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The SeaSonde HF radars for coastal current mapping with recent oceanographic applications

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Abstract : HF radar technology in the U. S. has evolved away from large phased arrays and conventional high–power pulsed waveforms in two respects: (1) the large cumbersome phased arrays are replaced by compact crossed–loop systems that can be mounted on a single post or building rooftop; (2) an efficient digitally synthesized, PC–processed waveform is used that greatly reduces radiated power levels while achieving longer ranges. These improvements lead to both lower initial prices and operating costs. Called the SeaSonde, variations on this family of products can achieve ranges to 300 km in certain cases, or fine spatial resolutions to 100 m suitable for smaller–scale bays and harbors. Many comparisons with other sensors have validated system function and show accuracies equal to or better than the older, conventional, larger phased array systems. Ongoing research includes real–time assimilation of the HF radar data into numerical models for nowcasting and forecasting ocean conditions. The Rutgers University Regional Ocean Model System (ROMS) showed dramatic improvement in nowcast skill during a coastal upwelling event off New Jersey when the HF radar current vectors, or even single–site current radial components, were included in the assimilation.

Key words : *HF radar, ocean currents, remote sensing, circulation modeling*

1. Evolution of HF coastal current–mapping radars in the U. S.

The HF/VHF part of the radio spectrum is used to map surface currents from shore because the interaction of the radar signals with the ocean waves is well understood and leads to simple interpretations of the echo. An additional advantage is the ability of vertically polarized signals at these frequencies to propagate well beyond the visible horizon over the highly conducting sea. The more familiar and ubiquitous microwave radars cannot map currents because they do not possess these advantages. The distinctive resonant peaks seen in HF echo from the sea were discovered experimentally 45 years ago (CROMBIE, 1955). The underlying theoretical nature of these dominant spectral echoes was shown (BARRICK, 1972) to be first–order Bragg scatter; he also derived expressions for the lower–level second–order spectral continuum surrounding these peaks. The Doppler shift of the first–order Bragg peaks is employed to obtain the radial velocities of the surface currents, while the secondorder continuum provides information about the sea state (e. g., waveheights, directions, etc.). Because a single radar detects only the radial component of the horizontal current velocity, two or more radars are normally deployed to synthesize a total current vector at each point on their common map area.

While conventional beam – forming techniques were well understood at microwave frequencies, the application of these same techniques to the HF band leads to quite large antenna sizes, as its lateral dimension must be many radio wavelengths in extent. Called phased arrays, these antenna systems combine signals from many array elements in software to form and scan their beams across bearing angle. Using large phased–array antennas on San Clemente Island, CA, BARRICK, CROMBIE and their colleagues established the utility of HF

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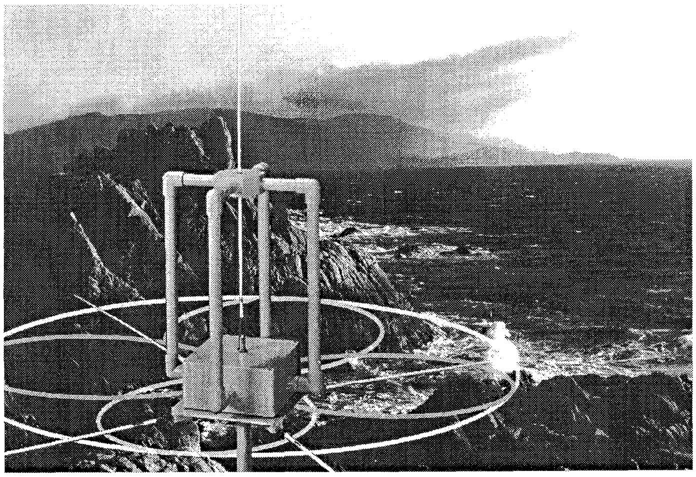

Fig. 1. Photo of SeaSonde crossed airloop receive antenna unit on post, with patterns sketched below.

radars for coastal surface-current mapping over 25 years ago (BARRICK *et. al.*, 1974; STEWART and JOY, 1974).

The major impediment to widespread HF radar use has been this large phased-array antenna size, demanding at least 100 meters of coast per site, not including their transmit antennas. Besides their large costs, this is a major inconvenience factor that often limits access to coastal points with desirable views, not to mention operation from offshore platforms. This obstacle was overcome by inventions at U. S. NOAA's research laboratories headed by BARRICK in the 1970s (BARRICK *et. al.*, 1977). Compact antennas replaced the large phased arrays, made possible by application of direction-finding (DF) principles instead of deam forming (LIPA and BARRIC, 1983; BARRIC and LIPA,1997). The SeaSonde family of products is its commercial culmination. Their compact antennas are kept out of reach, either on posts, building rooftops, or the derrick of an oil rig. Along with the introduction of a unique highly efficient waveform and its digital generation and processing, this low-powered compact system allows unmanned real-time operation. Some sites have continued for over six years uninterrupted. Its compact nature and ease of setup also makes it also well suited to quick-response deployments.

These breakthroughs-with resulting lower costs-increased the utility of HF radar, and may be responsible for the recent proliferation of SeaSondes. Although HF radar current mapping was demonstrated nearly 30 years ago, this revolutionary technology did not begin making its way into the oceanographic and user communities until the early 1990s. Over 50 units of the SeaSonde family have been built and sold since 1993 (most still operating today). These include standard systems with ranges of ~50 km, high-resolution versions for ports and harbors, and long-range units that can see beyond 200 km.

2. Accuracies achieved with direction-finding SeaSondes

One of the questions frequently asked is: how is it possible to get accuracies from compact radars that are equivalent to those from the large, conventional phased-array systems? The typical SeaSonde receive antenna is a crossed-loop/monopole unit mounted on a post, as shown in Fig. 1. Sketched underneath the antenna photo are plots of the idealized antenna patterns: two orthogonal cosine patterns(from the loops) and an omni-directional pattern (from the vertical monopole). When the antennas truly have these idealized patterns, a simple four-quadrant arctangent function will resolve the angle of the echo signal over 360° of bearing. In practice, the patterns are somewhat distorted by their environment, and measured patterns obtained during the initial system

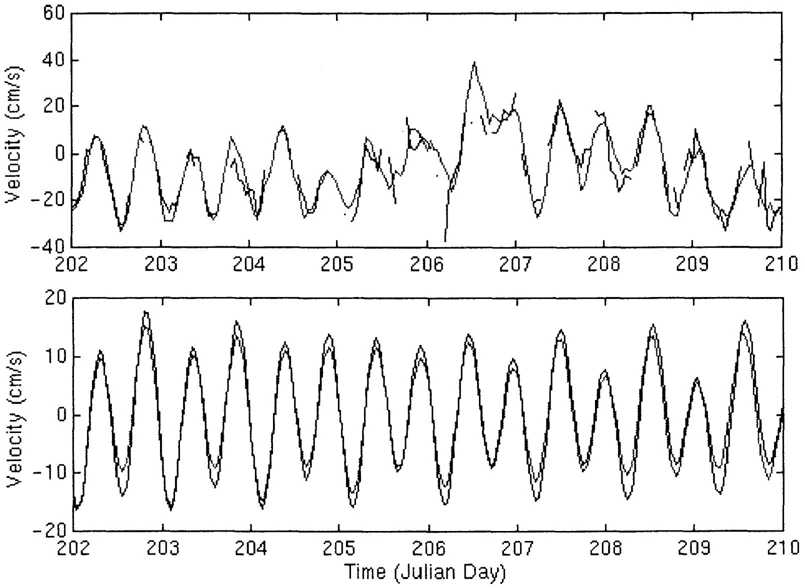

Fig. 2. Plots of raw radial current vector comparison (upper panel) for South site SeaSonde at Rutgers LEO-15 and ADCP bin 4.5 m below surface for one week; 6.7 cm/s rms difference. Lower is plot of radial tidal time series comparison for same week, with 2.3 cm/s rms difference. [From KOHUT *et al.*, 1999]

calibration are used in the DF algorithm to extract unbiased bearing angle. Bearing angle (DF) determination is done for each of the radial-velocity-shifted Doppler signals that comprise the first-order Bragg peaks.

Establishing accuracy with any HF surface-current mapping radar is difficult: no other instrument measures exactly the same thing. The HF radar senses the mean current within the upper meter, averaged over a horizontal radar cell. Multiple Lagrangian drifters have been tracked in Monterey Bay, CA for such comparisons. Perhaps the most frequently invoked comparison employs bottom-mounted acoustic Doppler current profilers (ADCPs), selecting their cell closest to the surface that is not contaminated by sidelobe reverberations; this is typically 3-5 meters deep. The water layer depth above this bin can also vary with tide height, being significant in some areas. Thus the ADCP output is essentially an Eulerian, point measurement that is then compared with an area average at different water depths. In additon, HF radar feels the Stokes drift (wave-induced current), whereas the ADCP does not. Nevertheless, this instrument comparison is probably the best available.

One recent such comparison was done with the Rutgers University SeaSondes deployed off New Jersey. Located 29 km from the southern SeaSond, the radials (i. e., current components at the ADCP pointing toward the radar) were compared hourly for one month, a typical week's data being shown in Fig. 2 (KOHUT *et al.*, 1999). The closest ADCP bin to the surface that could be used was 4.5 m deep. The rms difference in the raw, hourly time series over one month was 6.7 cm/s. The radial tidal components that were extracted from the month time series are shown in the lower panel of Fig. 2 for the same week, their rms difference is 2.3 cm/s. Not all of these differences are errors in one or the other instrument, but it can be said with certainty that any instrumental error did not exceed these amounts. These differences are comparable to (slightly better than) those observed with the OSCR 100-m phased array operated by U. of Miami(CHAPMAN and GRABER, 1997).

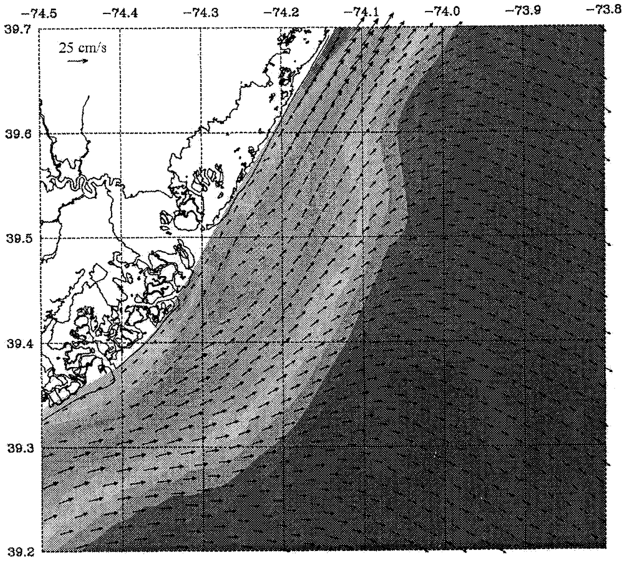

Fig. 3a. Ocean numerical circulation model outputs for July 17, 1998 without SeaSonde data assimilation. [From KOHUT *et al.*, 1999]

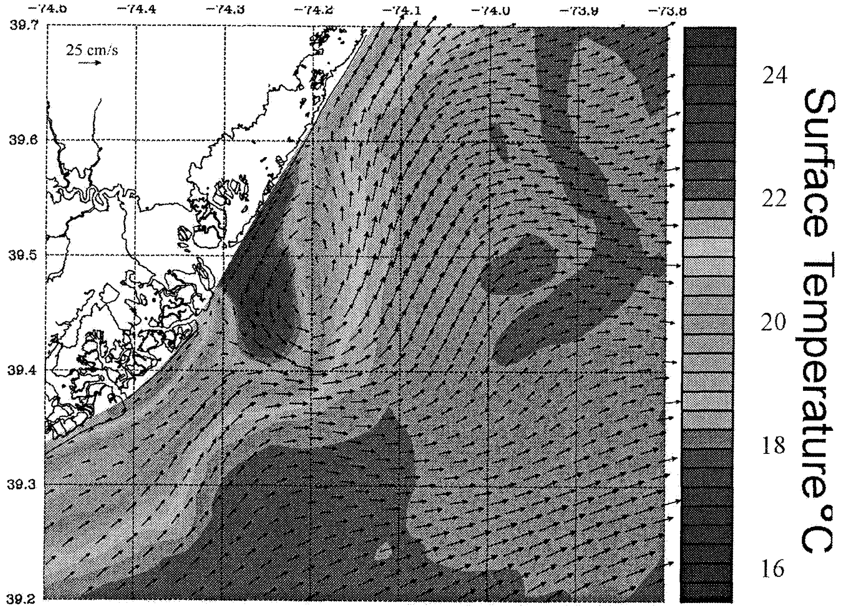

Fig. 3b. Ocean numerical circulation model outputs for July 17, with SeaSonde data assimilation. The assimilation dramatically improves the model's capability to forecast the observed eddy and upwelling center, as confirmed by independent observations. [From KOHUT *et al.*, 1999]

3. Benefits of assimilation of SeaSond current maps into circulation models

Variations of the Princeton Ocean model (POM) developed by Mellor and Blumberg in the 1970s(BLUMBERG and MELLOR, 1987) have been widely used for nowcasting and forecasting oceanographic conditions in coastal regions and marginal seas around the world. Like all numerical models, the POM's forecast skill depends on obtaining the best possible initial conditions and can be improved by data assimilation. Some work has already been done on assimilation of HF radar current data into the POM model in the Monterey Bay (LEWIS *et al.*, 1998). The results are encouraging, but indicate that additional smoothing of the radar data may be necessary for use with mass-conserving numerics. This work is continuing in the bay under the auspices of the National Ocean Partnership Program (NOPP). Recently, the Rutgers University Regional Ocean Modeling System (ROMS) has also been used to assimilate the CODAR SeaSond data. A key feature of the summertime oceangraphic situation off the New Jersey coast is the evolution of anticyclonic eddies that accompany upwelling events. Without SeaSonde surface current map data the ROMS model consistently omitted these essential features. The model was subsequently initiated both with and without the SeaSonde surface current information. The non-assimilative model did not reveal the development of an upwelling eddy on July 17, 1998 (Figure 3a), while the assimilative model clearly shows this feature (Figure 3b). The eddy's existence was confirmed by subsequent in-situ and satellite AVHRR observations. The assismilation in turn led to better forecasts that were useful in planning vessel sampling operations associated with LEO-15 (KOHUT *et al.*, 1999).

4. Conclusions

HF radars for coastal and offshore current mapping have found acceptance and are rapidly proliferating in recent years. Part of this may be due to the availability of compact, low-cost, easy-to-deploy and use SeaSonde-type radar designs since 1993. This makes both long-term deployments-as well as short several-week field campaigns-much easier to implement. Accuracies are demonstrably comparable to or better than those of the older larger phased array designs. Among the oceanographic and marine applications of radar current maps, we highlight here the improvement offered in numerical circulation forecasting based on their assimilation into these models.

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