC	OCRA	35.1	-75.96	5
University of South Carolina	2013	WERA	Caswell Beach, NC	CSW	33.88	-78.11	5
University of South Carolina	2012	WERA	Georgetown, SC	GTN	33.25	-79.15	5
University of South Carolina	2021	WERA	Myrtle Beach State Park, SC	MBP	33.64	-78.92	13
Skidaway Institute of Oceanography	2006	WERA	St. Catherines, GA	CAT	31.69	-81.13	5
Skidaway Institute of Oceanography	2009	WERA	Jekyll Island, GA	JEK	31.09	-81.41	13
Skidaway Institute of Oceanography	2022	WERA	Canaveral National Seashore, FL	CNS	28.93	-80.82	13
Skidaway Institute of Oceanography	2022	WERA	Kennedy Space Center, FL	KSC	28.59	-80.58	13
Florida Institute of Technology	2022	WERA	Treasure Shores Park, FL	TSP	27.798	-80.41	13
Florida Institute of Technology	T.B.D.	WERA	T.B.D.	T.B.D.	28.19	-80.59	13
University of Miami	2008	WERA	Dania Beach, FL	STF	26.08	-80.12	12
University of Miami	2008	WERA	Virginia Key, FL	VIR	25.74	-80.15	13
University of Miami	2004	WERA	Crandon Park, FL	CDN	25.71	-80.15	13
University of Miami	2021	WERA	North Key Largo, FL	NKL	25.24	-80.30	12
University of South Florida	2003	CODAR	Redington Shores, FL	RDSR	27.83	-82.83	5
University of South Florida	2004	CODAR	Venice, FL	VENI	27.07	-82.45	5

Table 1. The 27 High Frequency Radar installed in the SECOORA footprint are listed below. This includes the 20 SECOORA operated stations plus 7 stations that were installed through other funding efforts. The 7 non-SECOORA stations are located at the end of the table and they are highlighted in light grey.

HFR Operator	Year Installed	Type	Station Location	ID	Lat (°)	Long (°)	System MHz
University of South Florida	2005	CODAR	Naples, FL	NAPL	26.16	-81.81	5
University of South Florida	2010	WERA	Fort deSoto, FL	FDS	27.63	-82.73	13
University of South Florida	2010	WERA	Venice, FL	VEN	27.07	-82.45	13
University of South Florida	2019	CODAR	Marathon, FL	MARA	24.74	-80.98	5
University of South Florida	T.B.D.	CODAR	Key West, FL	WEST	24.55	-81.76	5
University of South Florida	T.B.D.	CODAR	Dry Tortugas/Ft. Jefferson National Park	JEFF	24.62	-82.87	5
Florida Atlantic University		CODAR	Hillsboro	HILL	26.26	-80.08	13
Florida Atlantic University		CODAR	Haulover	HAUL	25.91	-80.12	13

Table 2. Shay et al. (2008) identified HFR coverage gaps in the SECOORA region. One HFR is needed at each location to track the Loop Current, Florida Current, and Gulf Stream. Between 2007 and 2022, eleven gaps were filled by SECOORA PIs. See the far-right column for the name of the station, the location, and the operator for stations installed post-2008.

Location	Latitude (ºN)	Longitude (ºW)	HFR Station ID, location, and operator for stations installed after 2008
South Cape Hatteras, NC	35.23	-75.65	OCRA, Ocracoke, NC (UNC/CSI)
Cape Lookout, NC	34.75	-76.40	CORE, Core Banks, NC (UNC/CSI)
Pine Knoll Shores, NC	34.68	-76.80	
Surf City, NC	34.40	-77.60	
Oak Island, NC	33.92	-78.13	CSW, Caswell Beach, NC (UofSC)
North Myrtle Beach, SC	33.82	-78.68	MBP, Myrtle Beach State Park, (UofSC)
Murrells Inlet, SC	33.55	-79.05	
Cape Romain, SC	33.00	-79.45	
Amelia Island, FL	30.62	-81.45	
Ponte Vedra, FL	30.14	-81.38	
Marineland, FL	29.66	-81.15	
New Smyrna Beach, FL	29.05	-80.92	CNS, Canaveral National Seashore, (SkIO)
Cape Canaveral, FL	28.50	-80.60	KSC, Kennedy Space Center, (SkIO)
Melbourne, FL	28.12	-80.63	Hightower Park /TBD (FIT)
Vero Beach, FL	27.64	-80.39	TSP, Treasure Shores Park, (FIT)
Hobe Sound, FL	27.08	-80.14	
Palm Beach, FL	26.65	-80.02	
Upper Matacumbe, FL	24.90	-80.55	
Marathon, FL	24.73	-81.00	MARA, Marathon Key, (USF)
Big Pine Key, FL	24.62	-81.36	WEST, Key West, (USF)
Marquessas Key, FL	24.56	-82.12	JEFF, Dry Tortugas (USF)

Location	Latitude (ºN)	Longitude (ºW)	HFR Station ID, location, and operator for stations installed after 2008
Everglades Park, FL	25.24	-81.16	
Duck Rock, FL	25.71	-81.30	
Sanibel Island, FL	26.46	-82.17	
Coon Key, FL	28.51	-82.70	
Cedar Key, Fl	29.43	-83.30	
Horsebeach, FL	29.80	-83.75	
St Marks, FL	29.78	-84.65	
Alligator Pt, FL	29.90	-84.35	
Cape St George, FL	29.59	-85.05	
St Andrew Sound, FL	30.10	-85.75	
Pensacola, FL	30.35	-87.25	