PAPER

The Integrated Ocean Observing System High-Frequency Radar Network: Status and Local, Regional, and National Applications

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ABSTRACT

A national high-frequency radar network has been created over the past 20 years or so that provides hourly 2-D ocean surface current velocity fields in near real time from a few kilometers offshore out to approximately 200 km. This preoperational network is made up of more than 100 radars from 30 different institutions. The Integrated Ocean Observing System efforts have supported the standards-based ingest and delivery of these velocity fields to a number of applications such as coastal search and rescue, oil spill response, water quality monitoring, and safe and efficient marine navigation. Thus, regardless of the operating institution or location of the radar systems, emergency response managers, and other users, can rely on a common source and means of obtaining and using the data. Details of the history, the physics, and the application of high-frequency radar are discussed with successes of the integrated network highlighted.

History and Technical Background for HF Radar

History

The present state of the U.S. national high-frequency (HF) radar network has resulted from nearly 40 years of research and applications. HF radar observations of the ocean surface truly began with Crombie's (1955) experimental discovery of the mechanism behind his puzzling analog sea-echo spectral plots. Don Barrick (1968, 1972) theoretically derived the model that indeed showed that this resonant scatter was in fact "Bragg scatter" and related the echo strength to the ocean wave height spectrum at the Bragg wave number. Barrick was invited to present his results at seminars in Boulder, Colorado, as the National Oceanic and Atmospheric Administration (NOAA), and its Boulder laboratories were being formed in 1970. A group was formed within NOAA's new Environmental Research Laboratories to build a compact antenna system to be used for coastal ocean surface current mapping. This was the Coastal Ocean Dynamics Applications Radar (CODAR) program. After demonstrating its effectiveness, the NOAA/National Ocean Service formed a Transitional Engineering Program in 1978 to encourage development of a commercial version of CODAR. With only a small potential market, no existing radar companies were interested in commercializing CODAR so a small group left NOAA to start CODAR Ocean Sensors, Ltd. in the early 1980s.

In the 1990s, the Office of Naval Research and the National Science Foundation funds were used to acquire radars at several universities including the Oregon State University, the Rutgers University, the University of California-Santa Barbara, the Naval Postgraduate School, the University of Rhode Island, and the University of Connecticut. This was followed by a surge in acquisition because of the National Oceanographic Partnership Program, an NOAA/Office of Naval Research/National Science Foundation program that funded coastal oceanographic research at many of these same universities.

In 2002, California voters approved funds that led to a program called the Coastal Ocean Currents Monitoring Program, which allowed for the investment of $21 million to create a California network of HF radars to measure ocean surface currents to ensure the monitoring of coastal water quality. The acquisition began in 2005 with 40 CODAR radars eventually being integrated with the then-existing 14 CODARs in California.

On a national scale, the Integrated Ocean Observing System (IOOS®) Program has been facilitating the development of a national data management and distribution system for all U.S. HF radars as well as radars operated by the Canadian Coast Guard in Nova Scotia. Presently, more than 100 HF radars and 30 institutions are part of the network, and their data are delivered by IOOS national data servers. The development server and data display are provided by Scripps Institution of Oceanography's Coastal Observing Research and Development Center (http://cordc.ucsd.edu/projects/mapping/), and its mirror is at the NOAA National Data Buoy Center (http://hfradar.ndbc.noaa.gov/) while data failover redundancy is also provided at Rutgers University. Data file management and distribution follow internationally accepted standards, for example, netCDF-CF file and metadata formats and OpenGIS® *Web Coverage Service* Interface Standard for interoperable delivery of gridded data. Nationally, an additional focus has been the effort to acquire primary radio frequency licenses. To form an operational network, the radars need to operate at dedicated radio frequencies, which requires the approval of the International Telecommunications Union as well as U.S. agencies. The process to acquire those frequencies has been supported by NOAA IOOS for nearly 5 years, with the expectation that the final approvals will be given at the World Radiocommunications Conference in January 2012 (Figure 1).

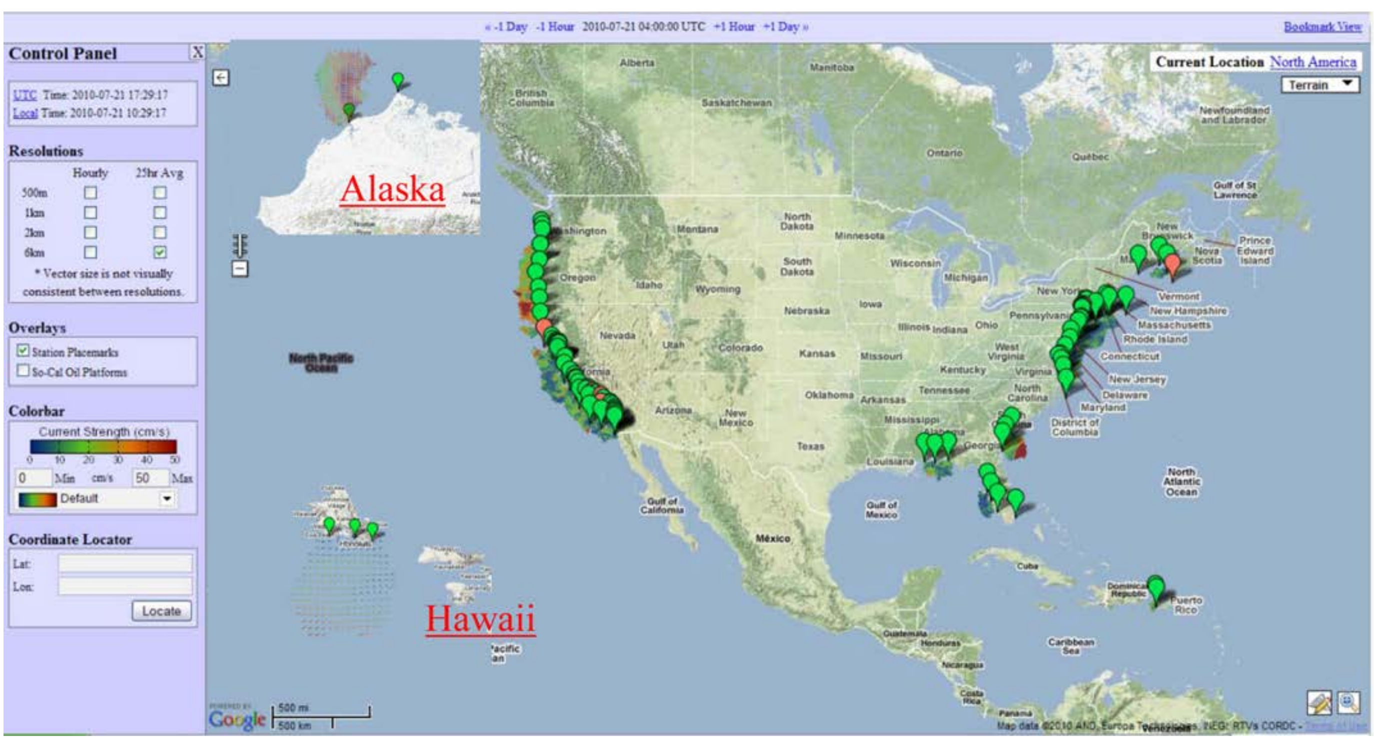
Physics of HF Radar Current Monitoring

Why HF radar?

HF denotes that part of the electromagnetic spectrum having frequencies from 3 to 30 MHz, which is equivalent to radio wavelengths of 10 to 100 m. HF radar has been shown to be the optimal method for coastal sea surface current mapping for a number of reasons. First, the targets required to produce coherent sea echo using HF are surface gravity waves, typically of several to a few tens of meters wavelength, which are well understood and nearly always present in the open ocean. Second, vertically polarized HF waves can propagate over conductive seawater via coupling to the mean spherical sea surface, producing measurement ranges

FIGURE 1

Montage of U.S. HF radar site locations. Green sites are sending data on schedule. Red sites have delayed data. (Color versions of figures available online at: http://www.ingentaconnect.com/content/mts/mtsj/2010/00000044/00000006.)



beyond line of sight, out to 200 km or more offshore. Third, Doppler sea echo at HF, under most wave conditions, has a well-defined signal from wave–current interactions that is easily distinguishable from wave–wave processes. This allows for robust extraction of current velocities. It is primarily these three features, along with the spatial resolutions that are possible due to the frequency modulation discussed below, which place the HF band in a unique status for coastal current monitoring.

Physics of HF Sea Scattering

The two environmental conditions necessary for HF current mapping are conductive surface water and the presence of surface gravity waves of sufficient length and height. Conductivity of water is primarily determined by salinity, which is typically 32–37 PSU in the open ocean. As salinity decreases, so does the strength of the sea echo and, therefore, range of measurement. Since freshwater is inherently 5,000 times less conductive than seawater, HF signals do not travel nearly as far (e.g. Fernandez et al., 2000). It has been observed in bays and around river mouths that during times of high freshwater discharge ranges can be significantly reduced (e.g., Long et al., 2006).

The ocean surface, at any given moment, contains a random structure of crests and troughs, the slopes of which scatter radar signals in all directions. However, within the random surface, it is only the periodic structure of surface waves whose wavelength, λ_o, is precisely half the radar wavelength, λ, that will produce coherent backscatter. This is an analytic result known as Bragg scattering. In the case of a standard backscatter (or monostatic) radar, the scattered energy will be shifted in Doppler proportional to the relative speed of the ocean wave traveling directly toward or away from the radar. The transmit frequency of the radar determines the radar wavelength and, hence, determines the length of ocean waves from which the radar wave will backscatter. Because attenuation increases as frequency increases, the result is that higher frequency radars (shorter radar wavelength) have a shorter maximum range. Approximately one third of the radars in the United States are in the 4- to 5-MHz band, which can achieve 200 km or more, depending on conditions. Another third operates in the 12- to 14-MHz band and can achieve an approximately 90-km range. Approximately one quarter of the radars operate in the 24- to 27-MHz band and achieve ranges of approximately 45 km. At the higher frequencies, it is possible to obtain greater radio spectrum bandwidth that in turn allows for higher range resolution. The resolutions vary from less than 1 km to approximately 6 km. Regardless of the operating frequency, the physics is the same. Assuming a stationary radar, the relative wave speed is comprised of the phase speed of the Bragg wave plus any underlying current. For deep water, the phase speed for surface waves is well known as a function of λ_o:

$$c = \sqrt{\frac{g\lambda_o}{2\pi}}$$

which can be subtracted leaving only the velocity of the current. This velocity is the projection of the actual current along the ray from the radar location to the scattering area and is generally referred to as a *radial velocity*. In water of shallow or intermediate depth, the water depth, D, must be also be known at each measurement location *a priori* to properly remove the Bragg wave phase speed:

$$c = \sqrt{\frac{g\lambda_o}{2\pi}\tanh\left(\frac{2\pi D}{\lambda_o}\right)}$$

Range and Velocity Determination

All HF radar systems currently used for ocean measurements use some form of frequency-modulated continuous wave (FMCW) waveform for range determination. FMCW has the benefit of much lower maximum power requirements to achieve the same average power and, therefore, range performance as older time-gated pulsed radars (Barrick, 1973). For closely spaced or colocated transmit and receive antennas, a pulsed and gated FMCW (or FMiCW, "i" = interrupted) waveform is desirable whereby the transmit signal is cycled on and off and radar echo received in opposition over a period determined by the system's achievable range. This is done to prevent saturation of the electronics as well as the received echo by the much stronger transmit signal. For both cases, the fundamental range determination is the same (Barrick, 1973).

A continuous linear frequency sweep (or chirp) over a fixed bandwidth and pulse repetition frequency is generated in the receiver and amplified for transmit. As scattered energy is received, it is delayed by the two-way travel time and shifted in Doppler on the basis of the target velocity. When mixed with the coherent linear sweep still generated inside the receiver, the time delay of the received echo results in a difference frequency train, which is digitized for range and Doppler processing. By applying a fast Fourier transform to the digitized signal, the data can be sorted into discrete range bins at each sweep. Application of a second fast Fourier transform at each range bin over multiple sweeps produces a Doppler spectrum at each range.

A typical Doppler spectrum for a single receive antenna is shown in Figure 2. The characteristic Bragg peaks from surface wave echoes are indicated with a positive Doppler shifted peak resulting from waves approaching the radar and negative Doppler shifted peak from waves retreating from the radar. Each peak is further spread because of the underlying current velocities present across the entire arc at the selected range. Also shown is the weaker second-order sea echo, which is a harmonic of the first order, whereby longer waves, not currents, modify the Doppler of the Bragg waves. Wave state information can be extracted from second-order spectra for certain wave conditions that vary by radar frequency (Lipa, 1977) (Figure 3).

FIGURE 2

CODAR SeaSonde on San Clemente Island, CA.

Bearing Determination Methods

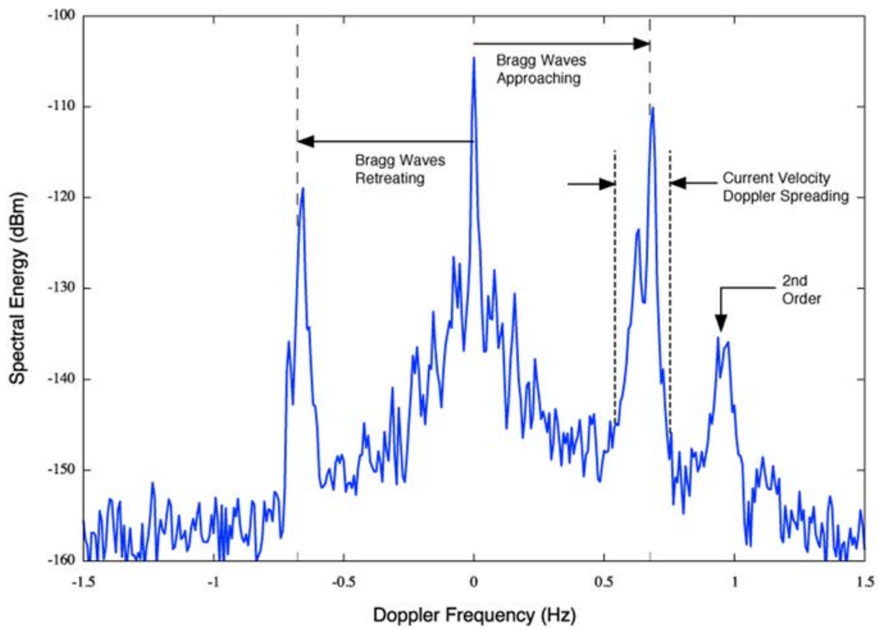
The final stage of processing radial vectors is bearing determination. A single antenna can detect all of the current velocities present at a given range, but more information is needed to determine the bearing to which each velocity can be attributed. In general, there are two classifications of bearing determination commonly used for HF radar: beam forming and direction finding.

Direction finding uses the phase and amplitude differences between receive antenna elements, known as the antenna response pattern. These differences are applied to each Doppler bin in the spectra of the individual elements to determine the most likely direction of arrival. Direction finding can be applied to compact directional antennas or to phased array antennas. It is most commonly used with the three colocated elements of the compact cross–loop/monopole configuration (e.g., Miller et al., 1985). Approximately 90% of the HF radars in the United States use a direction finding method.

Beam forming uses an array of receiving antenna elements, typically between 8 and 16 in a linear alignment and spaced about half of the radar wavelength apart. Phase differences exist between signals received on the array elements that depend on the direction of arrival. When the Doppler spectra of the individual array elements are summed with the proper phase differences applied for a given bearing, a digital narrow beam is formed and a peak-picking algorithm used on the resultant spectrum. The digital beam width depends on the ratio of the wavelength divided by the array length and on the bearing toward which the beam is steered (Skolnik, 1990).

FIGURE 3

Representative HF radar Doppler spectrum.



Methods for Combining Radial Current Vectors

Although there are a variety of uses for radial vectors by themselves, most often the radial velocity vectors from two or more sites must be combined to produce a 2-D map of the surface current velocity. The problem inherent in any combining method, however, is that each radar inherently outputs radial vector data in a polar grid centered on the radar location.

Mapping multiple sets of radial vectors from displaced polar grids onto a Cartesian coordinate system results in variations in data density, signal strength, and geometric dilution of statistical accuracy (Chapman et al., 1997) across the field of coverage.

A number of combining methods have been developed including but not limited to simple interpolation with vector addition, least squares methods on vectors falling inside a defined averaging circle, and objective mapping. Recently, efforts have been made both in applying modal analysis to multiple radial data sets (Lekien et al., 2004) as well as assimilating radial velocity data directly into models without performing a separate radial combining step (Shulman et al., 2007).

IOOS HF Radar: An Exemplary Partnership

In 1999, a number of HF radar researchers gathered informally in Oregon as a side meeting to a National Oceanographic Partnership Program awardees workshop. The clear benefits to everyone from having meetings specifically designed to exchange information and research about HF radar gave birth to the Radiowave Oceanography Workshop (http://radiowaveoceanography.org/) series of meetings starting in 2001, which have continued annually ever since. Although completely self-funded, these meetings have been successful in annually bringing together HF radar experts at a dedicated forum in which to share state-of-the-art knowledge. This series of workshops illustrates the level of cooperation and commitment within the HF radar community.

There are presently 30 institutions that contribute their data to the national HF radar network data management system, which is funded by IOOS but relies on the voluntary adherence to data file format standards by the HF radar operators. Users from these institutions also routinely volunteer their time for workshops such as the Radar Operators Working Group (http://www.rowg.org), information collection efforts such as the gap analyses, and standards compiled for the creation of the National Surface Current Mapping Plan (http://www.ioos.gov/hfradar) and advisory panels such as the National HF Radar Technical Steering Team to help make the transition to an operational national HF radar network.

National Applications

On a national scale, there are two main applications presently underway: (1) the U.S. Coast Guard (USCG) Search and Rescue (SAR) operations and (2) the NOAA oil spill response operations. These applications use ocean surface current data to track and predict the flow of the uppermost layer of the ocean, and IOOS within NOAA is providing resources to bring new capabilities to both of them.

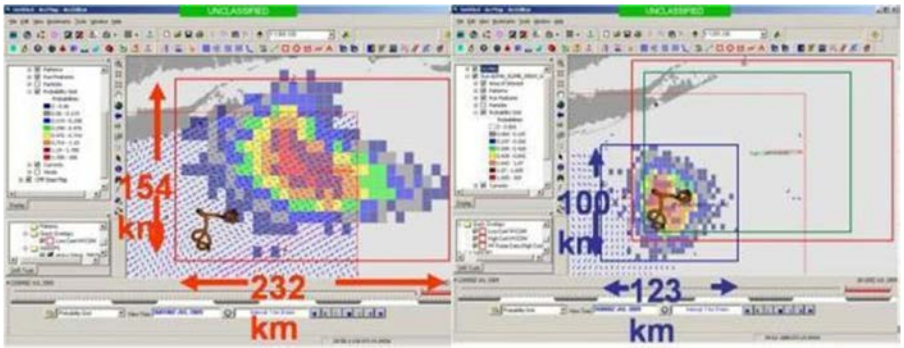
USCG SAR Optimal Planning System

Beginning in 2000, the USCG Research and Development Center began a multiyear investigation into the utility of real-time HF radar surface–current measurements for search and rescue (SAR). In collaboration with the University of Connecticut, the University of Rhode Island, and the Rutgers University, these drifter-verified tests were based around the CODAR SeaSonde (CODAR Ocean Sensors, Ltd.) standard-range and long-range HF radar systems operating on the eastern coast of the United States. The USCG assessed the improvement from HF radar data in their SAR planning process (Ullman et al, 2003). This study showed better comparison when CODAR-derived currents were compared against available NOAA tidal current predictions. Along with these key comparisons, an equally important product was developed, the Short-Term Predictive System (STPS), which provides a 24-h forecast of surface currents based on the statistics of the previous 30 days of CODAR surface current data. Following these evaluation studies, available *in situ* data were used to evaluate and define appropriate parameters for inclusion in the USCG search planning tool. In May 2009, the current velocities from the Mid-Atlantic long-range CODAR network and long-range STPS forecasts were included in the operational USCG SAR Optimal Planning System. For SAR cases in the Mid-Atlantic, planners now have access to these data and forecasts within their operational planning tool.

Because SAR is a national mission encompassing all U.S. coastal waters, the IOOS Program in NOAA is extending these Mid-Atlantic data products to all coastal areas where HF radars are located. This is a partnership with the USCG, the Scripps Institution of Oceanography, the University of Connecticut, the Rutgers University, and the Applied Sciences Associates that will extend the STPS and also provide a gap-filled current velocity field using optimal interpolation (e.g., Kim et al., 2008) as input to the STPS. These groups provide expertise from a spectrum of topics that are needed to provide a real-time end-to-end product, including data handling from the

FIGURE 4

Screenshots from USCG SAROPS. Left: search area without using HF radar data. Right: search area reduced by 2/3 when HF radar data used. Both after 96 h.



radar site to multiple distributed national servers, intermediate products (STPS and optimal interpolation portions), and finally to the USCG Environmental Data Server (Figure 4).

Oil Spill Response

Although the main impetus for creating the NOAA CODAR system in the 1970s was for oil spill response, it was not until 2006 HF radar was used by official government spill responders. In August of 2006, the National Ocean Service and the USCG led an interagency field exercise, *Safe Seas 2006*, in the San Francisco Bay area to enhance the preparedness of oil spill responders. As part of that exercise, the IOOS program collaborated with the NOS Office of Response and Restoration (OR&R) to create hourly gap-filled maps of HF radar-derived surface currents. The IOOS partners at the San Francisco State University and the Naval Postgraduate School created new data handling software and implemented a real-time open-boundary modal analysis suite of algorithms (Kaplan and Lekien, 2007). These nowcasts were then formatted into files that were readily ingested by the General NOAA Oil Modeling Environment. Eleven HF radars, spanning more than 160 km of coastline and having 1- to 2-km resolution, provided continuous coverage during the 5-day exercise. This preparedness exercise provided a foundation for the use of HF radar data by the NOAA OR&R spill response trajectory modeling team (Figure 5).

When the container vessel *Cosco Busan* collided with the base of the Bay Bridge in San Francisco Bay in November of 2007, spilling more than 53,000 gallons of fuel oil, managers used surface current maps from HF radar data to monitor the spill trajectory, predicting movement as far north as Angel Island and westward along the San Francisco waterfront. This closely matched visual reports of oil on the shorelines of Alcatraz, Angel Island, and San Francisco and on a map produced by the NOAA OR&R. Once the oil moved into the Gulf of the Farallones, the HF radar data accurately predicted that the oil would not beach there. As HF radar capabilities are integrated into California oil spill response, spills like the *Cosco Busan*'s (which occurred in dense fog) can be more effectively tracked, with mitigation efforts unimpeded by lack of visual data.

The earlier *Safe Seas* exercise and use of HF radar data during the *Cosco Busan* spill allowed OR&R to make a seamless transition to utilizing Gulf of Mexico HF Radar data soon after the Deepwater Horizon platform in the northern Gulf of Mexico exploded and sank in April of 2010. As of this writing in August 2010, the HF radar data are still being used daily. Partners from the University of Southern Mississippi and the University of South Florida have monitored their radar systems constantly to ensure that they are operating while the Deepwater Horizon spill continued and that the data were delivered to the IOOS national

FIGURE 5

Schematic of data flow for new HF radar SAROPS project.

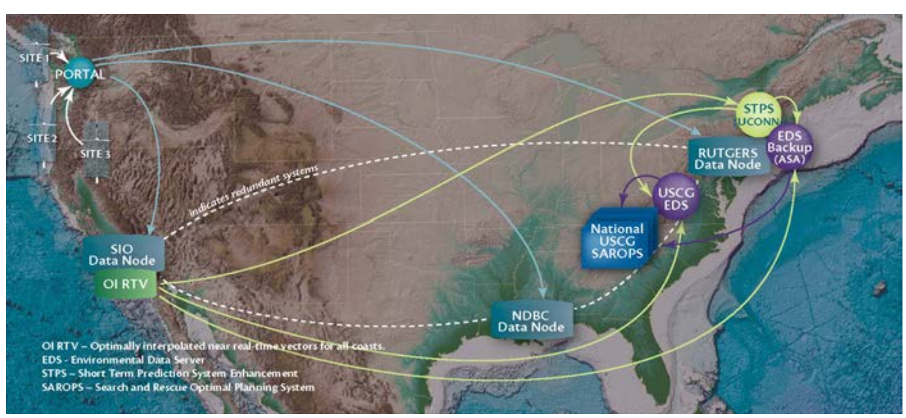
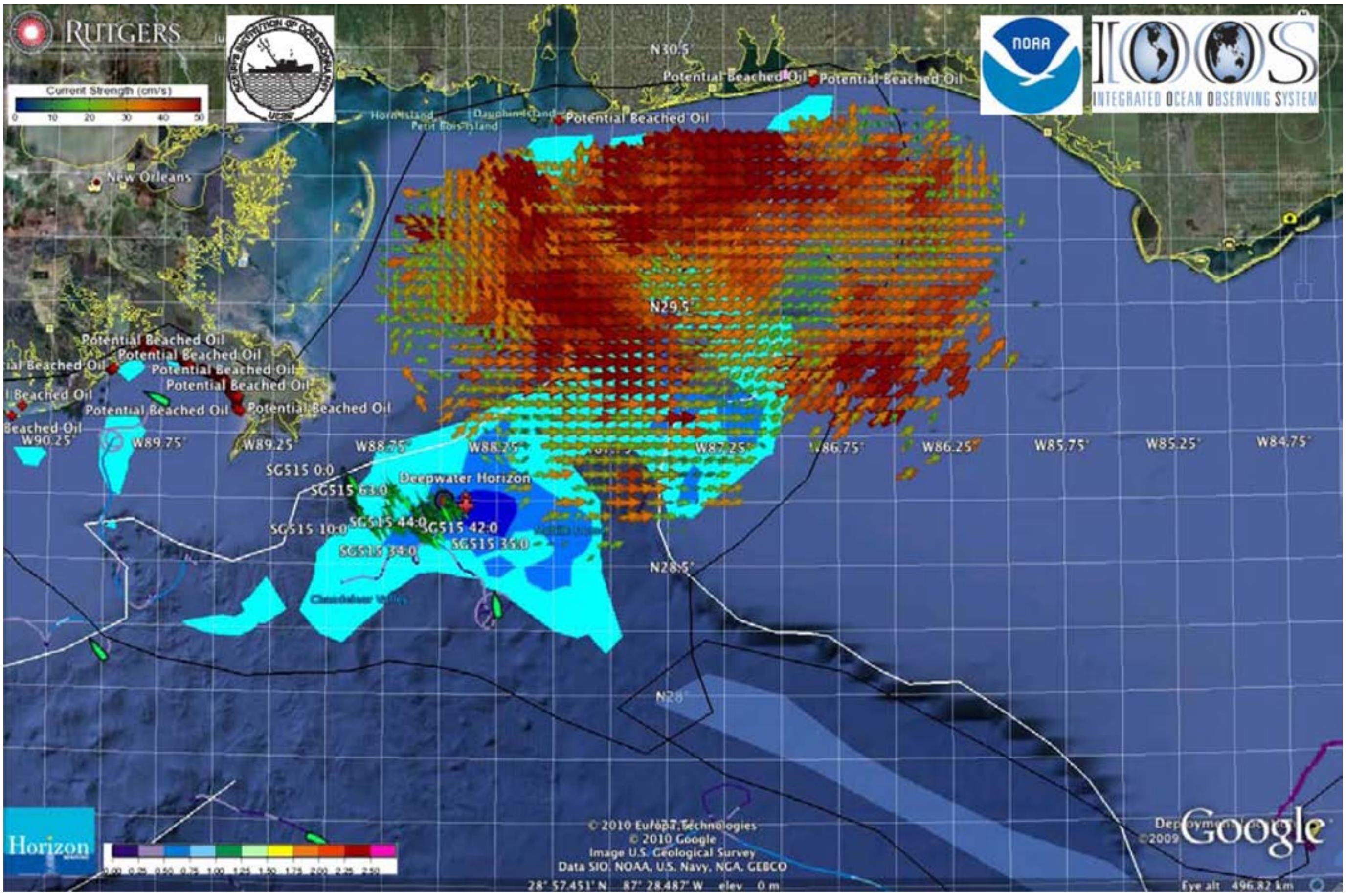


FIGURE 6

HF radar currents for June 4, 2010, overlaid with oil coverage in the Deepwater Horizon spill area in the northern Gulf of Mexico, courtesy Rutgers University Coastal Ocean Observation Lab.



HF radar data servers at Scripps Institution of Oceanography and the NOAA National Data Buoy Center. These Gulf of Mexico sites have been particularly valuable since they cover a good portion of the continental shelf in the Mississippi Bight, which is just to the north and northeast of the site where the Deepwater Horizon was located (Figure 6).

Similar to USCG SAR, the optimally interpolated current velocity fields, mentioned earlier, will also provide a product that can be ingested into the NOAA oil spill response team's General NOAA Oil Modeling Environment model for application wherever HF radars operate.

Regional Applications

Tracking Impacts on Marine Populations

Ocean conditions change from year to year and the ongoing measurements of surface currents made by HF radar are a crucial backbone for ocean observations along the coast. Unlike buoys and ships, which collect information at single points and times, HF radar provides full, archived mapping, day and night, of our coastal waters to 150 km offshore. Long-term monitoring of surface currents is used to track impacts on marine populations. Off Bodega Bay, California researchers are using HF radar-derived surface current data to obtain seasonal to annual information on ocean conditions that likely influence the survival rate of young salmon when they first enter the ocean. As smolts exit estuaries like the Russian River in early spring, strong northerly winds and southward-moving currents can carry weakly swimming small fish south to the predator-rich Gulf of Farallones in some years or alongshore to the north in others. Preliminary evidence suggests that surface flows in the months leading up to the spring emigration period may be important for the survival of salmon smolts and returns to the Russian River system years later (W.J. Sydeman/Farallon Institute and J.L. Largier/Bodega Marine Laboratory, unpublished data).

Reversing the collapse of the California salmon fishery requires an understanding of the migratory paths of young salmon as well as knowledge of the movement of nearshore surface currents and upwelling events that comprise their ocean going habitat.

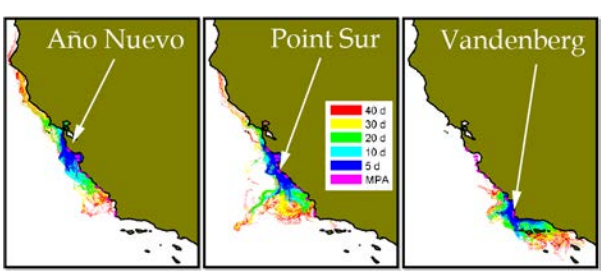
Coastal surface currents can also provide important input to establishing and evaluating marine protected areas (MPAs); it provides the only multiyear data with enough spatial coverage to assess how larvae of marine populations are dispersed from the location where they originate to where they settle and grow to maturity. HF radar data from a regional network in California have demonstrated the connectivity between central California marine protected areas (MPAs) by back-projecting trajectories from 10 MPAs more than a 40-day period. Clarifying this connectivity is an important step toward understanding the movement of invertebrate and fish larvae (Zelenke et al, 2009) (Figure 7).

HF radar data are also being used to identify and track large eddy features (tens of kilometers wide) off Cape Mendocino, Point Arena, and in the Santa Barbara Channel. These eddies play a critical role in connecting or disrupting marine populations that live along the coast of California. The California coast is experiencing an increasing frequency and toxicity of harmful algal blooms (HABs), exacting serious economic, human, and marine wildlife costs. Surface current mapping has proven to be an essential tool for managers and scientists to assess and respond to HABs and will be instrumental in developing the ability to predict these events. Like all food chain components, HABs are part of a larger marine ecosystem driven by the physics of winds, waves, and currents. HF radar has become a core technology for understanding these ecosystem processes.

A California statewide Harmful Algal Bloom Monitoring and Alert Program that was initiated by the NOAA, the California Ocean Science Trust, and the Southern California Coastal Water Research Project is supported through the Ocean Observing Regional Associations. Weekly bottle samples measure chlorophyll, nutrients, domoic acid, and harmful algal species. Data are posted to the Web and distributed via the California Harmful Algal Bloom Monitoring and Alert Program Listserv. When HABs are detected, opportunistic sampling from additional shore sites, HF radar-derived surface currents, gliders, and boats determines their extent and severity.

FIGURE 7

Color map: location of waters 40 days ago (red), 30 days ago (yellow), 20 days ago (green), 10 days ago (cyan), and 5 days ago (blue) before reaching the labeled MPA (magenta). Connectivity maps on the basis of measured surface currents show what waters are influencing MPAs and the potential extent of surface water larval transport.



Within the Northwest Association of Networked Ocean Observing Systems region, the Pacific Northwest Harmful Algal Bloom Bulletin has been developed by the NOAA and the University of Washington to provide a comprehensive early warning information system for Washington coast razor clam toxicity and amnesic shellfish poisoning events. The bulletin builds upon the Olympic Region HAB monitoring program and Ecology and Oceanography of Harmful Algal Blooms in the Pacific Northwest research by automating the aggregation of data into a single location on a Web-based information dashboard. Among the array of chemical and biological information included are currents from HF radars that operate within Northwest Association of Networked Ocean Observing Systems (Trainer and Hickey, 2010).

The goal of assimilating HF radar-derived currents into numerical circulation models has for a number of years remained a priority within the modeling and HF radar research communities. Generally, these models are developed for areas that scale to approximately that of an IOOS regional coastal ocean observing system. A number of successful modeling projects are described in the National Surface Current Mapping Plan (http://ioos.gov/hfradar), and a recent American Geophysical Union Meeting of the Americas 2010 (Foz do Iguaçu, Brazil, program available here) held a session on *Application of HF Radar Networks to Ocean Forecasts*. In addition, as part of the recently established National HF Radar Technical Steering Team, the IOOS HF radar community is presently undertaking a comprehensive review of the many modeling efforts that use HF radar data throughout the globe.

Local Applications

Coastal Water Quality

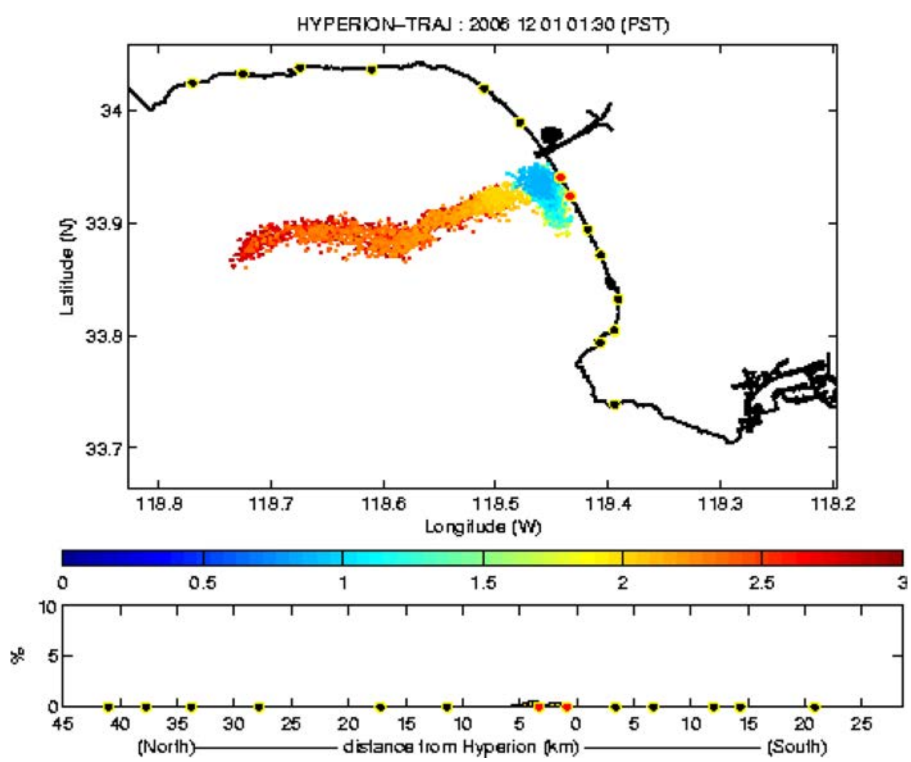
In southern California, HF radar-derived surface currents has allowed managers to track the movement of planned and unplanned discharges in our coastal waters, enabling more precise and timely management decisions. An Orange County Environmental Health Engineering Specialist, familiar with the Tijuana River outflow issues, wrote that "this real-time surface currents monitoring system has allowed the San Diego County Environmental Health Agency to predict when contaminated water from the Tijuana River will impact the southern beaches of San Diego County." In November of 2006, the City of Los Angeles diverted the flow from Hyperion—its oldest and largest wastewater treatment plant—from an outfall 5 miles from the shoreline to a rarely used pipe 1 mile offshore to allow inspection of the 5-mile pipe. The diversion lasted 3 days, and approximately 800 million gallons of secondary-treated wastewater was released 1 mile off the coast of Santa Monica. A division manager for the City of Los Angeles, Bureau of Sanitation's Environmental Monitoring Division writes that the city's monitoring effort greatly benefited from information provided through the HF radar system and that "the real-time current information provided through [the program] enabled us to adaptively modify our sampling grid to better track the discharge plume and to predict the dispersion of the plume."

In October of 2007, the end gate to the Southwest Ocean Outfall offshore Ocean Beach in San Francisco was lost; a buoyant mixture was released from the pipe 6.5 km offshore and rose to the surface. At the request of the San Francisco Public Utilities Commission, HF radar data were used to track movement of the effluents based on real-time observations of ocean surface currents from the HF radar network. "[A scientist] was able to rapidly provide daily and cumulative modeling of effluent trajectories that really demonstrated the immediate value of the existing program," said Michael Kellogg of the San Francisco Public Utilities Commission. This information significantly improved the decision-making and response capabilities of the utilities commission. The trajectories showed a weak onshore flow, indicating that the discharge would not move toward beaches by the time the rupture could be repaired; this allowed responding agencies to better manage beach closures, offshore and onshore water quality monitoring, and outfall repairs (Figure 8).

Since 2008, several floatable events along the New Jersey coast have prompted investigations on possible sources and ultimate fate of debris that has washed up on local beaches. For example, in August 2008, medical waste washed up on the shores near Avalon, New Jersey. The New Jersey Department of Environmental Protection asked the mid-Atlantic HF radar network managers at Rutgers University to provide information on the possible source. Using the location and the time of the initial beach location of the debris, Rutgers radar scientists were able to trace back its probable location several days before the washup. The weak currents indicated that if the debris were put into the ocean within several days of the initial siting, it had to be a local source. Consistent with the

FIGURE 8

Upper panel: shows the near real-time Hyperion Outfall plume trajectory color coded based on particle age (dark blue—0 days; red—3 days). The color coding is based on approximate life cycle of bacteria. Lower panel: distance along the coastline from the Hyperion Outfall with Los Angeles County sampling locations red if there is plume potential.



guidance from the HF radar data, the investigation determined that the source was in fact a dentist who dropped the waste from a boat just off the beaches of Avalon the day before. This result, along with other events in the region, has highlighted the need to extend the regional coverage of the present HF radar network closer to the coast. These local enhancements are being initiated in the Mid-Atlantic Bight with leveraged state agency resources to build out nested high-resolution HF radar sites and assimilation of these data into coastal models tuned to track particles along the coast.

Marine Navigation

HF radar data are a core component of a simple but very effective near real time, customized, interactive Website displaying environmental conditions at the entrance to the Ports of Los Angeles and Long Beach Harbor: http://www.sccoos.org/data/harbors/lalb. This Website could serve as a template for ports throughout the United States. This application is discussed more fully in a companion article by Thomas et al. in this issue.

Integrating HF radar data with existing conventional in situ sensors will also occur in an upcoming demonstration project in Mobile Bay, Alabama, involving Mobile's NOAA Physical Oceanographic Real-Time System (PORTS®) and two CODAR systems, operated by the University of Southern Mississippi. This project may provide a basis for consideration of a Gulfport, Mississippi HF radar-PORTS® equivalent.

Offshore Wind Energy

Rutgers University has been funded by the New Jersey Board of Public Utilities to develop a 3-D wind resource map to support the offshore wind energy community. The work will use available forecast models and a new deployment of a radar subnetwork (four sites) along the southern New Jersey coast. This is a 2-year grant that leverages IOOS infrastructure and creates a higher resolution HF radar coverage area within the Mid-Atlantic Bight.

Summary

HF radar as a tool for ocean surface current mapping has been in existence for more than 30 years. It has proven itself in a number of applications of national, regional, and local significance, especially during the last 10 years or so. The physics of the measurement and the technology that delivers the measured ocean current velocities provides a robust method for coastal monitoring from nearshore to more than 200 km offshore. Through an integrated network of radars distributed throughout U.S. coastal waters, data are delivered in near real time for use in a number of applications that are critical to the health, safety, ecology, and economies of coastal areas.

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