# A National Coastal Ocean Surface Current Mapping System for the United States

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# BACKGROUND Ocean Surface Currents

urrents play central roles in the scientric study and operational tracking of our oceans and their ecosystems. As indicators of the deeper circulation and as direct measurements of buoyant particle transport, surface currents are particularly important. The surface is where people's contact with the ocean is greatest and it is where air-sea interactions are responsible for the primary momentum and thermal forcing of ocean currents.

The measurement of surface currents has been conducted, historically, using a variety of techniques. Most widespread among them has been the inference of near-surface currents from the displacement of ships from their planned courses due to the combination of currents and winds (Richardson, 1989). Purposeful mapping of near-surface current fields during survey cruises became available with the development of the shipmounted Acoustic Doppler Current Profiler (ADCP; e.g. Joyce et al., 1982; Kosro and Huyer, 1986). These ship-drift currents provided the direct evidence for worldwide current patterns at horizontal resolutions of a few degrees of latitude and longitude. More recently, satellite-tracked drifting buoys have increased the accuracy and resolution of direct surface current mapping (Niiler et al., 1987) and, in particular, have expanded the

# ABSTRACT

A description is given for a nation-wide surface current mapping system for the U.S. continental shelf regions based on the emerging capabilities of high frequency (HF) radar backscatter instruments. These HF radar systems have the advantages of being real-time, non-invasive, shore-based instruments capable of mapping ocean surface currents out to ranges of ~200 km from shore. A framework for a national backbone system is described based on long-range HF radar systems and example results are provided from existing arrays off the northwest and northeast U.S. coastlines.

global coverage to high latitude regions seldom transited by ships (Niiler, 2001). Modern drifting buoy data sets provide much more accurate representations of the ocean currents and their Lagrangian statistics than can be achieved from ship drift information (e.g., Swenson and Niiler, 1996; Ralph and Niiler, 1999; Brink et al., 2000). Even more recently the long-term, large scale tracking of surface currents has become possible from accurate mapping of sea surface heights from satellite altimeters combined with in situ observations (Morrow and DeMey, 1995). At single locations, moored current observations using ADCPs are also capable of tracking near-surface currents and have the important advantage of tracking the vertical distribution of horizontal currents over a large portion of the water column (e.g., Chereskin, 1995).

## **High Frequency Radar**

None of the techniques mentioned above have the combined abilities of another surface current measurement technique, namely the use of radio wave backscatter. Instruments that exploit that remote sensing technique are known commonly as high frequency (HF) radars. HF radar systems deployed along the coastline are capable of mapping surface currents continuously with spatial scales of a few kilometers and temporal scales around one hour (Paduan and Graber, 1997). The offshore range of these systems can commonly extend out 200 km from shore covering an extremely important coastal regime in which the bulk of human activity, as well as primary productivity and higher trophic level foraging, take place.

Early on, a number of publications (e.g., Barrick et al., 1977; Lipa and Barrick, 1983; Prandle, 1991) described the methods themselves starting with Crombie's (1955) recognition of the resonant sea echo effect of Bragg scattering by surface ocean waves having wavelengths exactly one half as long as those of the outgoing electromagnetic waves. It is for this reason that the technique is limited to decameter-scale wavelengths in the HF portion of the electromagnetic spectrum. Only these waves interact resonantly with deep water surface gravity waves for which the wave's own phase speed is accurately known as a function of its wavelength. Other frequency bands, such as the microwave frequencies used by satellite scatterometers, would be highly desirable in terms of their smaller wavelengths that could support higher resolution measurements and much smaller instrumentation. These are not viable options, however, for ocean surface current mapping using this methodology because the phase speed of the reflecting waves cannot be accurately separated from the speed of the underlying ocean current.

There have been a number of applications of HF radar techniques to coastal oceanography problems in recent years, many of them supported through the National Ocean Partnership Program (NOPP). These data have established the viability and basic accuracies of HF radar-based mapping techniques (e.g., Paduan and Rosenfeld, 1996; Graber et al., 1997). In terms of ocean observing system components, it has been recognized that HF radar systems have a number of unique advantages. They support real-time data over large ocean areas at relatively low cost. They are non-invasive and can be managed and maintained completely from the shoreline. They support two-dimensional mapping of surface currents at resolutions that capture the complex structures related to coastal topography and the intrinsic instability scales of the coastal circulation. Although not sufficient on their own, surface currents provide information about deeper currents that can be formalized within data assimilating primitive equation circulation models (e.g., Oke et al., 2002; Paduan and Shulman, 2004). At least part of the benefit of direct surface current mapping at high resolution is an improvement of the representation of realistic horizontal variability in the coastal wind forcing (e.g., Pickett and Paduan, 2003), although the low-frequency circulation measured at the sea surface is clearly related to the deeper geostrophic flow as has been shown in several comparisons of subtidal period velocity maps and temperature patterns (e.g., Paduan and Rosenfeld, 1996; Kosro et al., 1997).

# Surface Current Mapping Initiative

Surface currents along the U.S. continental shelves have been repeatedly identified as a critical variable needed to meet many of the observing system goals of the Integrated Ocean Observing System (IOOS) as well as NSF's ORION program. Because of the advantages described above, mapping ocean currents using HF Radar systems is one of the recommendations that has been put forth as part of the IOOS planning process under the auspices of Ocean.US1 (Paduan et al., 2004). The recommendations describe the creation of a national Surface Current Mapping Initiative (SCMI), which will support the expansion and integration of several forms of current mapping from satellite altimetry to HF radar to data assimilating circulation models. In this note, we describe details of the proposal with regard to the unique capabilities of HF radar systems to monitor the coastal ocean surface currents for better understanding of, for example, the role of surface transport in ecosystem dynamics or the interaction of mesoscale eddy features and alongshore mean currents. In addition, the realtime, nationwide system that is envisioned will have great practical impact in terms of improved search and rescue and hazardous spill mitigation (e.g., Ullman et al., 2003).

## Direction-Finding and Phased-Array HF Radar Systems

HF radar networks require transmit and receive antennae at each site. Direction-finding implementations (e.g., SeaSonde™ manufactured by Codar Ocean Sensors, Ltd. of Los Altos, California) have a small number of antennae placed several ten's of feet apart and can look over wide angles, including 360 degrees from ocean platforms. Phased-array designs (e.g., WERA manufactured by Helzel Messtechnik GmbH of Kaltenkirchen, Germany) utilize more widely spaced antennae covering a large stretch of beach (~100 m). These systems steer their look angle over roughly ±45 degrees to the right and left of the array broadside direction. Ideal locations for both types of systems are just shoreward of open beaches. The radiowave signals can travel large distances along the groundwave path above conducting seawater. However, signal strength is quickly lost within just a few wavelengths over land. In addition to the nearshore space requirements, ideal HF radar sites must also be free of fences and power lines and other highly conducting structures in the nearfield of the receive antenna. Ideal sites, however, are often difficult to find in regions of high interest, so methods to correct for the resulting distortion of the ideal antenna beam pattern have been developed and tested (e.g., Paduan et al., 2001; Kohut & Glenn, 2003), and are now in widespread use.

Because of the more compact footprint, direction-finding systems are more practically deployed on headlands or in heavily populated areas where space is a premium. These systems do, of course, represent a compromise with phased-array systems in terms of less consistent spatial coverage for surface currents. Ancillary surface wave data presently can be obtained from both types of systems. Individual direction-finding systems can produce time series of directional wave spectra at a single nearshore point, while a pair of phased array systems can produce a map of directional wave spectra in the region of overlap. In terms of SCMI, the basic measurements provided by all systems are maps of radial currents (i.e., the component of ocean current approaching or receding from the radar site along radial lines emanating from the site). Vector currents are available for the region of overlapping coverage from two or more individual sites. At the mapping stage, it is possible to combine radial data from different types of HF radar systems, including from directionfinding and phased-array systems. The operating frequencies should be close to each other (within a few megahertz) as the nominal measurement depth increases with decreases in radiowave frequency. In all cases, the measurement depths are very near the surface and they range from about 0.5 m to 1.5 m for typical HF radar frequencies (Stewart and Joy, 1974). Research systems have been purposefully built to operate simultaneously on a range of frequencies to attempt to measure the very near surface velocity shear (Teague, 1986; Meadows, 2002; Teague et al., 2002)

#### Long-Range National Backbone

SCMI is recommending the development of a national backbone coastal surface current mapping capability that would be built on a network of long-range HF radar systems. Long-range in this context denotes about 150-200 km, which is the achievable range for commercial HF radar systems operating in the lower end of the HF band around 5 MHz. Resolution at these lower frequencies is limited mainly by the available broadcast bandwidth, which is inversely



proportional to the system's range resolution. The long-range systems can be expected to have horizontal resolution of 3-10 km and temporal resolution of 1-3 hr. For backbonelevel, non-redundant coverage, sites must be spaced about every 100 km along the coast.

Although many applications would benefit from the higher resolution available from standard-range HF radar systems operating at higher frequencies (typically near 13 MHz or 25 MHz), building a national monitoring network based on those instruments is not practical and likely unnecessary. SCMI recommends a nested approach in which longer range, lower resolution monitoring data would be available everywhere and specific regions would be able to enhance the resolution where desired by deploying additional long-range or standard-range HF radar systems. On its own, the resolution available from the long-range backbone will be highly useful and, it is argued, the development of the expertise and data systems needed for the backbone will allow regional associations to increase the resolution in their particular area for very marginal costs compared with developing the network from scratch. The recommended backbone system design and costs are outlined below following example results from existing long-range HF radar arrays.

### Example Results from Existing Long-Range HF Radar Arrays

Arrays of long-range HF radar systems exist in several places at this time, including offshore Japan and along the northeast and northwest U.S. coastlines. Some example results from the U.S. arrays are provided here to illustrate the potential of a national backbone covering much more of the U.S. coastline. The existing systems are of the SeaSonde<sup>TM</sup> direction-finding design manufactured by Codar Ocean Sensors, Ltd. Physically, the systems consist of two antenna masts mounted near the seashore: a shorter (~4 m) whip antenna with a small (30 cm x 30 cm) crossed-loop antenna box for receiving and a taller (~13 m) whip antenna for transmitting (Figure 1).

The long-range range array along the northwest U.S. coastline consists of four SeaSonde<sup>™</sup> sites: one near Crescent City in northern California and three to the north spanning much of the Oregon coast. The three southern sites were deployed as part of the NSF GLOBEC program and have been operating since March 2001 (the fourth site was deployed in September 2002). An example low-pass-filtered (subtidal) surface current map from the GLOBEC array is shown in Figure 2. The figure shows alongshore flow interrupted by several mesoscale eddy features. It is impressive in terms of its large area coverage, roughly 200 km x 250 km, and the number of mesoscale features that are elucidated along the continental shelf. Surface particle trajectories computed from the HF radar-derived velocity illustrate clearly how transport during this period was predominantly offshore. Two weeks prior (not shown), transport was predominantly along shore. This illustrates the ability of the long-range network to map the dominate features of the California Current System and to continuously track their changes.

The other region in which a large network of long-range HF radar systems potentially exists is along the northeast U.S. coastline. A number of science programs have deployed individual systems. Sharing of radial current observations among these many partners provides an example of the future products that can be delivered via group-to-group collaborations. The first-ever total vector surface current map for the U.S. eastern seaboard is shown in Figure 3. The radial data that contributed to the map originated from seven individual radar sites and four separate research groups.

#### **FIGURE 1**

SeaSonde<sup>™</sup> receive antenna at the Cape Blanco, Oregon lighthouse showing the center whip antenna element and the ~0.3 m square box for the crossed-loop antenna elements (below) and the SeaSonde<sup>™</sup> transmit antenna at the Heron Neck, Maine lighthouse (right; *photo by Karl Schlenker, GoMOOS/University of Maine School of Marine Science*).





#### FIGURE 2

Low-pass-filtered surface currents offshore Oregon and northern California on 14 January 2002 (top) and week-long particle trajectories ending on the same date computed from the surface current data (bottom; *courtesy of Bruce Lipphardt*). Locations of the three HF radar sites are shown as symbols along the coastlines, the trajectory end points are denoted by the dots, and the area within which continuous mapping was available for the trajectory calculations is denoted by the gray rectangle.





#### Recommended Backbone Structure

SCMI planning efforts have developed recommendations for implementing and managing the backbone surface current monitoring network. These recommendations are based on the collective experiences of several groups that have been involved with deploying and operating HF radar networks. The goal of the backbone network is continuous coverage in order to provide surface current maps for both science and operations. The recommendations recognize the need for trained personnel to track system performance and correct problems as they occur at individual HF radar installations. In addition, emphasis must be placed on reliable communication pathways to bring data together in real time, particularly from remote shore sites. Although radial data are easily shared from HF radar systems hundreds of kilometers apart, physical management of the instruments dictates that personnel be located within a day's drive of the field sites. These considerations lead to the consensus that, approximately, five longrange HF radar systems can be reasonably managed by one group or node. Within each node, two full-time technical staff are needed to provide for nearly continuous data flow. The skill sets required of these technicians are, firstly, a basic knowledge of electronics and computer operating systems and, secondly, a basic knowledge of computer programming and scripting. Nationwide, it will be critical to share technical information between nodes related to remote communication options and data exchange formats. User products and data distribution will be centralized in a smaller number of central product hubs and regional associations so that the primary tasks at the HF radar node level can be related to continuous data flow.

A schematic view of the recommended organizational structure is provided in Figure 4. The geographically distributed data nodes would collect data from, typically, five HF radar shore sites (colored pentagons) and feed those data into a central product hub. Having such a single-point data source will be essential for success of the operational components of the recommended program. Users, such as the U.S. Coast Guard or haz-

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#### **FIGURE 3**

Surface current map over the northeast continental shelf from seven individual HF radar sites (left; symbols) and a NASA Terra satellite image of Hurricane Isabel at the same time showing the nominal radar coverage area (right).





any regional association, but this will be rare. The main point to be made is that HF radar network deployment and management will benefit from a strong effort to share experiences and develop common products across regions, which is a pillar of the proposed backbone configuration.

Costs of the proposed long-range backbone scale with the percentage of total U.S. coastline that is to be covered by the operational system and by the desired level of redundancy. With a network of approximately 100 instruments, surface currents along the entire continental U.S. coastline could be monitored. A network that also covered significant portions of the coastline around Alaska and Hawaii would require double this number of instruments. The hardware costs for a complete implementation range from \$15M to \$44M, depending on the number of sites and the added costs involved with deployments in very remote areas. The operating costs of a national system, using the

ardous spill responders, require consistent and reliable output for any given location. As mentioned above, this level of national coordination for the long-range backbone network will provide for a significant economy of scales when regional associations choose to increase the coverage or resolution in their particular area. This is because the management expertise and data distribution pathways will be in place up front. It is also due to the fact that all HF radar radial current data is functionally equivalent and does not depend on the type of instrument that produced it or the range or resolution of the instrument. The data can be easily shared in a consistent way within the backbone network and between the backbone and regional associations.

It is also important to point out and to plan for interactions between the national backbone observing system and the regional associations, which represent the proposed implementation structure for IOOS. In the case of surface current mapping, regional associations are the most likely entity in which to locate the individual HF data nodes. In a few cases, geographic isolation may leave a node outside the jurisdiction of

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#### **FIGURE 4**

Schematic view of a national backbone surface current mapping network based on long-range HF radar systems operated by geographically distributed nodes feeding into a central product hub. A governing board, drawn from both stakeholder and implementation groups, is recommended along with a science board designed to foster continuous technical improvements.



estimate of two full-time technicians for every five HF radar installations, is between \$5M and \$14M annually. These estimates must continue to be refined as regional-scale pilot studies are created to build toward the national backbone. However, these estimates derive from concrete experiences in the research community and they can be used now to weigh the costs and benefits of the proposed monitoring network. It is also clear that operating costs will exceed the total equipment investment in just a few years, so it is the mechanisms for training and employing the technical labor force that need the most attention.

## Technical Challenges to Network Implementation

Finally, at the risk of ending on a cautionary note, it is important to point out top priority organizational and research areas that require attention if and when SCMI recommendations are implemented. Beyond the critical need to train new technicians to operate the network, the top priority issues identified by the SCMI planning process are listed in Table 1 along with brief descriptions of what is needed under each topic. More detailed information is available through Ocean.US<sup>2</sup> (Paduan et al., 2004).

#### Summary

The technical developments and recent scientific applications of HF radar for ocean surface current mapping have shown these instruments to be viable, cost-effective options for sustained ocean observations. The non-invasive, remote-sensing nature of the technology supports this conclusion. In addition, no other technique is capable of continuously mapping ocean currents over large stretches of the continental shelf. This note has described a vision for a national backbone observing network comprised of longrange HF radar systems that will provide continuous ocean current observations from the coastline out to, roughly, 180 km from shore with horizontal resolution around 6 km and temporal resolution of 1-3 hr. Specific examples of what can be imaged and tracked using these data were given for the coastal ocean offshore Oregon and the northeast seaboard. In addition, a vision for the economy of scale that will result from the backbone network that will greatly reduce the costs involved with regional-scale measurements was put forth. Finally, a list of technical areas that will benefit from a national approach to surface current mapping was given. In conclusion, this is an exciting time with respect to the potentially expanded

role to be played by surface current observations in both the operational IOOS and the scientific programs under ORION.

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# Endnotes

1. An Integrated and Sustained Ocean Observing System (IOOS) for the United States: Design and Implementation. Ocean.US Community Workshop, Airlie House, VA, March 2002

2. http://www.ocean.us/

#### TABLE 1

Top priority issues for current mapping identified by the SCMI planning process.

Торіс	Description
Governance of the integrated network	The management and operating structures for a national backbone observing network must continue to be researched and refined within the context of IOOS and the goal of creating economy of scale.
Siting of HF radar instruments	A nationwide approach is needed to the issue of locating instruments around the shoreline. Although benign and relatively unobtrusive, the locations needed for antenna deployments represent prime coastal real estate and the societal benefits of supporting these instruments must be put forth in an organized way.
Frequency allocations	HF radar systems require radio band broadcast frequency permissions from the Federal Communications Commission and other authorizing bodies. The competition for bandwidth is severe and, at the moment, all scientific HF radar broadcast licenses are issued as secondary, not-to-interfere licenses. System operators must learn to share HF frequency allocations whenever possible. Long term, a national effort to allocate primary operating bands for these instruments, similar to what has occurred in other frequency bands for weather radar operations, is needed.
Product development	Coordination of the creation and distribution of products based on the real-time surface current maps must take place in order to achieve the most effective interactions with the various research, education and applied end-user communities.
Research integration	Programs and mechanisms should be put in place to continue research into the performance of HF radar systems and the algorithms involved with them. It must be possible for improved methods or error characterizations to be incorporated smoothly into the operational system.

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