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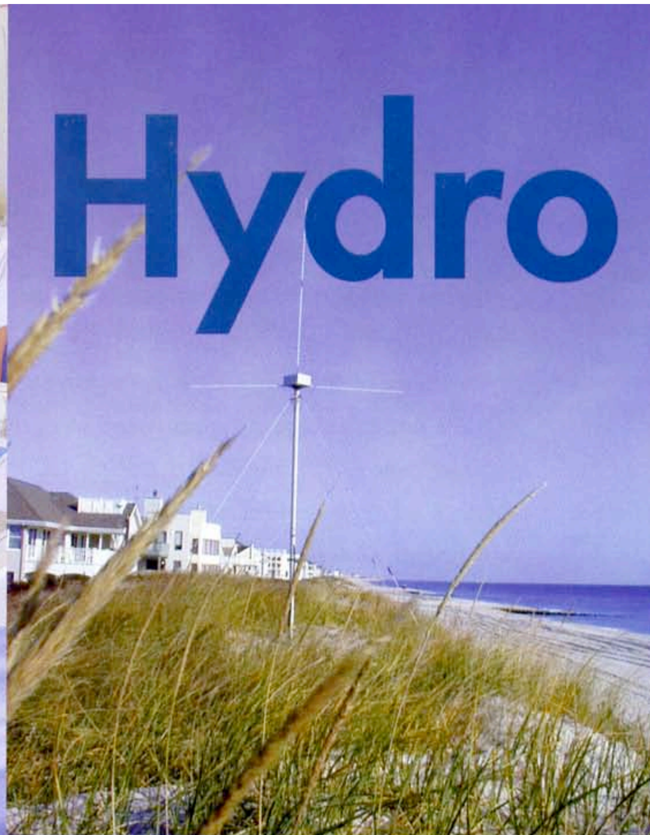
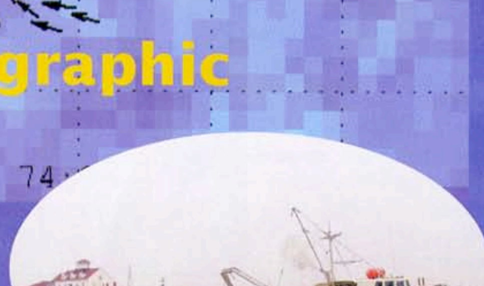


Tides and Currents

Tides in the Chilean Coasts

Improving the Accuracy of Coastal HF Radar Current Mapping

Establishing a Hydrographic Production Database



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Calibrating with measured antenna patterns and smoothing the raw velocities tightens the rms difference between surface HF radar data and subsurface ADCP data. Applying both remedies brings the overall rms differences to 8.7 cm/s. But does good agreement with ADCPs equate to good accuracy? To some extent, but not entirely. Data measured during COPE-3 on the Virginia coast provides some insight but raises additional questions.

By Jeff Paduan, Don Barrick, Dan Fernandez, Zack Hallock and Cal Teague

Improving the Accuracy of Coastal HF Radar Current Mapping

Application to SeaSonde

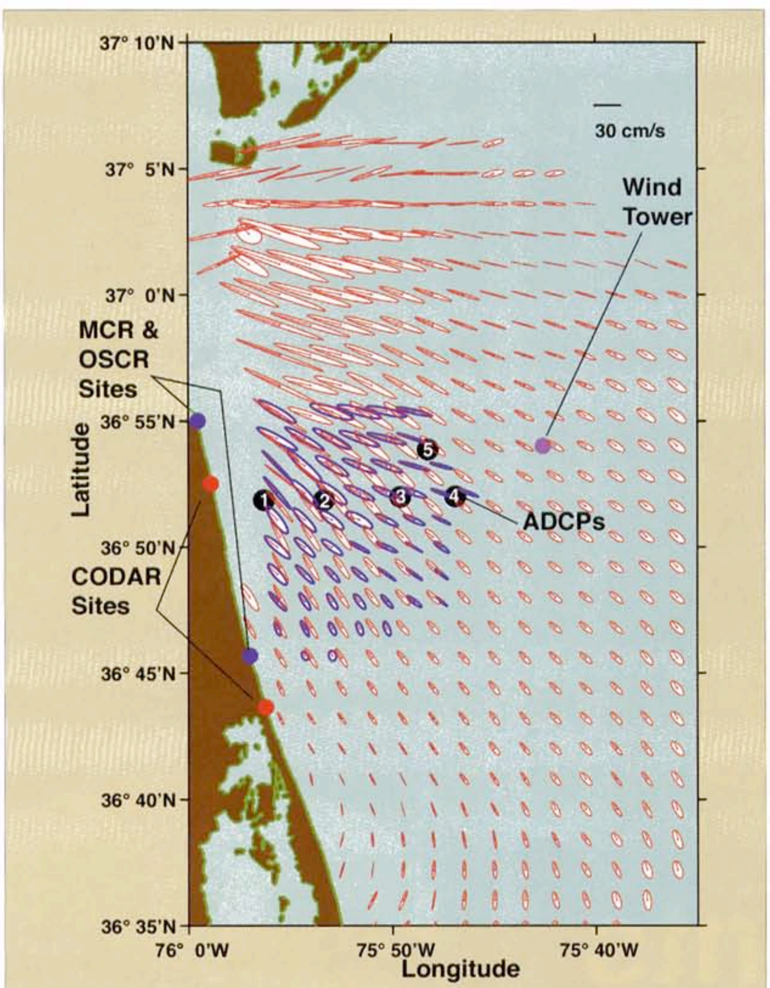

Figure 1: COPE-3 data area and geometry off Virginia Beach, VA. M2 tidal ellipses are shown, inferred from SeaSonde assuming ideal antenna patterns (red) and MCR (blue) HF radar current maps

The use of coastal HF radars to map surface currents has increased greatly over the last five years. The number of SeaSondes sold and operating worldwide evidences this: more than 70. Some of these are used over shorter ranges (less than 50 km), filling in high spatial detail as small as 200 metres. Some see out to 200 km with resolutions of 3-6 km. In many cases, real-time current maps from permanent networks are posted on websites available to the public (http://oc.nps.navy.mil/~icon and http://marine.rutgers.edu/mrs). Other users deploy transportable units during oil spills (http://www.cbi.tamucc.edu/projects/hfradar). Several groups are assimilating real-time current map data into numerical circulation models, with the goal of providing forecasts of circulation on and across the continental shelf, a job now easier with the 200-km systems being deployed.

The biggest source of error or bias in every HF radar creeps in when determining the bearing angle to the ocean echo source. Improving this angle estimate comes down to obtaining an accurate description of the antenna pattern and using it effectively in the current extraction processing. We examine this below. After eliminating system errors and biases as much as possible, we must

Figure 2: Photo of SeaSonde electronics (left) and antennas (right) at North site cottage

seek to explain remaining differences in comparisons with 'ground truth' from other instruments in terms of the differing natures of the various measurements.

How HF Radars Map Surface Currents

At HF, sharp Doppler peaks in sea echo come from approaching and receding gravity waves half the radar wavelength. This is Bragg scatter. Their wave periods at HF vary between 1.5 and 4.5 seconds, depending on the radar frequency. In the absence of currents, the Doppler positions of these peaks are known from the dispersion relation. The added shift from this known position is due to underlying currents near the surface. A single radar can observe only the component pointing towards or away from the radar at a given bearing and range; this is called the 'radial' component. Two radars are normally used to resolve the total horizontal current vector at each point observed by both simultaneously.

Range to the scatter cell and echo Doppler shift are measured very precisely by all properly functioning HF radars. The big differences arise in how they measure the bearing to the scattering point. Conventional phased-array systems scan beams formed by very large receiving antennas by changing phasings among the array's antenna elements. The compact SeaSonde crossed-loop antennas rely on DF (direction finding) principles rather than on beam forming. If the antenna patterns were perfect, one could take the arctangent of two crossed-loop signal ratio (one being a sine and the other a cosine function of angle), to get the bearing angle. In practice, a much more robust algorithm is used, called MUSIC.

An immediately noticeable difference in the appearance of radial vector maps are gaps that show up when DF is applied. For each consecutive radial velocity (or Doppler) bin, one or more angles are sought from which the echo originated. There may not always be an angle cell with a solution in it. With phased arrays, one generates phasings to steer the beam to each desired angle, and estimates the velocity from the Doppler shift of the Bragg peak. Thus, one gets a vector at each requested grid point, and these maps always appear filled in. However, the pleasing appearance may hide biased data if the antenna patterns are distorted.

What Are Distorted Antenna Patterns?

If antenna patterns depart from the ideal - and if this distortion is not known - then estimates of bearing for both beam forming (i.e. phased arrays) and direction finding (e.g. SeaSonde units) must occur. Thus, the 'apparent' radial velocity at one point is actually contaminated by the speed at another bearing. This is an error that can be eliminated. In practice, distortions are caused by the local environment near the antenna, rather than defects in manufacturing. In several instances, we have replaced the antenna at a given location by another unit several years later, but have seen the pattern remain the same, demonstrating that it's 'environment' rather than 'genes'. Nearby buildings, trees, posts, fences, the antenna cabling, and hilly terrain are possible culprits.

Remedies include moving to a better location. Often this is not an option because good site availability is difficult to find in crowded coastal regions. So one must live with the actual pattern by measuring it and using it to calibrate the received signals.

Antenna patterns are measured at all SeaSonde installations by circling the antenna with a boat-carried small battery-operated transponder. At a typical distance of 1 km, such a boat run takes about half an hour. When synchronised with an on-board GPS position log, the received transponder signal on the different antenna channels gives the level of distortion. Three degradations are observed: (i) amplitude imbalances or drifts among the different receive elements; (ii) phase differences or changes among the elements; and (iii) distortion of the individual antenna element patterns from ideal, i.e., the sine or omni-directional patterns of loops and monopoles become noticeably deformed. All of these degradations, if they are significant, are included in SeaSonde MUSIC bearing extraction algorithms.

COPE-3 Provides Comparative Measurements

During the Fall 1997, three pairs of coastal HF radars having totally different designs were operated simultaneously during the third Chesapeake Outfall Plume Experiment (COPE-3). Their locations are shown in Figure 1: the OSCR (ocean surface current radar) and MCR (multi-frequency coastal radar) are phased arrays that were collocated, while the sites of the SeaSonde pair were spaced about 3 km south of the phased-array pairs. The figure also shows the locations of five bottom-mounted ADCPs, and M2 tidal ellipses produced by the SeaSondes and MCRs over the area. With a few time gaps, data were gathered by all three systems from mid-October till the end of November.

The SeaSondes were based in summer cottages on the shore, with the antennas mounted on posts in the back yards. Figure 2 shows the North site arrangement. Antenna pattern measurements from a boat were attempted for both sites, but only the North site data was usable. The antenna patterns for that site are shown in Figure 3, along with ideal, desired sine pattern models as the heavy solid lines. Idealised patterns have been balanced in amplitude to match measured pattern strengths. The measured patterns differ noticeably from the ideal. This is due to the clutter in the back yard observed in Figure 2, with the fence, seawall, and nearby buildings. One should expect differences in the radial currents if the distortions are ignored and ideal patterns are used; these consequences are studied below.

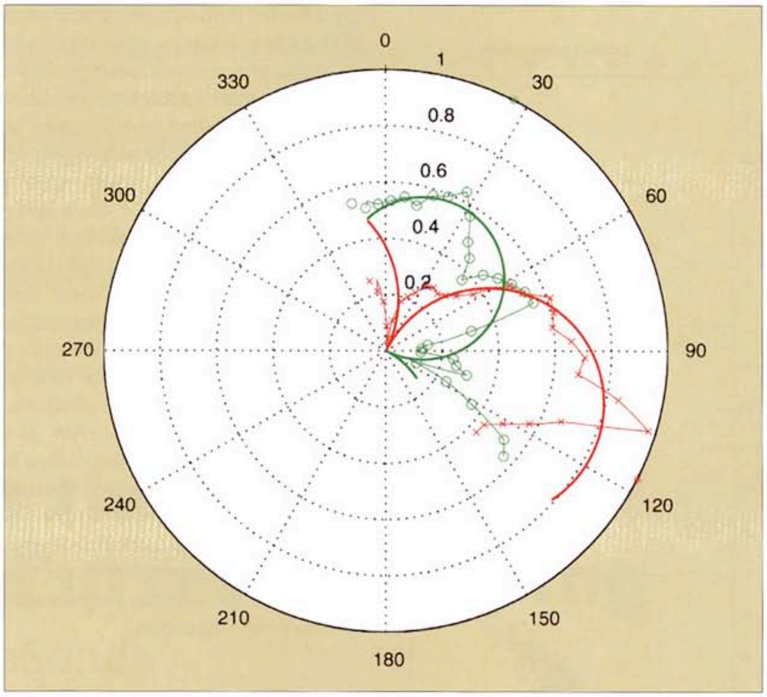

Figure 3: Plots of normalised, boat-measured crossed-loop amplitude patterns and ideal patterns (solid heavy curve)

How Do SeaSonde Radial Velocities Compare?

Hourly radial velocity maps that are produced at each site are combined to create total vector maps. We therefore want radial maps as free from error as possible. We show results in Figure 4 from three processing alternatives, all using the standard SeaSonde MUSIC direction-finding algorithm: (i) Using antenna patterns even though the actual patterns are not ideal; amplitude and phases among the antenna elements are balanced, however. (ii) Using measured patterns of Figure 3 and the normal 5° SeaSonde angle grid. (iii) Using measured patterns as in (ii) and then smoothing and interpolating the resulting radial currents over angle with a 15° Gaussian beam window.

When ideal patterns are used (Figure 4 top), angle solutions are sought over 360° of space. In principle, no vectors would fall over land if there was no error in the process. Distorted antenna patterns are a source of error. Consequently the appearance of vectors over land is a diagnostic of bearing bias severity. The narrow land sector with vectors here is considered acceptable. Note occasional gaps in the normal regular grid; their cause was discussed earlier.

When measured patterns are used with the same MUSIC algorithm, there are no vectors produced over land because the patterns - measured by boat - cover only the sea (Figure 4 middle). On the other hand, more gaps appear in the radial vector maps. The Gaussian interpolating and filtering done on these gappy maps fill them in nicely, the effect being a low-pass filter over angle with a width about 15°.

The right panels of Figure 4 show scatter plots of SeaSonde radials vs ADCP measurement of the radially directed component 2 m below the surface at Location 4, for the three respective processing methods.

From scatter plots like those of Figure 4, Table 1 summarises comparison statistics between ADCP and the SeaSonde radials for the three bearing processing methods at all five ADCP positions. The final row is the average of the rms differences and correlations over the five ADCP locations.

Discussion of Agreement and Unexpected Implications

Clearly, use of antenna patterns helps narrow the rms differences and increase the correlations at all locations. This, despite the general appearance of more gaps in coverage. The gap widths do not tend to be large, suggesting that interpolating and smoothing (filtering) is appropriate. This of course gives the maps a very pleasing appearance, but most of us tend to be wary that information can thereby be destroyed. Thus it is surprising that ADCP comparisons (both rms differences and correlation coefficients) show better agreement when smoothing is applied. The

ADCP Position	Ideal Pattern Used	Measured Pattern Only	Measured Pattern with Smoothing
1	13.9 cm/s 82% (459)	11.4 cm/s 79% (430)	8.3 cm/s 89% (546)
2	15.2 cm/s 77% (472)	13.3 cm/s 84% (254)	9.6 cm/s 90% (550)
3	16.8 cm/s 67% (403)	11.1 cm/s 85% (265)	9.2 cm/s 85% (549)
4	13.7 cm/s 68% (393)	10.5 cm/s 81% (247)	7.1 cm/s 87% (550)
5	13.1 cm/s 76% (207)	13.4 cm/s 84% (230)	9.5 cm/s 90% (249)
Average of All	14.5 cm/s 74%	11.9 cm/s 83%	8.7 cm/s 88%

Table 1: Root mean square difference and correlation expressed as a percentage, for hourly SeaSonde and ADCP data, followed by number of points (parentheses), in the analyses over the period October-November, 1997

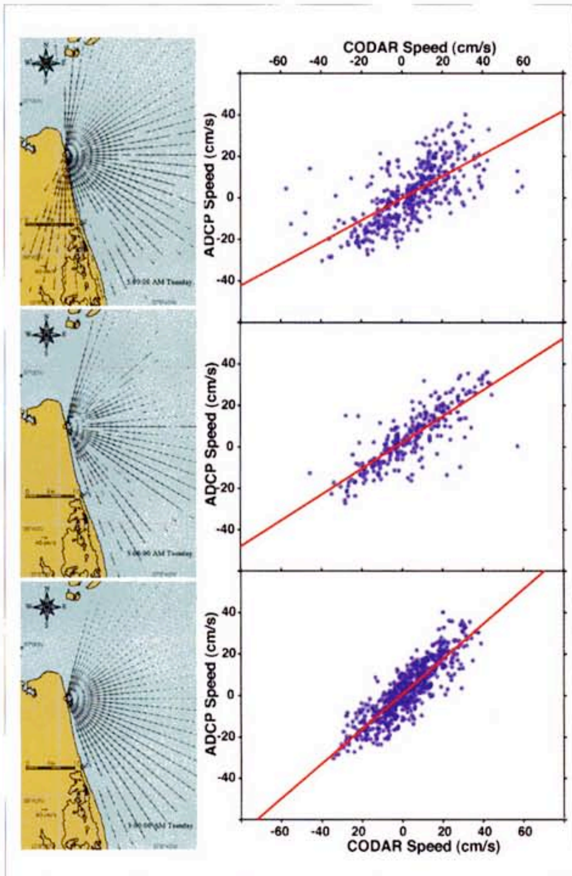

Figure 4: North-site SeaSonde radial velocity vector maps, to left. To the right are scatter plots of SeaSonde radial velocities compared to ADCP at Location #4. Top set is based on ideal antenna patterns; middle on actual measured patterns; bottom on measured with 15° radial velocity angle smoothing

sample size and number of different positions are sufficient to guarantee that these trends and conclusions are statistically significant. What is going on here?

The nature of the two measurements (HF radar and ADCP) is different. The two are respectively area and point measurements. More important, the HF radar feels currents on the surface (at a mean depth of 0.5 m in this case), while the ADCP senses currents deeper (2 m). Much of the wave motion and a large part of near-surface current turbulence may be damped at that depth. In addition, HF radar currents are measured indirectly through scatter from waves. This wave-scattered signal is a zero-mean Gaussian random variable. Hence, smoothing - both spatially (over angle) and temporally - will suppress some of these random effects near the surface, giving better ADCP agreements.

These results suggest the following hypothesis. If good agreement with ADCPs is a measure of quality, then go ahead and smooth, average, filter, etc., both over space and time. We have not established here the level of filtering at which agreement begins to deteriorate. But one is left with the nagging question, am I destroying information near the surface that could be useful in its own right? It is not clear at this point what this information is, or how to extract it. The inherent resolutions of the radars preclude any direct validation of fine-scale spatial/temporal variations, although it is possible that the 'noisiness' measured by the radars is related to the actual current fluctuations at sub-grid scales. Future HF radar experiments combined with ships, AUVs, or radar remote sensing at alternate frequencies may be able at answer this question.

How Do the Different Radars Compare?

MCR comparisons with all five ADCPs were recently calculated by Teague and Vesecky and will appear in IEEE Journal of Oceanic Engineering. In that analysis, MUSIC direction finding was used to estimate bearing angle with their 8-element phased array, rather than conventional beam forming. This represents the first reported uses of direction finding with linear phased arrays, and the rms difference comparisons in fact turned out better than previous COPE-3 MCR estimates when beam forming had been used. As with the SeaSonde, the MCR also calibrated its antenna patterns with boat measurements. We compare here results only at their upper frequency 21.8 MHz (the radar employs four frequencies simultaneously), because it is closest to the 25 MHz SeaSonde and OSCR frequencies. Also, it generally gave better ADCP agreement than the lower three frequencies. We compare the MCR 'u' (East) component of surface current, because the SeaSonde radial direction points nearly East along the ADCP mooring line. At the five consecutive ADCP locations, equivalent rms 'u' speed differences at the North Site are: σu = 20.2; 15.0; 9.2; 7.0; and 10.1 cm/s. These should be compared with those for the SeaSonde at the same locations in Table 1. The average of these rms differences is σu = 12.2 cm/s, compared to σr = 8.7 cm/s for the SeaSonde with pattern and filtering. For the OSCR system, radial comparisons with the ADCP have not been published. However, initial vector comparisons place the results within the 8.7 cm/s to 12.2 cm/s range from the SeaSonde and MCR systems.

Biographies

Jeffrey D. Paduan received his B.S.E. from the U. of Michigan and his Ph.D. in physical oceanography from Oregon State U. In 1991 he joined the faculty of the Department of Oceanography at the Naval Postgraduate School where his research has focused on the application of HF radar systems in coastal oceanography.

Donald E. Barrick received a B.E.E., M.Sc., and Ph.D. from the Ohio State U. in electrical engineering. In the mid 80s, he founded CODAR Ocean Sensors, Ltd., a company that has created and developed the SeaSonde line of HF radars. His scientific interests include radar remote sensing, electromagnetics, antennas, signal processing, and applications to oceanography and marine operations.

Daniel M. Fernandez received his B.S. in electrical engineering from Purdue U., and his M.S. and Ph.D. in electrical engineering from Stanford U. Since 1996 he has been a faculty member at California State U., Monterey Bay where he teaches physics and conducts research in HF radar and its applications to the marine environment.

Zachariah R. Hallock received a B.S. in physics from the Polytechnic Institute of Brooklyn, a M.S. and Ph.D. in physical oceanography from the Rosentiel School of Marine and Atmospheric Science of the U. of Miami. In 1981 he came to the oceanography division at NRL, where his present research focuses on coastal ocean processes including tidal studies, ocean front and internal wave effects on acoustics.

Calvin C. Teague received his B.S., M.S. and Ph.D. in electrical engineering from Stanford U. In 1971 he joined the research staff of Stanford U., full-time until 1991 as a Senior Research Associate, and remains there now part-time. His primary research has been a study of the use of resonant scatter of radio energy by ocean surface waves as a remote sensing tool. ■